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COMPETITION BETWEEN KEY PROJECT PARTICIPANTS DURING PROJECT EXECUTION: A SYSTEM DYNAMICS APPROACH

by

Mutizwa Alfred Chitongo
12279422

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Supervisor: Professor Leon Pretorius

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I, Mutizwa Alfred Chitongo declare that -

the thesis, which I hereby submit for the degree at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

I have obtained, for the research described in this work, the applicable research ethics approval. I have observed the ethical standards required in terms of the University of Pretoria's Code of ethics for researchers and the Policy guidelines for responsible research.

Abstract

Project management is one of the most important forms of management due to its versatility, demand and widespread use in almost every field and organisation. Yet, poor project performance continues to be commonplace. Existing literature highlighted conflict as one of the inevitable challenges encountered during project execution owing to the inherent interdependencies and interactions among project stakeholders, who often have different objectives and expectations, and take different decisions and control actions aimed at protecting their different and competing performance measures and targets. Though often intendedly rational, such different controls turn out to be mutually-exclusive, resulting in the use of competition (aimed at win-lose results) as a conflict-handling style. Indeed, some previous researchers highlighted the prevalence of such competition during project execution. However, project dynamics emanating from such competition are largely under-researched in the reviewed literature.

This research study sought to address this gap. Specifically, it investigated, using system dynamics: how competition develops between two key project participants (client and engineering consultant) during project execution; how the competition influence both project performance and the engineering consultant's project business performance; and, how the competition can be improved to yield win-win long-term results. It followed a mixed methods research design, incorporating the system dynamics approach. Firstly, appropriate dynamic hypotheses and a system dynamics conceptual model of the competition were formulated from a combination of existing literature, an embedded multiple-case study, and systems thinking. Then, an appropriate system dynamics simulation model of the competition was formulated. Data gathered for 18 unique raw water infrastructure-related projects were used for model calibration, as well as simulation and optimisation experiments.

Simulations and impact analyses results were counterintuitive, highlighting the dynamic complexity of the competition. Firstly, client project cost controls (aimed at reducing project cost overrun) generated some unintended effects that increased the project cost overrun. Secondly, engineering consultant project revenue controls (aimed at reducing project revenue shortfall) generated some unintended effects that increased the project revenue shortfall. Thirdly, the competition (aimed at win-lose results) negatively influenced both project performance (client's interest) and engineering consultant's project business performance (lose-lose long-term results).

Policy optimisation results suggested key interventions that improved the competition, enhancing both project performance and engineering consultant's project business performance (win-win long-term results). Firstly, the two key project participants need to adequately apply systems thinking, recognising that: they are interdependent subsystems of a bigger system (the project) whose emergent properties include project performance and engineering consultant's project business performance, as neither participant can individually achieve his/her performance targets; and thus, they cannot afford to operate in 'silos', taking project controls aimed at win-lose results. Secondly, they need to fully align their individual performance targets, as this eliminates/minimises the performance gaps that trigger the competing project controls.

This research study made some novel contributions that expand knowledge in a number of areas. Firstly, the model calibrations, simulations, impact analyses and policy optimisations experiments were conducted separately for each set of unique projects (10 asset management planning and support-related, and 8 asset-renewal related), with subsequent comparison and discussion of the results aimed at enhancing the validity of the above-highlighted research results. This is a novel extension to the existing system dynamics model validation body of knowledge, currently limited to the use of only one project or multiple projects of the same type.

Secondly, the formulated system dynamics simulation model of the competition is unique as no appropriate system dynamics model could be identified, in the reviewed literature, that considered competition among project participants, with their different and competing performance measures and targets during project execution. It is a novel extension to the existing project dynamics models (that only focus on one project participant) and helps project managers to deepen their understanding of project dynamics. Thirdly, the finding that the competition (aimed at win-lose results) yields lose-lose long-term results provides an alternative explanation as to why poor project performance is common. This and the recommended interventions that yield win-win long-term results are novel contributions to conflict handling and project performance bodies of knowledge.

Lastly, the findings highlighted that the engineering consultant's project business performance is another key emergent property of the project system, like project performance, essential to yield win-win long-term results. This is a novel contribution to the application of systems thinking to project management body of knowledge, currently narrowly focussed on only project performance.

Keywords: business performance; competition; project controls; project participants; project performance; system dynamics; unintended effects.

List of Related Publications

Journal Articles

Chitongo, A. M. and Pretorius, L. 2018. Client project time schedule controls — An empirically-based System Dynamics conceptual model. *The South African Journal of Industrial Engineering,* vol. 29, no. 1**,** pp. 169-183.

Chitongo A. M. and Pretorius L., 2018. Unintended negative effects of client project cost controls: A System Dynamics Approach, *The South African Journal of Industrial Engineering,* vol. 29, no. 3**,** pp. 121-131.

Conference Papers

Chitongo A. M. and Pretorius L., 2016. Competition among project participants: a preliminary System Dynamics conceptual model. *12th INCOSE South Africa Systems Engineering Conference*. Pretoria.

Chitongo, A. M. and Pretorius, L. , 2017. Engineering Consultant Project Cash Flow Controls - An Empirically-Supported System Dynamics Conceptual Model. *Proceedings of PICMET '17: Technology Management for Interconnected World*. Portland.

Chitongo, A. M. and Pretorius, L., 2017. Engineering Consultant Project Revenue Controls: A System Dynamics Conceptual Model. *5th Annual System Dynamics Conference in South Africa*. Johannesburg.

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List of Abbreviations

CLD	:	Causal loop diagram
CPI	:	Cost Performance Index
DSR	:	Design Science Research
INCOSE	:	International Council on Systems Engineering
ISO	:	International Organization for Standardization
KPIs	:	Key performance indicators
MAPE	:	Mean absolute percentage error
MMR	:	Mixed Methods Research
MoP	:	Management of Projects
PMBoK Guide	:	A Guide to the Project Management Body of Knowledge
PMI	:	Project Management Institute
QUAL	:	Qualitative primary/core component of an MMR design
QUAN	:	Quantitative primary/core component of an MMR design
qual	:	Qualitative supplementary component of an MMR design
quan	:	Quantitative supplementary component of an MMR design
RPI	:	Revenue Performance Index
SPI	:	Schedule Performance Index
SFD	:	Stock and flow diagram
SOS	:	System of systems

1. Introduction, Purpose and Expected Contribution of this Study

1.1. Introduction

This chapter provides an introduction to the current research study as well as to this thesis report. It begins with a contextualising background, discussing projects as systems, defining ‘key project participants’, highlighting competition among project participants during project execution, and the need for system dynamics. It then formulates the problem statement, and indicates the rationale for the study. Next, it formulates appropriate research objectives and research questions, highlighting the key expected contributions of the study. Subsequently, it outlines the research methodology followed, and then presents a layout of this thesis report, indicating the key activities and/or outputs of each chapter. Lastly, it highlights the key constraints and assumptions of the study.

1.2. Background to the Research Study

1.2.1. Systems, Projects and their Life Cycles

Systems

Different scholars use different words in defining what a ‘system’ is. Nonetheless, there is general congruence in the reviewed literature that: a system is made up of a number of inter-related elements that, through inter-relationships and interactions, achieve a common objective; the system, as a whole, has emergent properties (created from the interactions and inter-relationships of its elements) that are greater than the sum of those of its individual elements (holism); and a system may exist within some hierarchy having different layers of systems, system of systems (SOS), in which sometimes the system is viewed as a system and sometimes as a subsystem (Blanchard, 2008; Checkland, 2012; Monat and Gannon, 2015; Walden, Roedler, Forsberg, Hamelin and Shortell, 2015). Monat and Gannon (2015) also highlighted that the inter-relationships among the elements of a system are, at least, as important as the system’s individual elements in shaping the behaviour and performance of the system. A system also needs to be adaptive, in order to survive, as its environment changes and delivers some ‘shocks’ to it (Checkland, 2012).

Systems may be classified into two broad categories, namely: natural systems (e.g., the solar system); and human-made systems (e.g., a road network), as highlighted by Monat and Gannon (2015). Typical examples of the elements/subsystems of a human-made system include: people, equipment, products (hardware, software, firmware), facilities, data and information, policies, processes, documents, and services, among others (Blanchard, 2008; Walden et al., 2015).

Projects as Systems

A 'project' is a temporary (definite start and finish) endeavour that is undertaken to create a unique deliverable (product, service or result, or any combination of the three) (Project Management Institute, 2017). It is a human-made complex dynamic system (Locatelli, Mancini and Romano, 2014; Nicholas and Steyn, 2012; Pourdehnad, 2007). There are two systems generally associated with any single project, namely: the 'created system' (a system of the project deliverables) and the 'creating system' (the project itself, being a system of human resources, facilities, equipment, materials, data and information, documents, and other elements required to produce the project deliverables), according to Nicholas and Steyn (2012). The current research study focusses on the project as a 'creating' system.

System Life Cycle and Project Life Cycle

A system life cycle is the series of stages through which the system passes through, from the identification of the need for the system to the disposal of the system (Blanchard, 2008; Monat and Gannon, 2015; Walden et al., 2015). Typical life cycle stages of an engineered (human-made) system are: concept (identification of the need for the system, conceptual/preliminary design); development (detail design and development); production and/or construction (including integration and commissioning); utilisation/operation and maintenance support; and retirement/ decommissioning and disposal (Blanchard, 2008; Walden et al., 2015). Whilst these system life cycle stages are logically sequential, in practice the stages may overlap; the activities within the different stages may be interdependent, overlap or run concurrently (Blanchard, 2008; Walden et al., 2015).

A project life cycle is the series of phases that the project evolves through from its initiation to its completion (Project Management Institute, 2017). It can typically be split into three main phases (which may overlap), namely: conception (problem definition, user needs, and feasibility); definition (solution definition – user requirements, system objectives and system requirements) and execution (design, construct, hand-over to client and close-out) phases (Nicholas and Steyn, 2012). Thus, a project life cycle is basically that part of a system life cycle that involves the creation or upgrading of systems (Walden et al., 2015).

The current research study focusses on the project execution phase as it is the most challenging phase to manage in a project life cycle (Pourdehnad, 2007), yet it is one of the most crucial as its final output needs to be handed over to the client as a complete system ready for effective and efficient realisation of the intended project benefits. The next sub-section indicates the particular type of projects that this research study focusses on.

1.2.2. Infrastructure Projects

Infrastructure development plays a pivotal supporting role in the economic development and growth of any country, as highlighted by many scholars including Ansar, Flyvbjerg, Budzier and Lunn (2016), Henckel and McKibbin (2017), and Vickerman (2018). Previous project research studies covered different types of infrastructure, such as: educational facilities (Ngacho and Das, 2014; Parvan, Rahmandad and Haghani, 2015); electricity (Nguyen, Chileshe, Rameezdeen and Wood, 2019; Ogano, 2016); rail transportation (Vickerman, 2018); road transportation (Kaliba, Muya and Mumba, 2009); sports facilities (Molloy and Chetty, 2015); telecommunications (Kim, Lee and Ahn, 2006); and water (Wen, Qiang and Peter, 2018; Zarghami, Gunawan and Schultmann, 2018), among others.

While some infrastructure projects are success stories, there are many cases of poor project performance (especially time schedule delays and cost budget over-runs) as highlighted by Ansar et al. (2016), Morris (2008), and Kaliba et al. (2009). The current research study focusses on raw-water infrastructure-related projects. The next sub-section defines what is meant by the term ‘key project participants.

1.2.3. Key Project Participants During Project Execution

Project stakeholders may be classified into two main groups, namely: those actively involved in the execution of the project; and those whose interests may be affected (either positively or negatively) by the execution or completion of the project (Project Management Institute, 2017). Those project stakeholders who are actively involved in the execution of the project are, in this research study, referred to as project participants, in line with Shen, Song, Hao and Tam (2008), to differentiate them from the latter group.

Project participants typically include the project manager and his/her team, client (customer/owner), engineering consultant (designer), sub-consultants, construction contractor (builder), sub-contractors, suppliers, and government departments (Davis, 2014; De Wit, 1988; Ngacho and Das, 2014; Project Management Institute, 2017; Shen et al., 2008; Toor and Ogunlana, 2010). In this research study, the term ‘project participants’ (not project stakeholders) is used since the focus of this study is only on those stakeholders actively involved in the execution of the project. The key project participants during the execution of engineering projects are the client, engineering consultant and construction contractor (Ngacho and Das, 2014; Toor and Ogunlana, 2010). In this research study, only the client and the engineering consultant are considered. The next sub-section defines project management and highlights some of the key knowledge areas essential for a project manager’s competency, and some of the key challenges encountered during project execution.

1.2.4. Project Management and Challenges During Project Execution

Project management entails the application of relevant knowledge, skills, tools and techniques to project activities to ensure that the project objectives are met (Project Management Institute 2017). It is both an art (e.g., it relies on and deals with human beings and their behaviour) and a science (e.g., it makes use of information and communication technology-based tools and techniques, metrics, and industry and discipline standards) (Pourdehnad, 2007).

The Project Management Institute (PMI) publishes “A Guide to the Project Management Body of Knowledge (PMBoK Guide)”, from the first edition in 1996 to the current (sixth) edition released in 2017. The current PMBoK Guide identifies ten project management knowledge areas (integration, scope, schedule, cost, quality, resources, communications, risk, procurement, and stakeholder management) deemed essential for a project manager to effectively and efficiently manage a project from its inception to close-out (Project Management Institute, 2017). The International Organization for Standardization (ISO) also identified the same ten project management knowledge areas in its ISO 21500 guidance on project management standard (International Organization for Standardisation, 2012).

While the PMBoK Guide is quite useful in assisting the management of project execution, a number of researchers and scholars have criticised it for excluding some knowledge areas that are essential for the successful management of projects. Such knowledge areas include: conflict, conflict-handling and dispute management (Dogbegah, Owusu-Manu and Omoteso, 2011; Hwang and Ng, 2013; Morris, 2013); knowledge management (Dogbegah et al., 2011; Walden et al., 2015); project benefits management (Cha, Newman and Winch, 2018; Morris, 2013); project definition (front-end) (Cha et al., 2018; Morris, 2013); project governance and strategy (Cha et al., 2018; Locatelli et al., 2014; Morris, 2013); and systems thinking (Morris, 2012; Pourdehnad, 2007), among others. All these essential knowledge areas have largely been ignored by the PMI as evident in its current (sixth) edition of the PMBoK Guide (Project Management Institute, 2017). The current research study examines two of these additional knowledge areas, namely: conflict, conflict-handling and dispute management; and systems thinking.

Existing project management literature is replete with many challenges that are encountered during project execution as the project stakeholders interact. Such challenges include: different and competing objectives and expectations of the project participants (Cha et al., 2018; De Wit, 1988); conflict and competition among project participants (Barki and Hartwick, 2001; Lyneis and Ford, 2007; Mohammed, White and Prabhakar, 2009; Sutterfield, Friday-Stroud and Shivers-Blackwell, 2007); lack of trust among project participants (Manu, Ankrah, Chinyio and

Proverbs, 2015; Suprapto, Bakker and Mooi, 2015a; Suprapto, Bakker, Mooi and Moree, 2015b); language and culture barriers (da Silva, Costa and Prikladinicki, 2010); and inadequate knowledge and skills of project team and management (Rwelamila and Purushottam, 2012; Sommer, Dukovska-Popovska and Steger-Jensen, 2014), among others. These challenges (all of which are human behaviour-related) tend to worsen project dynamic complexity and, subsequently, project performance and project success, as effectively highlighted by the cited scholars. The next sub-section examines further the challenge of conflict and competition among project participants during project execution.

1.2.5. Competition Among Project Participants During Project Execution

Projects often have dependent activities (Zhu and Mostafavi, 2017) that are carried out by a number of people with different objectives (Cha et al., 2018; De Wit, 1988) and competing expectations (Project Management Institute, 2017). As a result, conflict is inevitable during project execution (Barki and Hartwick, 2001; Hwang and Ng, 2013; Morris, 2013; Project Management Institute, 2017).

Schermerhorn, Osborn, Uhl-Bien and Hunt (2012) highlighted two main categories of conflict, namely: functional/constructive conflict, which helps expose problems so that they can be solved, thereby benefiting the parties involved; and dysfunctional/destructive conflict, which creates negative energies and hostilities, hurts team cohesion, and disadvantages the parties involved. There are five different ways (styles) in which project participants can handle conflict, namely through: avoidance (withdrawing); accommodation (sacrificing); collaboration (problem-solving); competition (forcing/dominating); and compromising (Barki and Hartwick, 2001; Marques, Lourenço, Dimas and Rebelo, 2015; Project Management Institute, 2017; Rahim, 2002; Schermerhorn et al., 2012).

Collaboration is the ideal conflict-handling style since it results in win-win solutions, benefiting all the parties involved. However, competition, as a conflict-handling style, has been shown by some previous researchers (Lyneis and Ford, 2007; Mohammed et al., 2009; Sutterfield et al., 2007) to be quite common among project participants during project execution. Competition, as a handling conflict style, is whereby one party seeks victory (win-lose) by exerting power, force, superior skill, aggression or domination at the expense of others (Barki and Hartwick, 2001; Marques et al., 2015; Project Management Institute, 2017; Rahim, 2002).

Conflict is, thus, one of the key factors that influence competition among project participants. Another factor that can influence competition is the use of different/competing performance measures among project participants during project participants. On the one hand, during project execution, clients are particularly interested in project performance: they set their project performance targets and priorities, and take appropriate decisions and control actions to protect them. There are varying measures for project performance. For instance, Ngacho and Das (2014) proposed six key performance indicators, namely time, cost, quality, safety, site disputes, and environmental impact. On the other hand, the 'operations' of other project participants (such as the engineering consultant), as projectised organisations, entail execution of projects (Cha et al., 2018). Hence, such project participants are particularly interested in their business performance and its associated measures, and they also set their targets and priorities accordingly. There are also varying measures for business performance.

Other factors that can also influence competition, as evident in previous studies, include: asynchronous performance reviews; intended rationality (Sterman, 2000); mistrust (Manu et al., 2015); client scope changes (da Silva et al., 2010); and penalties (von Branconi and Loch, 2004), among others. The next section discusses system dynamics and its relevance to project management and competition.

1.2.6. System Dynamics Relevance to Project Management and Competition

System Dynamics (Systems Thinking and Modelling)

System dynamics is a multi-disciplinary approach whose goal is to assist managers improve their understanding of systems characterised by dynamic complexity, and use such understanding to design and develop more effective, high-leverage policies and structures that solve real-world problems and improve the performance of the systems (Martinez-Moyano and Richardson, 2013; Sterman, 2000). It was founded by Jay Wright Forrester in the late 1950s and early 1960s (Forrester, 2007a).

Systems are characterised by organised complexity, thus system problems can neither be solved analytically nor statistically (Checkland, 2012; Monat and Gannon, 2015; Weaver, 1948). Rather, systems thinking is a useful perspective towards understanding and dealing with problems of organised complexity (Checkland, 2012; Monat and Gannon, 2015; Pourdehnad, 2007; Weinberg, 1975). Monat and Gannon (2015) define systems thinking as "a perspective, a language, and a set of tools". They view systems thinking as: a holistic *perspective* that recognises systems as collections of inter-related components, and whose (systems') behaviours and overall performances (emergent properties) are dominated by the inter-relationships among the system components; a *language* that is made up of such key terms as complexity, events, patterns of behaviour; systemic structure, mental models, feedback loops, holism, unintended consequences, and leverage points, among others; and a *set of tools* that includes behaviour-over-time graphs, systemigrams, system archetypes, causal loop diagrams, and stock and flow diagrams, among others (Monat and Gannon, 2015). Checkland (2012), Pourdehnad (2007), and Sterman (2000) generally share the same view of what systems thinking entails.

Systems thinking is a useful first step towards understanding complex dynamic system problems; however, it is insufficient on its own (Forrester, 2007a). It relies on the human mind which is incapable of solving problems in systems characterised by dynamic complexity (Forrester, 2007b). Furthermore, experimentation in most real-world systems (such as projects) is very difficult, if not impossible, to carry out due to time and space differences between causes and effects (Sterman, 2002).

In order to gain a full understanding of complex dynamic system problems, identify the low-leverage policies and structures causing such problems, and develop more effective, high-leverage policies and structures that solve the problems and improve the performance of the systems, computer modelling and simulation are required (Forrester, 2007a; Forrester, 2007b; Sterman, 2000; Sterman, 2002). The founder of system dynamics emphasised this point by indicating that systems thinking contributes only about 5% towards the understanding of complex dynamic systems; with computer modelling and simulation essential in providing the remaining 95% (Forrester, 2007a). System dynamics, which is systems thinking plus computer modelling and simulation, is required for full understanding of complex dynamic systems (Forrester, 2007a; Forrester, 2007b; Sterman, 2000; Sterman, 2002).

A number of different versions of the system dynamics modelling process have been suggested in the existing literature. For instance, Sterman (2000) proposed a five-step system dynamics modelling process comprising problem articulation (boundary selection), dynamic hypothesis formulation, simulation model formulation, testing, and policy design and evaluation. More recently, Martinez-Moyano and Richardson (2013) proposed a six-stage system dynamics modelling process comprising problem identification and definition, system conceptualisation, model formulation, model testing and evaluation, model use, implementation and dissemination, and design of learning strategy/infrastructure. Their six-stage system dynamics modelling process does incorporate most of the five steps proposed by Sterman (2000). While different number of stages for the system dynamics modelling process have been proposed in the reviewed existing literature, system dynamics basically entails developing and testing of two key elements, namely a causal map and a simulation model of the system problem (Sterman, 2000; Sterman, 2001).

System Dynamics and Project Management

Systems dynamics helps managers to improve their understanding of systems characterised by dynamic complexity, and to use such understanding to design and develop more effective, high-leverage policies and structures that solve real-world problems and improve the performance of the systems (Martinez-Moyano and Richardson, 2013; Sterman, 2000). Dynamic complexity arises from the fact that systems are dynamic, tightly coupled (the system's components are inter-related and they interact with each other and also with the external environment), governed by feedbacks (some balancing/negative, and some reinforcing/positive), nonlinear (effect is often not proportional to cause), history-dependent and self-organising (path dependence), adaptive, counterintuitive (cause and effect are usually distant in both time and space), policy resistant, and are characterised by trade-offs (time delays in the feedbacks lead to differences between short-term and long-term responses to an intervention; and low-leverage policies lead to better-before-worse behaviour, while high-leverage policies lead to worse-before-better behaviour); and all these are characteristics of dynamic complexity (Sterman, 2000).

Projects, as systems (Daniel and Daniel, 2018; Nicholas and Steyn, 2012; Pourdehnad, 2007), are also characterised by dynamic complexity as highlighted by Daniel and Daniel (2018), and Zhu and Mostafavi (2017). Thus, systems dynamics may be usefully applied to projects and the management thereof so as to enhance project performance (Daniel and Daniel, 2018; Lyneis and Ford, 2007; Sterman, 1992). Zhu and Mostafavi (2017) emphasise the importance of understanding project dynamic complexity as key to enhancing project performance. Indeed, system dynamics has been extensively applied to the field of project management (Lyneis and Ford, 2007).

Dynamic Complexity of Competition and Need for System Dynamics

Human behaviour is one of the key factors that influence project dynamic complexity, according to Lyneis and Ford (2007), and Zhu and Mostafavi (2017). Competition among project participants, which essentially involves human behaviour and takes places within a project environment characterised by dynamic complexity, is thus inherently characterised by dynamic complexity. For instance: different project participants have different objectives (Cha et al., 2018; De Wit, 1988); and competing expectations (Project Management Institute, 2017), and thus define and measure performance differently; there are many interdependencies and interactions among the project participants; the project participants make decisions, usually intendedly rational, and take different control actions; there are often delays between the decisions/actions, their effects (some unintended and counterintuitive, as cause and effect are usually distant in both time and space) and the responses (feedbacks) of the other project participants; and there tend to be differences between short-term and long-term results (due to time delays and feedbacks) – all of which are characteristics of dynamic complexity (Sterman, 1992; Sterman, 2000).

Competition (aimed at win-lose results) among project participants tends to affect the whole system (the project, including project participants). Solving problems (such as competition) affecting the whole system requires systems thinking (Monat and Gannon, 2015; Weinberg, 1975). Furthermore, solving system problems involving dynamic complexity (such as competition) is not possible with the human mind alone; computer modelling and simulation are needed to support human decision making and management policies, as highlighted by Forrester (2007b) and Sterman (2000). Systems dynamics helps managers to improve their understanding of systems characterised by dynamic complexity, and to use such understanding to design and develop more effective, high-leverage policies and structures that solve real-world problems and improve the performance of the systems (Martinez-Moyano and Richardson, 2013; Sterman, 2000). Thus, system dynamics may be usefully applied in understanding and solving the problem of competition among project participants project execution. The next section highlights the problem statement for the current research study.

1.3. Problem Statement

Project management has proven to be one of the most important forms of management due to its versatility, demand and widespread use in almost every discipline, field and organisation. Yet, poor project performance continues to be commonplace (Molloy and Chetty, 2015; Morris, 2008; Standish, 2014; Sterman, 1992). Such poor project performance can be attributed, at least partly, to inadequate project management knowledge and skills (Hwang and Ng, 2013; Rwelamila and Purushottam, 2012; Sommer et al., 2014).

Indeed, many scholars highlighted the need for project managers to extend their knowledge beyond the ten knowledge areas recommended by the Project Management Institute (2017) to be fully competent. They proposed a number of additional knowledge areas, essential for the successful management of projects, including ‘conflict, conflict-handling and dispute management’ (Dogbegah et al., 2011; Hwang and Ng, 2013; Morris, 2013). Indeed, one of the challenges commonly encountered during project execution is conflict among project participants (Dogbegah et al., 2011; Sutterfield et al., 2007). Dysfunctional conflict is inevitable during project execution (Barki and Hartwick, 2001; Hwang and Ng, 2013; Morris, 2013) owing to the different objectives (Cha et al., 2018; De Wit, 1988), competing expectations (Project Management Institute, 2017), and the inherent interactions and interdependencies among the project participants (Barki and Hartwick, 2001).

The different objectives and expectations result in the project participants having different performance measures, targets and priorities during project execution. According to Tseng, Chiu and Chen (2009), financial performance is one of the key dimensions for measuring the business performance of an organisation. Indeed, other scholars, such as Goldratt and Cox (2004), and Gupta and Boyd (2008) emphasised that the goal of a 'for-profit' organisation is to benefit financially from its operations. As such, each project participant needs to benefit financially from the project, some during and some after project execution.

On the one hand, the 'operations' of an engineering consultant (or construction contractor), as a projectised organisation, basically entail execution of projects (Cha et al., 2018). Thus, the engineering consultant (or construction contractor) seeks to benefit financially (good financial performance, and thus good business performance) during project execution. Accordingly, the engineering consultant (or construction contractor) uses appropriate measures for business performance, sets certain targets, and takes appropriate controls aimed at protecting his/her business performance targets, during project execution.

On the other hand, the 'operations' of a client entail making use of the project deliverables to generate intended project benefits (Cha et al., 2018). Thus, the client can only benefit financially after project execution since the intended benefits can only be realised during operation and maintenance of the project deliverables; assuming a sequential system life-cycle, where operation and maintenance of project deliverables follows project execution (Blanchard, 2008; Cha et al., 2018).

During project execution, the client, thus, naturally focusses on minimising his/her investment into the project; whilst other project participants (such as engineering consultant and construction contractor) focus on generating financial benefits. Put differently, on the one hand, during project execution, the client is particularly interested in project performance and its associated measures, and sets targets and priorities accordingly. On the other hand, other project participants (such as the engineering consultant and the construction contractor) are particularly interested in business performance (of their own organisations) and its associated measures, and set targets and priorities accordingly, during project execution.

Accordingly, different project participants tend to take different decisions and control actions, in a bid to protect their different and competing performance measures when they face a particular challenge during project execution. Though often intendedly rational (Sterman, 2000), such different decisions and control actions turn out to be mutually-exclusive, leading to the use of competition (aimed at win-lose end-results) as a conflict-handling style. Indeed, Lyneis and Ford (2007), Mohammed et al. (2009), and Sutterfield et al. (2007) highlighted that the use of competition as a conflict-handling style is quite common among project participants during project execution. Nonetheless, no appropriate study could be identified, in the reviewed literature, that specifically investigated the influence of such competition on project performance and on the business performance of the engineering consultant (or construction contractor) during project execution.

Solving problems involving dynamic complexity (such as competition among project participants) is not possible with the human mind alone: system dynamics (which is systems thinking plus computer modelling and simulation) is quite useful in that regard (Forrester, 2007a; Forrester, 2007b; Sterman, 2000; Sterman, 2002). Yet, no appropriate system dynamics project model could be identified, in the reviewed literature, that considers competition among project participants, with their different and competing performance measures and targets during project execution. Indeed, some scholars also called for research towards modelling (using system dynamics) and improvement of the competition among the different project participants (Lyneis and Ford, 2007). Furthermore, current project dynamics models are limited to project performance control actions of mainly one project participant (the engineering consultant or construction contractor). Control actions taken by the client to protect project performance; and control actions taken by the engineering consultant and construction contractor to protect their business performances are sparingly covered in the reviewed existing literature. Also, current project performance controls seem to be only aimed at achieving project time schedule target. Yet, time schedule is just one of the many measures of project performance.

This research study, thus seeks to address the abovementioned gaps in the reviewed existing literature, but with a particular focus on time-based contracts and raw-water infrastructure-related projects. The problem statement for this research study can, thus, be summarised as follows:

> How can the competition between two key project participants (the client and the engineering consultant) be modelled using system dynamics, and how does it influence the individual performance measures of the two key project participants during project execution, in the particular case of time based-contracts and raw water infrastructure-related projects?

1.4. Rationale for the Research Study

The reviewed existing project management literature shows that during project execution: different project participants tend to have different and competing objectives, performance measures and targets; interdependencies and interactions of project participants are inherent; dysfunctional conflict is inevitable; and the use of competition, as a conflict-handling style is quite common. The reviewed literature also shows that: projects, as systems, are characterised by dynamic complexity; and system dynamics can be applied to projects to enhance project performance.

It is felt that a research study is necessary to investigate, using system dynamics, how competition between two key project participants (the client and the engineering consultant), with their different and competing performance measures and targets, develops and influences both project performance (client's interest) and the business performance of the engineering consultant during project execution. The research study is expected to reveal, considering that the competition is aimed at win-lose results, who wins/loses in the short-term, and who wins/loses in the long-term: project performance (the client) or the business performance of the engineering consultant. The research study is also expected to illuminate how the competition can be improved so as to enhance both project performance and business performance of the engineering consultant, yielding 'win-win' long-term results for the two key project participants.

1.5. Research objectives

To guide the investigation of the research problem stated in Section 1.3, in line with the rationale for the research study stated in the preceding section, the objectives of the current research study are:

1) to investigate, from a combination of existing literature, empirical study and using system dynamics, how competition develops between two key project participants (the client and the engineering consultant) during project execution;
2) to investigate, using system dynamics, how the competition between the two key project participants (the client and the engineering consultant) influences project performance during project execution;
3) to investigate, using system dynamics, how the competition between the two key project participants (the client and the engineering consultant) influences the business performance of the engineering consultant during project execution; and
4) to investigate, using system dynamics, how the competition can be improved so as to enhance both the project performance and the business performance of the engineering consultant during project execution, yielding 'win-win' long-term results for the two key project participants.

1.6. Research questions

Following the research problem statement, rationale for the research study and the research objectives stated in the preceding Sections 1.3 to 1.5, the associated research questions for the current research study are as shown in Table 1.1:

Table 1.1: Research questions

No.	Research question	Related research objective	Applicable chapter
1	How can competition between two key project participants (client and engineering consultant) during project execution be conceptually modelled using systems thinking?	1	Chapter 4
2	How can the competition between the two key project participants (client and engineering consultant) during project execution be quantitatively modelled (simulation model) using system dynamics?	1	Chapter 5
3	How does the competition between the two key project participants (client and engineering consultant) influence project performance?	2	Chapter 6
4	How does the competition between the two key project participants (client and engineering consultant) influence the business performance of the engineering consultant?	3	Chapter 6
5	How can the competition be improved so as to enhance both the project performance and the business performance of the engineering consultant during project execution, yielding 'win-win' long-term results for the two key project participants?	4	Chapter 6

1.7. Expected Research Contributions

This research study is expected to benefit both theory and practice, as outlined next.

Project and Business Performance, and System Dynamics Theory

The current research study is expected to enrich current conflict handling theory (for both project management and engineering consulting business management), in particular with regards to the use of competition as a conflict-handling style. The long-term influence of the competition (aimed at win-lose results) on both project performance and the engineering consultant's project business performance of the will be assessed, through system dynamics model simulation experiments and impact analyses, to assess whether it is really a win-lose result (and in whose favour) or otherwise. Subsequent policy optimisation experiments are expected to identify high-leverage policies that improve the competition, yielding win-win long-term results for the two key project participants. The findings are expected to enrich system dynamics, project performance risk mitigation and business performance risk mitigation (for a projectised organisation) bodies of knowledge.

In the reviewed literature: current project dynamics models, are limited to project performance control actions of mainly one project participant (the engineering consultant or construction contractor); and current project performance controls are only aimed at achieving project time schedule target, yet, time schedule is just one of the many measures of project performance. The current research study is expected to expand the boundaries of the current project dynamics models by including, in the system dynamics model of the competition to be formulated: control actions taken by the client to protect project performance; control actions taken by the engineering consultant to protect his/her business performance; and another measure (cost) of project performance, in addition to time schedule.

Project Management and Engineering Consulting Business Management Practice

It is envisaged that the system dynamics model of the project participants competition, to be formulated in the current research study, will identify high-leverage policies, and expand the boundaries of the mental models of both the client and the engineering consultant to include some important feedbacks and organisations previously excluded. Thus, the model may be used practically as a project management and engineering consulting business decision-making tool. Firstly, the model is expected to assist in predicting/monitoring and control of both project performance (which is of special interest to the client) and the business performance of the engineering consultant during project execution; thereby assisting in both project risk management (client) and business risk management (engineering consultant). Secondly, during or after project execution, the model may also be used for dispute resolution between the two key project participants.

1.8. Research Methodology

The research methodology utilised in the current research study was mixed methods research (MMR) methodology (Cameron, Sankaran and Scales, 2015; Morse and Niehaus, 2009), incorporating the system dynamics approach (Martinez-Moyano and Richardson, 2013; Sterman, 2000). MMR was selected because of its notable advantages over the traditional quantitative and qualitative methodologies. Firstly, it provides deeper insights and better understanding of the research problem, resulting in better quality and validity of the research findings than either the quantitative or qualitative methodology when used alone (Cameron et al., 2015; Morse and Niehaus, 2009). System dynamics inherently utilises some combination of the traditional quantitative and qualitative methodologies (Barlas, 1996; Martinez-Moyano and Richardson, 2013; Sterman, 2000).

Secondly, MMR is ideal for studying complex phenomena (Morse and Niehaus, 2009). Competition between two key project participants (the client and the engineering consultant) during project execution, a key focus of this study, is inherently characterised by high levels of dynamic complexity. Solving problems involving dynamic complexity (such as the competition between the project participants) is not possible with the human mind alone; system dynamics (which is systems thinking plus computer modelling and simulation) is quite useful in that regard (Forrester, 2007a; Forrester, 2007b; Sterman, 2000; Sterman, 2002). Hence, the choice of MMR, incorporating system dynamics for this research study.

The particular type of MMR design chosen for this research study was qualitatively-driven with sequential quantitative and qualitative supplementary components, conducted simultaneously, i.e. QUAL → quan+qual. It was, effectively, a two-stage research design. The first stage was a qualitative, embedded multiple-case study research (Yin, 2014). It entailed formulating appropriate dynamic hypotheses and a system dynamics conceptual model (qualitative modelling) of the competition between two key project participants (the client and the engineering consultant) during project execution, from a combination of: existing literature; key findings from an embedded multiple-case study (Cooper and Schindler, 2014; Parvan et al., 2015; Yin, 2014) that captured the relevant mental models of the two key project participants (Luna-Reyes and Andersen, 2003; Martinez-Moyano and Richardson, 2013; Sterman, 2000); and making use of causal loop diagrams (system dynamics' systems thinking tool) (Monat and Gannon, 2015; Sterman, 2000). This helped to strengthen the validity of the formulated dynamic hypotheses and system dynamics conceptual model, as recommended by Barlas (1996), Luna-Reyes and Andersen (2003), Martinez-Moyano and Richardson (2013), and Sterman (2000).

The first stage of the research study, effectively, covered the first two stages (problem identification and definition, and system conceptualisation) of the system dynamics modelling process recommended by Martinez-Moyano and Richardson (2013). Its key outputs included: dynamic hypotheses; a system dynamics conceptual model; and a provisional answer for research question number 1 (posed in Section 1.6).

The second stage of this research study was a causal explanatory research, simultaneous quantitative and qualitative (quan + qual) mixed methods research design (Cameron et al., 2015; Morse and Niehaus, 2009), involving multiple cases (multiple projects) (Yin, 2014). It was causal explanatory research because it sought understanding of causal relationships among variables/constructs (such as the influence of the competition on both project performance and the engineering consultant's project business performance) (Martinez-Moyano and Richardson, 2013; Sterman, 2000), as opposed to correlational analyses (Cooper and Schindler, 2014; Welman, Kruger and Mitchell, 2012). It entailed: formulating an appropriate system dynamics simulation model (quantitative modelling) of the competition;

testing and calibration of the system dynamics simulation model; conducting simulation experiments (testing the dynamic hypotheses), utilising both quantitative (mainly) and some qualitative data from multiple-cases (18 unique raw water infrastructure-related projects); and conducting optimisation experiments aimed at improving the competition, yielding win-win long-term results for the two key project participants.

It, effectively, covered the simulation model formulation, model testing and evaluation, as well as policy analysis and design stages of the system dynamics modelling process recommended in existing literature (Martinez-Moyano and Richardson, 2013; Sterman, 2000). Its key outputs included, a system dynamics simulation model, dynamic hypotheses test results, and provisional answers for research questions number 2 to 5 (posed in Section 1.6).

1.9. Thesis Layout

Table 1.2 shows the structure of this thesis report.

Table 1.2: Thesis layout

Chapter	Key activities and / or outputs
Chapter 1: Introduction, Purpose and Expected Contribution of this Study	- Background for the current research study. - Research problem statement, rationale for the study, research objectives, research questions, expected contributions of the research, thesis layout, and thesis constraints/assumptions.
Chapter 2: Research Design and Methodology	- Selection and description of the research methodology and design (including sampling methods, data-collection methods, research instruments, and data-analysis methods)
Chapter 3: Project Participants Performance and Competition, and System Dynamics Literature Review	- Critical analysis of current theory and past research on: systems and projects; project complexity; project participants; project performance; business performance; competition (as a conflict-handling style) among project participants; systems thinking; system dynamics; application of system dynamics to project performance, business performance and competition. - Identification of appropriate gaps in current theory and past research for the current research study to focus on.
Chapter 4: Project Participants Competition System Dynamics Conceptual Model (Qualitative Modelling)	- Formulation of appropriate dynamic hypotheses and a system dynamics conceptual model (qualitative modelling) of the competition between two key project participants (the client and the engineering consultant) during project execution, from a combination of: existing literature; an embedded multiple-case study (non-project specific data); and making use of one of system dynamics' systems thinking tools (causal loop diagram). - Discussion of results and provisional answer for research question number 1 (posed in Section 1.6).

Chapter	Key activities and / or outputs
Chapter 5: Project Participants Competition System Dynamics Simulation Model (Quantitative Modelling)	- Formulation of an appropriate system dynamics simulation model (quantitative modelling) of the competition, from the system dynamics conceptual model formulated in Chapter 4. - Discussion of results and provisional answer for research question number 2 (posed in Section 1.6).
Chapter 6: Project Participants Competition System Dynamics Simulation Model Validation	- Testing and validation of the system dynamics simulation model; - Calibration of system dynamics simulation model with gathered project-specific data from multiple projects. - Model simulation experiments, impact analyses and optimisation experiments. - Discussion of results and provisional answers for research questions number 3 to 5 (posed in Section 1.6).
Chapter 7: Conclusions and Recommendations	- Summary of key research results, and comparisons to the research objectives and identified research gaps. - Theoretical and managerial practice implications and contributions of this research study. - Limitations of the research findings. - Recommendations for further research.

Sources: Adapted from Cameron et al. (2015), Cooper and Schindler (2014), Martinez-Moyano and Richardson (2013), Morse and Niehaus (2009), Parvan et al. (2015), Rahmandad and Sterman (2012), Sterman (2000), Walwyn (2016), and Yin (2014).

1.10. Thesis Constraints and Assumptions

The following constraints and assumptions apply to the current research study:

- the study focussed only on project execution. All other project life cycle stages were excluded;
- only two key project participants (the client and the engineering consultant) were considered. All other project participants and stakeholders were excluded; and
- only time-based contracts with a ceiling price (Turner, 2004) between the client and the engineering consultant were considered, with only the time-based costs for the engineering consultant services considered for the project cost.

1.11. Conclusion

Projects, as systems, are characterised by dynamic complexity. Different project participants often have different objectives and competing expectations during project execution. The client naturally focusses on minimising his/her investment into the project, whilst other project participants (such as the engineering consultant) focus on generating financial benefits, during project execution. Put differently, on the one hand, during project execution, the client is particularly interested in project performance and its associated measures, and sets targets and priorities accordingly. On the other hand, other project participants (such as the engineering consultant) are particularly interested in business performance (of their own organisations) and its associated measures, and set targets and priorities accordingly, during project execution.

Different project participants, thus, tend to take different decisions and control actions, in a bid to protect their different and competing performance measures when they face a particular challenge. Though often intendedly rational, such different decisions and control actions turn out to be mutually-exclusive, leading to the use of competition (aimed at win-lose end-results) as a conflict-handling style. Indeed, some previous scholars highlighted that the use of competition as a conflict-handling style is quite common among project participants.

Nonetheless, no appropriate study could be identified, in the reviewed literature, that specifically investigated the influence of such competition on project performance and on the business performance of the engineering consultant (or construction contractor) during project execution. Solving problems involving dynamic complexity (such as competition among project participants) is not possible with the human mind alone: system dynamics (which is systems thinking plus computer modelling and simulation) is quite useful in that regard as highlighted by some scholars. Yet, no appropriate system dynamics project model could be identified, in the reviewed literature, that considers competition among project participants, with their different and competing performance measures and targets during project execution.

The objectives of the current research study are, thus, to investigate, using system dynamics: existing literature and empirically, how competition develops between two key project participants (the client and the engineering consultant) during project execution; how the competition influences project performance during project execution; how it influences the business performance of the engineering consultant during project execution; and how the competition can be improved so as to enhance both the project performance and the business performance of the engineering consultant during project execution, yielding ‘win-win’ long-term results. Associated research questions were also formulated.

Key research constraints and assumptions for the current study are that: the study focusses only on the project execution stage of a project life cycle; only two key project participants (the client and engineering consultant) are considered; and only time-based contracts, with a ceiling price, between the two key project participants are considered. The next chapter selects (with justification) and discusses the research design and methodology for the current research study.

2. Research Design and Methodology

2.1. Introduction

This chapter outlines the research design and methodology followed in the current research study. It begins by highlighting the traditional scientific research methodologies and their limitations. It proceeds to discuss some emerging research approaches, highlighting their key advantages. Next, appropriate research methodology and design for the current research study are selected and described. The associated data-collection methods, research instruments, and data-analysis methods selected are also described. Steps taken to ensure research credibility are outlined, and, in the end, adherence to research ethics is highlighted.

2.2. Traditional Research Methodologies and their Limitations

There are two traditionally accepted methodologies for research studies aimed at expansion of scientific knowledge, namely quantitative research (experimental, quasi-experimental and non-experimental research designs), and qualitative research (Welman et al., 2012). Table 2.1 summarises the traditional dichotomous view (quantitative or qualitative) to scientific research as applied to social sciences, as well as the limitations and criticisms of each methodology.

Table 2.1: Traditional social sciences research methodologies and their limitations

Item	Quantitative research	Qualitative research
Some key differences	▪ Positivism epistemological position (social sciences research needs to be conducted similarly to the natural sciences research; treating people and their institutions the same way as objects of the natural sciences). ▪ Deductive approach (theory guides the research). ▪ Theory testing (hypothesis testing). ▪ The researcher is detached from the research subjects (aims at an outsider's perspective). ▪ Static image of the social reality. ▪ Behaviour of the people. ▪ Artificial settings. ▪ Covers many cases and seeks to generalise to the population.	▪ Interpretivism epistemological position (social sciences research needs to be conducted differently from the natural sciences research; treating people and their institutions distinctively from objects of the natural sciences). ▪ Inductive approach (theory is an outcome of the research). ▪ Theory building. ▪ The researcher is involved with the research participants (aims at an insider's perspective). ▪ Dynamic nature of social reality: interconnected process between the social actors. ▪ Meaning of people's actions. ▪ Natural settings. ▪ Covers one or a few cases and seeks deep understanding of the context.

Item	Quantitative research	Qualitative research
Limitations / criticisms	▪ Treats people and the social world the same way as the objects in the natural world. Yet, people think and "interpret the world around them" (ignores people's capacity for self-reflection), something that objects in the natural sciences cannot do. ▪ Its measurement process is inherently artificial, giving a "false sense of precision and accuracy". For instance, in a survey research, respondents may interpret the measures (key terms in the research questions) differently, resulting in responses that are out of synch with reality. ▪ Fails to consider "how a relationship between two or more variables has been produced by the people to whom it applies", thereby creating a static view of the social reality. Put differently, it ignores the dynamic complexity typical of social systems.	▪ Tends to be too subjective: qualitative research findings tend to rely on the researcher's often preconceived and unsystematic views; and the researcher tends to develop close relationships with the research participants. ▪ It is often difficult to replicate qualitative research findings: what is considered significant may differ from one researcher to the other; and how research participants respond tends to be influenced by their inter-personal relationships with the researcher, and by the researcher's characteristics (e.g., age, gender, and personality). ▪ It is impossible to generalise qualitative research findings to other settings, as they are based on only one or a few cases.

Sources: Adapted from Bryman, Bell, Hirschsohn, Dos Santos, Du Toit, Masenge, Van Aardt and Wagner (2014), Cameron et al. (2015), Cooper and Schindler (2014), Sterman (2000), Welman et al. (2012), and Yin (2014).

2.3. Emerging Research Approaches

A review of existing literature shows that a number of other research approaches are emerging and/or increasingly becoming more accepted as they address some of the shortcomings of the traditional quantitative and qualitative research approaches. The next three sub-sections discuss three of these research approaches, namely system dynamics, design science research, and mixed methods research, respectively.

2.3.1. System Dynamics Approach

System dynamics is a multi-disciplinary approach whose goal is to assist managers improve their understanding of systems characterised by dynamic complexity, and to use such understanding to design and develop more effective, high-leverage operating policies and structures that solve real world problems and improve the performance of the systems (Martinez-Moyano and Richardson, 2013; Sterman, 2000). Thus, system dynamics addresses one of the key weaknesses of the traditional quantitative approach: it captures the dynamic complexity of social systems, rather than just creating a static view of the social reality.

A number of different versions of the system dynamics modelling process have been suggested in the existing system dynamics literature. For instance, Sterman (2000) proposed a five-step system dynamics modelling process comprising: problem articulation (boundary selection); dynamic hypothesis formulation; simulation model formulation; testing; and policy design and evaluation. More recently, Martinez-Moyano and Richardson (2013), interviewed a group of system dynamics experts comprised of presidents of the System Dynamics Society and winners of the Society's awards, and subsequently proposed a six-stage system dynamics modelling process comprising: problem identification and definition; system conceptualisation; model formulation; model testing and evaluation; model use, implementation and dissemination; and design of learning strategy/infrastructure. Their six-stage system dynamics modelling process does incorporate most of the five steps proposed by Sterman (2000). They also recommended specific key activities for each of the six stages in prescriptive, rule-like statements for best practice system dynamics modelling (Martinez-Moyano and Richardson, 2013).

The six-stage system dynamics modelling process proposed by Martinez-Moyano and Richardson (2013) is ideal for a full model lifecycle (including model use). Table 2.2 summarises the key stages of the system dynamics modelling process typical for a PhD research study, as adapted from the existing system dynamics literature.

Table 2.2: System dynamics modelling process for a typical PhD study

Stage	Key activities and/or outputs
Problem identification and definition	▪ identifying the problem owner (client); ▪ capturing the problem to be modelled; ▪ outlining the purpose of the modelling effort; and ▪ identifying the reference modes.
System conceptualisation	▪ capturing the client's mental models and dynamic hypotheses; ▪ identifying the critical stocks describing the system; ▪ describing the core feedback structures in the dynamic hypotheses using causal-loop diagrams.
Model formulation	▪ developing the model structure (stock and flows, with feedback loops); ▪ ensuring all variables have real-life meaning; ▪ formulating associated equations, ensuring dimensional consistency; ▪ specifying initial conditions.
Model testing and evaluation	▪ testing for extreme conditions; ▪ model calibration (estimating model parameters); ▪ model validation, comparison of the simulated behaviour patterns with the real behaviour (data).
Policy analysis and design	▪ policy (new strategies, structures, decision rules) analysis; ▪ sensitivity analysis; ▪ policy recommendations.

Sources: Adapted from Martinez-Moyano and Richardson (2013), Sterman (2000), Parvan (2012), and Parvan et al. (2015).

System dynamics utilises some combination of the traditionally accepted quantitative and qualitative methodologies. Indeed, system dynamics best-practices demand the use of multiple sources of information (e.g., existing literature, interviews, direct observation, and documents review, among others) that capture both quantitative and qualitative data, in order to elicit the organisational structures, managerial objectives, targets and decisions rules, thereby enabling the correct specification of the relationships in the models (Barlas, 1996; Luna-Reyes and Andersen, 2003; Martinez-Moyano and Richardson, 2013; Sterman, 1992; Sterman, 2000). Furthermore, while evaluation of system dynamics simulation models largely relies on quantitative data, the models must also be evaluated qualitatively to ensure fit for purpose (Barlas, 1996; Forrester and Senge, 1980; Sterman, 2000).

Rahmandad and Sterman (2012) lamented the lack of transparency (e.g., non-disclosure of model equations, and parameter values) in most simulation-based research reports, making it very difficult for other researchers to independently reproduce such research results. They then proposed a set of guidelines for reporting simulation-based (particularly system dynamics) research aimed at enhancing research reproducibility within the social sciences fraternity, i.e., guidelines for reporting the model, simulation experiments, and optimisation experiments (Rahmandad and Sterman, 2012). For each guidelines type (model, simulation experiments, and optimisation experiments), they proposed minimum reporting requirements (which are imperative for reproducibility of the research), and preferred reporting requirements (aimed at enhancing "communication and transparency" among researchers). They also provided guidelines for general model visualisation, including 'look and feel' (Rahmandad and Sterman, 2012).

Some recent research studies have shown an interesting shift in system dynamics academic research studies from the traditional single case or a few cases, less than five (Kim et al., 2006; Nasirzadeh and Nojedehi, 2013; Oosthuizen, 2014; Pretorius, Pretorius and Benade, 2015), to multiple randomly-selected cases, at least 15, (Parvan, 2012; Parvan et al., 2015). This enhances the generalizability of the research findings, a characteristic feature of the quantitative approach.

2.3.2. Design Science Research

Emerging from the information systems discipline, Design Science Research (DSR) consists of six stages, namely: problem identification and motivation; definition of solution objectives; design and development; demonstration; evaluation; and communication (Peffers, Tuunanen, Rothenberger and Chatterjee, 2007). A comparison of system dynamics and DSR reveals some interesting similarities, as shown in Table 2.3. Some researchers, such as Oosthuizen (2014), have, indeed, successfully utilised DSR in combination with systems dynamics in the same study.

Table 2.3: System dynamics versus design science research

Feature	System dynamics	Design science research
First step	Research problem identification and definition	Research problem identification and motivation
Key focus	Developing a model that helps to understand the causes and effects of the identified problem so that new policies or structures can be designed to solve the problem.	Developing an artefact (which can be a model) that solves the identified problem.
Typical sources of information for model or artefact formulation and evaluation	Literature review, direct observation, interviews, documents and records.	Literature review, direct observation, interviews, documents and records.
Hypotheses formulation	Dynamic hypotheses are formulated to capture the relationships in the model.	Hypotheses are not explicitly covered in the literature reviewed. But, it should, arguably, be possible to capture them during the design and development stage.
Process flow	Iterative	Iterative
Empirical evaluation	The developed model is calibrated and validated with real world empirical data using computer simulation and optimisation experiments.	The developed artefact is evaluated (e.g. validity, efficacy, utility) with real world empirical data, e.g., using computer simulation and optimisation experiments.
Hypotheses testing	Dynamic hypotheses are tested through computer simulations.	Not explicitly covered in the literature reviewed. But, it should, arguably, be possible to conduct hypothesis testing during the demonstration / evaluation stages.
Ultimate goal	A better understanding of the problem and the system, enabling system performance enhancement.	A better understanding of the problem, enabling performance enhancement.

Sources: Adapted from Gregor and Hevner (2013), Martinez-Moyano and Richardson (2013), Peffers et al. (2007), and Sterman (2000).

2.3.3. Mixed Methods Research

Mixed Methods Research (MMR) is a combination of at least two quantitative and/or qualitative approaches in one study (Cameron et al., 2015; Morse and Niehaus, 2009). It is establishing itself as the third research methodology of choice, after the traditional quantitative and qualitative methodologies (Cameron et al., 2015). MMR leads to a better and deeper understanding of the phenomena under research than either quantitative or qualitative methodology when used alone (Cameron et al., 2015).

A MMR design consists of a primary/core component (research design method that addresses the main part of the research questions), coupled (concurrently or sequentially) with one or more secondary/supplementary component (research design method that enhances the quality and validity of the research findings) (Morse and Niehaus, 2009). Table 2.4 summarises the minimum key elements and guidelines for conducting and reporting a research study with an MMR design.

Table 2.4: Minimum key features of a Mixed Method Research design

No.	Feature	Description
1	Theoretical drive	▪ This is the overall direction (inductive or deductive) of the study. ▪ It is derived and evident from the main research aim.
2	Primary/core component	▪ This is the dominant research method and it addresses the main part of the research questions. ▪ It forms the backbone, of the research design, onto which all other supplementary components are then attached. ▪ It can either be qualitative or quantitative, and is represented in capital letters: 'QUAL' or 'QUAN', respectively. ▪ It is always determined from the theoretical drive, i.e. a qualitatively-driven study always has a QUAL core component; and a quantitatively-driven study always has a QUAN core component.
3	Secondary/ supplementary component	▪ This is the supporting research strategy that addresses the remaining part of the research questions. ▪ It complements the core component, and is aimed at enhancing the quality and validity of the research findings. ▪ It can either be qualitative or quantitative, and is represented in small letters: 'qual' or 'quan', respectively.
4	Pacing of the components	▪ This refers to how the core and supplementary components are synchronised: concurrently (indicated by '+') or sequentially (indicated by '→'). ▪ For example, a qualitatively-driven study with a simultaneous quantitative supplementary component is represented as: QUAL + quan
5	Point of interface for the components	▪ The core and supplementary components are conducted separately, and they only 'meet' at the point of interface. ▪ The two components can only meet either at the research results narrative or at data analysis of the core component.
6	Type of MMR design	▪ The core component (QUAL/QUAN) and the supplementary component (qual/quan) can be paced simultaneously or sequentially (+ or →) in eight different combinations, giving rise to eight main types of MMR designs: e.g. QUAL + qual, QUAL → quan; QUAN + qual, and the like. ▪ Using more than one supplementary component leads to other types of MMR designs, e.g. QUAL → quan + qual.
7	Flowchart	▪ The MMR design must be summarised by a flowchart showing: the primary component on the left-hand side and the supplementary component(s) on the right-hand side; the methods used; pacing and point of interface for the components.

Source: Adapted from Morse and Niehaus (2009), and Cameron et al. (2015)

Cameron et al. (2015) observed that although the use of the MMR design is increasing in project management, it is not growing as fast as it is in other business and management fields, such as operations management, strategic management and organisational behaviour. Subsequently, they called for more project management research utilising MMR designs, and better reporting quality thereof, as such research methodology provides deeper insights and better understanding of the research problem (Cameron et al., 2015).

As evident in the preceding sub-sections, both system dynamics and DSR approaches actually utilise some combination of the traditionally accepted quantitative and qualitative methodologies. It can, thus, be argued that both system dynamics and DSR are essentially variants of the MMR methodology. Indeed, an analysis of some previous studies involving system dynamics reveals that the MMR designs are inherent in most of such studies, although not explicitly stated as such by their authors. For instance, the PhD study of Parvan (2012), that investigated the influence of building information modelling (BIM) on project performance using system dynamics, followed the following logic: research problem definition; literature review; formulation of system dynamics models (one without BIM, formulated from literature; and another with BIM, formulated through qualitative, semi-structured interviews, expert elicitation); data gathering (archive survey with a randomised sample); data analysis (mainly system dynamics simulation, Monte Carlo simulation, impact analysis, and sensitivity analysis); and conclusions and recommendations. Arguably, this is essentially a MMR design, *QUAL → quan+qual*, although not explicitly stated as such by Parvan (2012). The sext section discusses the research methodology selected for the current research study.

2.4. Research Methodology and Design for this Research Study

In view of the limitations of the traditional research methodologies, and the strengths of the emerging research designs discussed in the preceding sections, the appropriate research methodology selected for the current research study is Mixed Methods Research methodology (Cameron et al., 2015; Morse and Niehaus, 2009), incorporating the system dynamics approach (Martinez-Moyano and Richardson, 2013; Sterman, 2000).

2.4.1. Justification for the Selected Research Methodology

MMR is a combination of at least two quantitative and/or qualitative methodologies in one research study (Cameron et al., 2015; Morse and Niehaus, 2009). It has notable advantages over the traditional quantitative and qualitative methodologies. Firstly, it provides deeper insights and better understanding of the research problem or phenomena under research, resulting in better quality and validity of research findings than either the quantitative or qualitative methodology when used alone (Cameron et al., 2015; Morse and Niehaus, 2009). System dynamics inherently utilises some combination of the quantitative and qualitative methodologies (Barlas, 1996; Martinez-Moyano and Richardson, 2013; Sterman, 2000).

Secondly, MMR is ideal for studying complex phenomena (Morse and Niehaus, 2009). Competition between two key project participants (the client and the engineering consultant), a key focus of this research study, is inherently characterised by dynamic complexity, as discussed in Chapters 1 and 3. Solving problems involving dynamic complexity (such the competition) is not possible with the human mind alone; system dynamics is quite useful in that regard (Forrester, 2007a; Forrester, 2007b; Sterman, 2000; Sterman, 2002). Also, system dynamics is particularly useful when investigating the causes and effects of human behaviour (Sterman, 2000). This research study seeks to investigate some of the causes and effects of the competition (which is essentially human behaviour). Furthermore, system dynamics is aimed at improving system performance (Sterman, 2000). The current research study seeks to improve the competition between the two key project participants, leading to an improvement of both the project performance (client's interest) and the business performance of the engineering consultant.

By making use of MMR methodology, this research study essentially heeds the call made by Cameron et al. (2015) for more project management research utilising MMR designs which lead to deeper insights and better understanding of the research problem. MMR designs have also been successfully utilised, although not explicitly acknowledged, in some previous studies involving system dynamics, project management and/or competition (Gilkinson and Dangerfield, 2013; Nasirzadeh and Nojedehi, 2013; Parvan, 2012; Parvan et al., 2015). Thus, the current research study follows emerging research design trends in system dynamics and project management research. The MMR design used in this research study also incorporates many key features of the system dynamics (Martinez-Moyano and Richardson, 2013; Sterman, 2000) and DSR methodologies (Gregor and Hevner, 2013; Oosthuizen, 2014; Peffers et al., 2007) highlighted in the preceding sections.

2.4.2. Overview of the Research Approach and Design

The overall research methodology used in this research study is MMR methodology (Cameron et al., 2015; Morse and Niehaus, 2009), incorporating the system dynamics approach (Martinez-Moyano and Richardson, 2013; Sterman, 2000), as motivated for in the preceding sub-section. The particular type of MMR design used was qualitatively-driven with sequential quantitative and qualitative supplementary components, conducted simultaneously, i.e., *QUAL → quan+qual* (Morse and Niehaus, 2009). It was, effectively, a two-stage research design (Cooper and

Schindler, 2014). The two stages, discussed in the next two sub-sections, were: *stage 1 (qualitative, embedded multiple-case study research),* aimed at formulating appropriate dynamic hypotheses and a system dynamics conceptual model of the competition between the two key project participants (the client and the engineering consultant); and *stage 2 (causal explanatory, mixed methods research),* aimed at formulating an appropriate system dynamics simulation model, and evaluating the model, testing the dynamic hypotheses through computer simulation experiments, and conducting computer optimisation experiments aimed at improving the competition, yielding win-win long-term results for the two key project participants.

Table 2.5 shows the key features for the research design used in this research study, in line with the minimum reporting guidelines for MMR designs (Cameron et al., 2015; Morse and Niehaus, 2009).

Table 2.5: Key features of the Mixed Method Research design used in this study

No.	Feature	Description
1	Type of MMR design	▪ Qualitatively-driven MMR with sequential quantitative and qualitative supplementary components, conducted simultaneously, i.e. QUAL → quan+qual.
2	Theoretical drive	▪ Stage 1 (Qualitative, embedded multiple-case study research): inductive; ▪ Stage 2 (Causal explanatory, simultaneous quantitative and qualitative Mixed Methods Research): deductive; ▪ Overall: inductive (as Stage 2 relies on the qualitative dynamic hypotheses and model formulated in Stage 1).
3	Primary/core component	▪ Qualitative (QUAL).
4	Secondary/supplementary component	▪ Quantitative (quan) and qualitative (qual).
5	Pacing of the components	▪ Sequential (→) for the core and the supplementary components: QUAL → quan+qual. ▪ Simultaneously (+) for the two supplementary components: quan + qual.
6	Point of interface for the components	▪ The point of interface for the supplementary components (quan + qual) is at data analysis of the quan component. ▪ The point of interface for the primary component (QUAL) and supplementary components (quan + qual) is at the research results narrative for the whole study.
7	Flowchart for the MMR design used	▪ See Figure 2.1

Source: Adapted from Cameron et al. (2015), and Morse and Niehaus (2009).

Figure 2.1 summarises the two-stage MMR, incorporating the system dynamics approach, used in this research study.

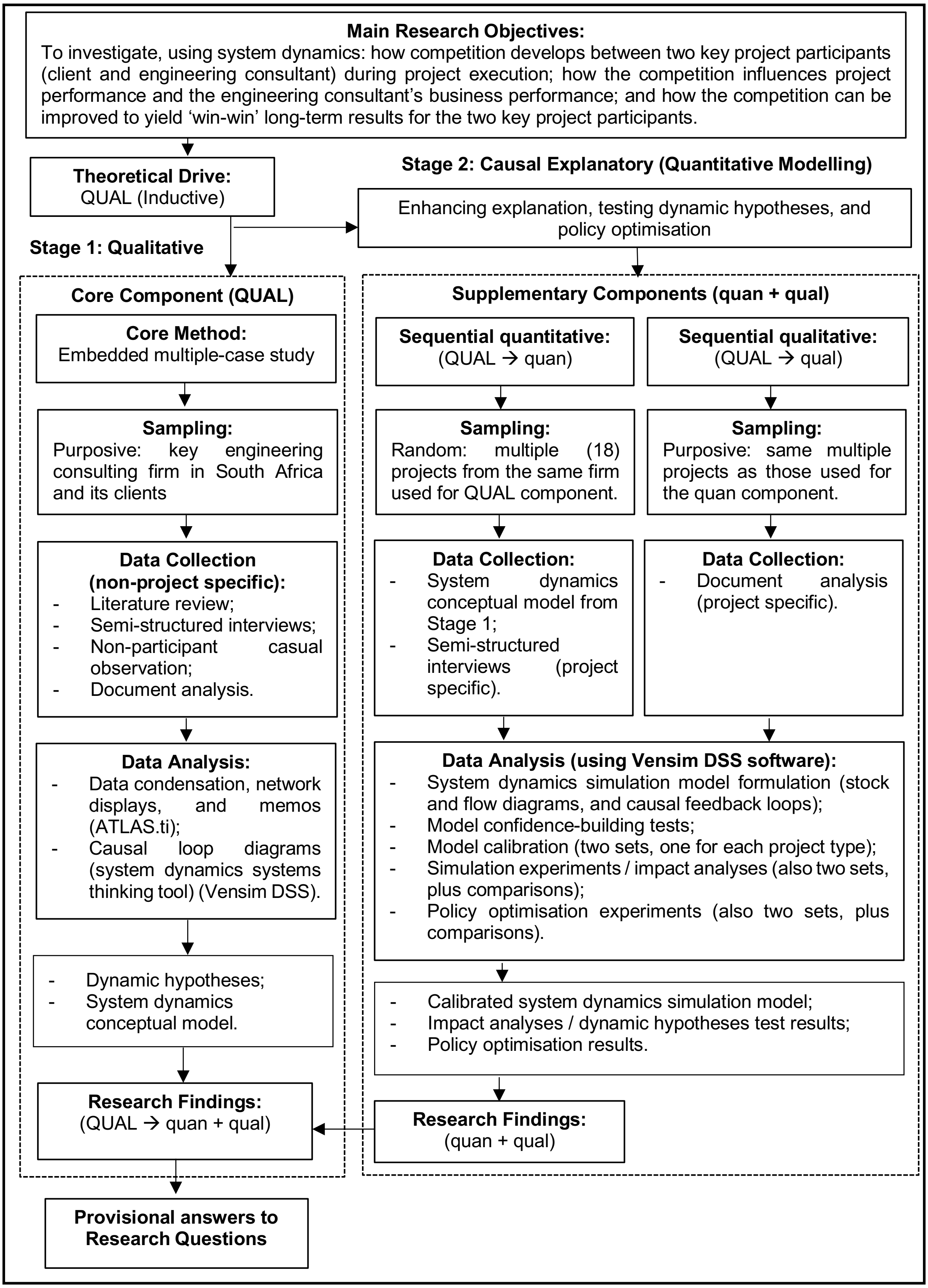


Figure 2.1: Overview of the research design for this study (Mixed Methods Research, incorporating the system dynamics approach)

Source: Adapted from Cameron et al. (2015), Cooper and Schindler (2014), Martinez-Moyano and Richardson (2013), Miles, Huberman and Saldana (2014), Morse and Niehaus (2009), Parvan et al. (2015), Sterman (2000), and Yin (2014).

2.4.3. Stage 1 – Qualitative, Embedded Multiple-Case Study (Qualitative Modelling)

The first stage of the research design for the current study was a qualitative, embedded multiple-case study (Yin, 2014) as it involved capturing current practices and experiences (Cooper and Schindler, 2014) during project execution from contemporary key project participants (client and engineering consultant project managers). Put differently, in system dynamics terminology, it involved capturing the relevant mental models (Luna-Reyes and Andersen, 2003; Martinez-Moyano and Richardson, 2013; Sterman, 2000) of contemporary key project participants.

It entailed formulating appropriate dynamic hypotheses and a system dynamics conceptual model (qualitative modelling) of the competition between two key project participants (the client and the engineering consultant) during project execution, from a combination of: existing literature; key findings from an embedded multiple-case study (Cooper and Schindler, 2014; Parvan et al., 2015; Yin, 2014) that captured the relevant mental models of the two key project participants (contemporary client and engineering consultant project managers) (Luna-Reyes and Andersen, 2003; Martinez-Moyano and Richardson, 2013; Sterman, 2000); and using causal loop diagrams (system dynamics' systems thinking tools) (Monat and Gannon, 2015; Sterman, 2000). This helped to strengthen the validity of the formulated dynamic hypotheses and system dynamics conceptual model, as recommended by Barlas (1996), Luna-Reyes and Andersen (2003), Martinez-Moyano and Richardson (2013), and Sterman (2000).

The first stage of the research design, effectively, covered the first two stages (problem identification and definition, and system conceptualisation) of the system dynamics modelling process recommended by Martinez-Moyano and Richardson (2013). It began with the identification of the research problem, and the formulation of appropriate research objectives and research questions (Chapter 1). Subsequently, it proceeded with a critical review of the relevant existing literature, identifying key factors that influence the competition, and appropriate gaps (Chapter 3). It then captured the relevant mental models of the two key project participants through an embedded multiple-case study, and subsequently formulated appropriate dynamic hypotheses and a system dynamics conceptual model (system conceptualisation) of the competition, also making use of causal loop diagrams (a system dynamics' systems thinking tool), and provided a provisional answer for research question number 1, posed in Section 1.6 (Chapter 4).

Sampling

For a qualitative research study, only non-probability sampling (such as accidental, purposive, snowball or convenience) is applicable (Cooper and Schindler, 2014; Welman et al., 2012) as the intention is not to obtain a sample representative of the population (randomly selected and adequate size for quantitative analyses), but to obtain information from appropriate and insightful sources (Cooper and Schindler, 2014) that are purposefully selected (Morse and Niehaus, 2009; Welman et al., 2012). This is also in line with the system dynamics emphasis on capturing the relevant mental models of system actors, as highlighted earlier in this subsection. Accordingly, this research study utilises a purposefully-selected case of a key engineering consulting firm with many infrastructure projects in South Africa. Some previous system dynamics research studies (Parvan, 2012; Rodrigues and Williams, 1998) also utilised purposive sampling.

Investigating the impact of competition between key project participants on project performance can be applied to any type of project. However, the current research study focusses only on raw-water infrastructure-related projects in South Africa. The specific focus on raw-water infrastructure-related projects was inspired by the fact that infrastructure development plays a pivotal supporting role in the economic development and growth of any country (Ansar et al., 2016; Henckel and McKibbin, 2017; Vickerman, 2018), and there cannot be any human life without water; yet there are many cases of poor project performance (Ansar et al., 2016; Kaliba et al., 2009; Molloy and Chetty, 2015).

The embedded multiple-case study (one engineering consultant with varying clients) used in this research study has cases that are grouped into two: the client and the engineering consultant (the two key project participants). Five client project managers and six engineering consultant project managers were interviewed in this study. The number of research participants used in this study is comparable to those of some previous studies (Mikulskiene and Pitrenaite-Zileniene, 2013; Parvan, 2012; Parvan et al., 2015). As a result of the competition between the two key project participants, and in line with Yin (2014), it was expected that: similar results would be realised from cases in the same group (“literal replication”); and the two groups would yield different results (“theoretical replication”).

Data Collection

Table 2.6 shows the: main sources of the non-project-specific qualitative data that were collected for this stage of the research study; relevant literature that recommended the sources; and some examples of previous system dynamics, project management and/or competition studies that used similar sources.

Table 2.6: Sources of qualitative data for Stage 1 (Qualitative) of the research study

No.	Source of data	Recommended by	Also used by
1	Literature review	Cooper and Schindler (2014); Manu et al. (2015); Sterman (2000); Welman et al. (2012)	Mikulskiene and Pitrenaite-Zileniene (2013); Nasirzadeh and Nojedehi (2013); Oosthuizen (2014); Parvan (2012); Parvan et al. (2015); Yaghootkar (2010)
2	Individual face-to-face semi-structured interviews	Cooper and Schindler (2014); Luna-Reyes and Andersen (2003); Manu et al. (2015); Martinez-Moyano and Richardson (2013); Sterman (2000); Welman et al. (2012); Yin (2014)	Mikulskiene and Pitrenaite-Zileniene (2013); Nasirzadeh and Nojedehi (2013); Parvan (2012); Parvan et al. (2015); Yaghootkar (2010)
3	Organisational document analysis	Cooper and Schindler (2014); Manu et al. (2015); Sterman (2000); Yin (2014)	Nasirzadeh and Nojedehi (2013); Yaghootkar (2010)
4	Direct observation	Yin (2014)	Yaghootkar (2010)

In brief, non-project-specific qualitative data were collected using: a critical review of existing literature; individual face-to-face semi-structured interviews with five client project managers and six engineering consultant project managers; analysis of relevant non-project-specific documents; and non-participant casual observation during the interviews. The use of such different sources of qualitative empirical evidence enabled the production of research findings supported by multiple sources of evidence (triangulation), thereby enhancing the construct validity of the case study, as recommended by Yin (2014). The gathered non-project-specific data were also not necessarily limited to the engineering consultant in question.

Research instrument (semi-structured interview questionnaire)

The semi-structured interview questionnaire used for the first stage of this research study is as shown in Appendix A.

Data Analysis

The non-project-specific qualitative data gathered in this study were analysed using a three-streamed, iterative, qualitative data analysis process recommended by Miles et al. (2014). ATLAS.ti, a computer assisted qualitative data analysis software (ATLAS.ti, 2016), was used in this research study to aid the qualitative data analysis.

According to Miles et al. (2014), the first stream of qualitative data analysis is “data condensation” and it involves sorting, clustering, selecting portions of, coding, and summarising the gathered qualitative empirical data. In this research study, data condensation was conducted using ATLAS.ti software as described next. Firstly, the gathered qualitative empirical data (interview write-ups, non-participant casual observation notes, and non-project specific organisational documents) were imported into ATLAS.ti and grouped according to their type. Next, the researcher went through each text document, selecting and marking sections of the document (quotations) deemed relevant to the research questions. Codes were created (mainly from the literature reviewed but also from the gathered data) and linked to the quotations in the documents (a process called coding). The codes were grouped according to themes or constructs derived from literature or emerging from the empirical data. Code-code (e.g. one code is cause of another code) and quotation-quotation (e.g. one quotation supports another quotation) links were created in line with relationships evident in the empirical data. Lastly, memos were used to describe relationships between codes as evident in the gathered data.

The second stream of qualitative data analysis, according to Miles et al. (2014), is called “data display” and it involves presenting information from the empirical data in an organised, compact form (such as with tables, matrices, causal network diagrams or graphs) that simplify the drawing of conclusions. Ackermann and Alexander (2016) highlighted the value of causal maps/networks (in particular, systemic view and improved understanding of project dynamics) and, subsequently, called for more project management research utilising causal maps. Accordingly, in this research study, data display was done using the Network View tool of ATLAS.ti software, yielding appropriate causal networks (refer to Chapter 4).

The last stream of qualitative data analysis, recommended by Miles et al. (2014), is called “conclusion drawing and verification”, and entails documenting and verifying the research findings (meanings, explanations, causal relationships, themes or patterns). In this research study, research conclusions were also done in ATLAS.ti using memos. Empirical data from multiple sources of evidence (interview write-ups, non-participant casual observation notes, and non-project specific organisational documents) were used to verify and support the conclusions; thereby enhancing the construct validity of the case study, in line with Yin (2014).

The results of the qualitative empirical data analysis were discussed and compared with appropriate existing literature. Subsequently, appropriate dynamic hypotheses and a system dynamics conceptual model of the competition between the two key project participants (the client and the engineering consultant) during project execution, was formulated by integrating the results of the qualitative empirical data analysis with the existing literature, and using system dynamics’ systems thinking tool (causal loop diagrams) (refer to Chapter 4).

2.4.4. Stage 2 – Causal Explanatory, Mixed Methods Research (Quantitative Modelling and Evaluation)

The second stage of the research study was a causal explanatory research, simultaneous quantitative and qualitative (quan + qual) mixed methods research design (Cameron et al., 2015; Morse and Niehaus, 2009), involving multiple cases (multiple projects) (Yin, 2014). It was causal explanatory research because it sought understanding of causal relationships among variables/constructs (such as the influence of the competition on both project performance and the engineering consultant's project business performance) (Martinez-Moyano and Richardson, 2013; Sterman, 2000), as opposed to correlational analyses (Cooper and Schindler, 2014; Welman et al., 2012). As such, it sought to formulate a system dynamics simulation model, which is a causal-descriptive (white-box) model (where individual casual relationships within the internal model structure are clearly articulated and help to explain how the model output behaviour is generated, effectively suggesting how the behaviour may be changed so as to enhance the performance of the system); as opposed to a correlational (black-box) model (where the individual casual relationships within the internal model structure are hidden, and only the overall model output behaviour is of interest) (Barlas, 1996).

The second stage of the research study, thus, entailed: formulating an appropriate system dynamics simulation model (quantitative modelling) of the competition between two key project participants (the client and the engineering consultant) during project execution; and evaluating the model, utilising both quantitative (mainly) and qualitative data from multiple-cases, testing the dynamic hypotheses through computer simulation experiments, and conducting computer optimisation experiments aimed at improving the competition, yielding win-win long-term results for the two key project participants. It, effectively, covered the simulation model formulation, model testing and evaluation, as well as policy analysis and design stages of the system dynamics modelling process recommended in existing literature (Martinez-Moyano and Richardson, 2013; Sterman, 2000). Its key outputs included: a system dynamics simulation model, providing a provisional answer for the research question number 2 (Chapter 5); dynamic hypotheses test results, and provisional answers for research questions number 3 to 5, posed in Section 1.6 (Chapter 6).

Sampling

The same key engineering consulting firm utilised in the first stage was also utilised in the second stage of the research study. However, in the second stage, the term 'multiple-cases' referred to multiple projects. Projects investigated (sampling frame) came from the firm's pool of projects completed within the last six years.

Data Collection

Project-specific data were gathered through: individual face-to-face semi-structured interviews, for primary data, (Welman et al., 2012) with the two key project participants (client and engineering consultant project managers); and analysis of relevant project-specific documents and records (such as project plans and progress reports), for secondary data (Nasirzadeh and Nojedehi, 2013; Welman et al., 2012). The gathered project-specific data was both quantitative (mainly) and qualitative; mainly time-series data (project performance and business performance related), policies and decision rules, as required for system dynamics simulations in line with Martinez-Moyano and Richardson (2013), and Sterman (2000).

The gathered data were for 18 unique raw water infrastructure-related projects (made up of 10 asset management planning and support-related projects, and 8 asset renewal-related projects) from the same engineering consultant (firm), but from varying clients. All the projects made use of time-based contracts, with a ceiling price, between the client and the engineering consultant. Key statistics of the gathered project-specific data are provided in Sections 6.4.1 and 6.5.1.

Research instrument (semi-structured interview questionnaire)

The semi-structured interview questionnaire used for the second stage of this research study is as shown in Appendix B.

Data Analysis

The system dynamics conceptual model of the competition, formulated in the first stage of the research study, was converted to an appropriate system dynamics simulation model, using Vensim DSS software, by: developing an appropriate full model structure (stocks and flows, and feedback loops); specifying mathematical equations for the relationships among the different model variables and parameters (constants), whilst ensuring dimensional consistency in all equations; specifying initial conditions, where applicable; and testing for extreme conditions, as recommended by Martinez-Moyano and Richardson (2013) and Sterman (2000). The formulated system dynamics simulation model is presented in Chapter 5.

Multiple model confidence-building tests were conducted iteratively throughout the system dynamics modelling process, in line with systems dynamics best practices. They included: direct structure tests (such as model boundary adequacy, dimensional consistency, and direct extreme conditions), structure-oriented behaviour tests (indirect extreme conditions, family member, behaviour reproduction, model calibration, and behaviour sensitivity analysis), model behaviour pattern tests, and partial model testing to ascertain intended rationality. Refer to Section 6.3.2 for more details.

Model calibration (estimation of model parameters) was conducted as an optimisation process (making use of the Powell conjugate search algorithm) using the gathered data. Two sets of model calibrations were conducted, one for each of the two sets of unique raw water infrastructure projects (asset management planning and support-related, made up of 10 projects; and asset-renewal related, made up of 8 projects) considered in this study. Refer to Sections 6.4 and 6.5 for more details.

Data gathered from the multiple-cases (18 projects) were analysed qualitatively and quantitatively through system dynamics computer simulations (Barlas, 1996; Luna-Reyes and Andersen, 2003; Martinez-Moyano and Richardson, 2013; Parvan et al., 2015; Sterman, 2000) using Vensim DSS software. The current research study sought to analyse causal relationships among variables/constructs (Martinez-Moyano and Richardson, 2013; Sterman, 2000), as opposed to correlational analyses (Cooper and Schindler, 2014; Welman et al., 2012). As such, the dynamic hypotheses formulated in the first stage of the research study were tested through system dynamics computer simulations of the model, using the Vensim DSS software (Sterman, 2000). System dynamics computer simulation was used to analyse the dynamic hypotheses in line with the system dynamics modelling process (Martinez-Moyano and Richardson, 2013; Sterman, 2000), as opposed to statistical hypothesis testing (Cooper and Schindler, 2014; Welman et al., 2012).

Two sets of simulation experiments (one for each of the two project sets) were conducted, using Vensim software, on the calibrated system dynamics simulation model to assess the impact/influence of the competition between the two key project participants (client and engineering consultant) on project performance (as measured by project time schedule performance and project cost performance) for each project. For each set, a multivariate Monte Carlo behaviour mode sensitivity analysis was then conducted to assess the sensitivity of the impact of the competition on project performance to uncertainty/changes in the key calibrated model parameters for each project. The results from both the impact analyses and the sensitivity analyses conducted for the two sets of projects considered were compared (in terms of the polarity and behaviour mode sensitivity of the impact of the competition on project performance). Appropriate conclusions were then drawn regarding the test results of the associated dynamic hypotheses and provisional answers provided for the associated research questions (refer to Section 6.6).

Subsequently, a similar process (to that described in the preceding paragraph) was followed for assessing the impact of the competition on the engineering consultant's project business performance (as measured by project time schedule performance and project revenue performance). Refer to Section 6.7 for more details.

Finally, two sets of optimisation experiments (one for each of the two project sets) were conducted, using Vensim software, on the calibrated system dynamics simulation model to find appropriate policies that improve the competition (minimising its impact on both the project performance and the engineering consultant's project business performance), yielding win-win long-term results for the two key project participants. Appropriate comparisons were made and conclusions drawn, providing a provisional answer for the associated research question (refer to Section 6.8).

2.5. Research Credibility (Validity and Reliability)

The quality and credibility of a research study are influenced by construct validity, internal validity, external validity, and reliability (Cooper and Schindler, 2014; Welman et al., 2012; Yaghootkar, 2010; Yin, 2014).

Validity

Construct validity is the extent to which operational measures accurately measure the intended construct (Welman et al., 2012; Yin, 2014). During qualitative data collection, it can be enhanced by: using multiple sources of evidence (triangulation) and establishing chains of evidence; and by having the draft case study research report reviewed by some key research participants, according to Yin (2014). System dynamics inherently demands the use of multiple sources of evidence to correctly capture the mental models of system actors (Luna-Reyes and Andersen, 2003; Martinez-Moyano and Richardson, 2013; Sterman, 2000). As such, the correct use of system dynamics can greatly enhance the construct validity. Arguably, making use of established operational definitions from previous studies can help enhance construct validity in quantitative studies.

Internal validity refers to the extent to which causal relationships are precise and exclusive, i.e. the extent to which the dependent variable (Y) is attributable to the independent variable (X) and not to some other variable(s) (Z) (Welman et al., 2012; Yin, 2014). System dynamics is concerned with formulating causal relationships among system components, in line with the system actors' mental models, and testing those causal relationships through computer simulations (Martinez-Moyano and Richardson, 2013; Sterman, 2000). Furthermore, a system dynamics model boundary shows which variables are included endogenously, included exogenously, or excluded from the model (Sterman, 2000). Thus, system dynamics modelling and simulation inherently enhances the internal validity of research findings, as also highlighted by Yaghootkar (2010). Internal validity is enhanced by ensuring that all the variables related to the research questions are treated endogenously. In the analysis of qualitative data, network displays (Welman et al., 2012) and/or system dynamics causal loop diagrams (Martinez-Moyano and Richardson, 2013; Sterman, 2000) are used to identify and show causal relationships among system variables.

External validity refers to the extent to which research findings can be generalised beyond their associated research study (Welman et al., 2012). Yin (2014) highlighted the important distinction between statistical generalisation (from sample to population, which is typical of quantitative research) and analytical generalisation (from specific case or experiment to other situations - conceptual level, applicable to case study and experimental research). With case study research, external validity can be enhanced by making use of multiple-cases, with the cases carefully chosen to either yield literal replication (prediction of similar research findings) or theoretical replication (prediction of different research findings but for foreseeable reasons) (Yin, 2014). In system dynamics, grounding the model with empirical data and continually testing the model throughout the modelling process can help to enhance external validity of the research findings (Yaghootkar, 2010).

In the final analysis, models (be it formal or mental) are just simplified (and thus, limited) representations of real-world systems, but some are useful (Barlas, 1996; Sterman, 2000). As such, models cannot be viewed as being either true or false, as they rather lie on a continuum of usefulness (Barlas and Carpenter, 1990). Thus, model validation entails building confidence in: the appropriateness of the model's internal structure in representing aspects of the system which are relevant to the problematic behaviour to be addressed; the accuracy of the model output in matching the observed system behaviour; and, the usefulness of the model in policy analysis and designing of new intervention strategies that help to address the problematic system behaviour, thereby enhancing system performance (Barlas, 1996; Forrester and Senge, 1980; Lane, 2015). Section 6.2 discusses system dynamics model validation and testing best practices in more details, while Section 6.3 discusses in more detail the different measures taken to build confidence in the system dynamics model (model validation), as well as the core system dynamics model confidence-building tests conducted in this research study.

Reliability (Replicability)

The *reliability* of research findings refers to the extent to which the research operations (e.g. data collection and analysis) can be repeated/replicated (by different researchers) and still yield the same research findings and conclusions

(Cooper and Schindler, 2014; Welman et al., 2012; Yin, 2014). Research reliability is a necessary, but not sufficient, condition for the research's validity (Cooper and Schindler, 2014). Yin (2014) highlighted that, for a case study research, reliability can be enhanced by: developing and utilising a case study protocol (that includes well-documented research objectives, data collection methods, and questionnaires); and by developing and maintaining a case study database of the collected evidence. With regards to system dynamics studies, reliability can be enhanced by including, in a research report, a well-documented model, complete with full model structure, associated equations, initial conditions, and parameters; all in line with system dynamics best practices (Rahmandad and Sterman, 2012; Sterman, 2000).

Research Credibility Measures Taken for this Research Study

Tables 2.7 and 2.8 show the measures taken to ensure research credibility during the first and second stages of this research study, respectively.

Table 2.7: Measures taken to enhance Stage 1 (Qualitative) research credibility

Research credibility dimension	Measures taken to ensure research credibility dimension
Construct Validity	▪ Multiple sources of evidence (review of existing literature, semi-structured interviews, non-participant casual observation during the interviews, and analysis of non-project-specific documents); ▪ Establishing chains of evidence during qualitative data analysis with ATLAS.ti software.
Internal Validity	Followed system dynamics best-practices in formulating dynamic hypotheses and the system dynamics conceptual model, such as: ▪ Model boundary charts; ▪ Model sub-systems chart; ▪ Causal network display (generated using ATLAS.ti); ▪ System dynamics causal loop diagrams (systems thinking tool).
External Validity	▪ Made use of multiple-cases; ▪ Made use of existing literature, empirical data and systems thinking to formulate the system dynamics conceptual model.
Reliability (Replicability)	▪ Well-documented research design: from research objectives, through data collection, data analysis, to research results narrative (as presented in this thesis report); ▪ Well-documented system dynamics conceptual model, in line with system dynamics best-practices; ▪ Case study database of research evidence in ATLAS.ti.

Sources: Adapted from Cooper and Schindler (2014), Martinez-Moyano and Richardson (2013), Rahmandad and Sterman (2012), Sterman (2000), Welman et al. (2012), Yaghootkar (2010), and Yin (2014).

Table 2.8: Measures taken to enhance Stage 2 (Causal Explanatory) research credibility

Research credibility dimension	Measures taken to ensure research credibility dimension
Construct Validity	For qualitative data: ▪ Multiple sources of evidence (review of existing literature, semi-structured interviews, and analysis of project-specific documents); For quantitative data: ▪ Adopted some established operational definitions from previous studies.
Internal Validity	Followed system dynamics best practices in formulating and testing the system dynamics simulation model, such as: ▪ Model boundary charts; ▪ Model sub-systems chart; ▪ Stock and flow diagrams, with appropriate causal feedback loops; ▪ Multiple model tests (direct structure tests, structure-oriented behaviour tests, and model behaviour pattern tests) conducted iteratively throughout the modelling process.
External Validity	▪ Made use of multiple-cases; ▪ Made use of existing literature, empirical data, systems thinking, and the conceptual model formulated in Stage 1 of the research study to formulate the system dynamics simulation model; ▪ Multiple model tests conducted iteratively throughout the modelling process.
Reliability (Replicability)	▪ Well-documented research design: from research objectives, through data collection, data analysis, to research results narrative (as presented in this thesis report); ▪ Well-documented system dynamics simulation model, inclusive of model graphical representations, and associated equations.

Sources: Adapted from Cooper and Schindler (2014), Martinez-Moyano and Richardson (2013), Rahmandad and Sterman (2012), Sterman (2000), Welman et al. (2012), Yaghootkar (2010), and Yin (2014).

2.6. Research Ethics

This research study was conducted in line with the prescripts of the University of Pretoria's 'Code of Ethics for Research' and with the well-established best-practices for conducting research ethically (Cooper and Schindler, 2014; Welman et al., 2012; Yin, 2014). Accordingly, a request for an ethics approval was first submitted to the Faculty of Engineering, the Built Environment and Information Technology's 'Ethics Committee for Research Ethics and Integrity'. The submitted application package included, among other things: a fully completed application form outlining the title of the research study, research study objectives, research design, handling of confidential information and how voluntary participation would be ensured; research participant informed consent form template; letter of authorisation to conduct the research from the company where the research was to be conducted; and interview questionnaires to be used. Appendix C shows the ethics approval letter obtained for this research study.

Data collection for this research study only started after receipt of the above-mentioned letter. Informed consent was obtained from each individual research participant, before data gathering from the research participant began, using the 'Research Participant Informed Consent Form' (refer to Appendix D). To ensure voluntary participation, the research participants were neither forced nor promised or given any undue compensation to obtain their consent.

The research participants were assured that the information obtained from them would be strictly confidential and anonymous, and only used for this PhD research study. Throughout this research study, the highest standards of ethical behaviour were upheld to protect the privacy and anonymity of the research participants (no personal information, such as name, gender or cell phone number, were collected) and confidentiality of the information gathered.

2.7. Conclusion

The research methodology utilised in the current research study is Mixed Methods Research (MMR) methodology, incorporating the system dynamics approach. MMR was selected because of its notable advantages over the traditional quantitative and qualitative methodologies. Firstly, it provides deeper insights and better understanding of the research problem, resulting in better quality and validity of the research findings than either the quantitative or qualitative methodology when used alone. System dynamics inherently utilises some combination of the traditionally accepted quantitative and qualitative methodologies. Secondly, MMR is ideal for studying complex phenomena. Competition between two key project participants (the client and the engineering consultant) during project execution, a key focus of this study, is inherently characterised by high levels of dynamic complexity. System dynamics (which is systems thinking plus computer modelling and simulation) is quite useful in solving problems involving dynamic complexity (such as the competition between the project participants). Hence, the choice of MMR, incorporating system dynamics for this research study.

The particular type of MMR design chosen for this research study is qualitatively-driven with sequential quantitative and qualitative supplementary components, conducted simultaneously, i.e. QUAL → quan+qual. It is, effectively, a two-stage research design. The first stage of the research design for this study was qualitative, embedded multiple-case study. It entailed formulating appropriate dynamic hypotheses and a system dynamics conceptual model (qualitative modelling) of the competition between two key project participants (the client and the engineering consultant) during project execution, from a combination of: existing literature; key findings from an embedded multiple-case study (one engineering consultant with varying clients) that captured the relevant mental models of the two key project participants (contemporary client and engineering consultant project managers); as well as making use of one of system dynamics' systems thinking tools (causal loop diagram). This helped to strengthen the validity of the formulated dynamic hypotheses and system dynamics conceptual model. Its key outputs included: dynamic hypotheses; a system dynamics conceptual model; and a provisional answer for research question number 1 (posed in Section 1.6).

The second stage of this research study was a causal explanatory research, simultaneous quantitative and qualitative (quan + qual) mixed methods research design, involving multiple cases (18 unique raw water infrastructure-related projects). It was causal explanatory research as the focus was on analyses of causal relationships among variables/constructs, as opposed to correlational analyses. It entailed: formulating an appropriate system dynamics simulation model (quantitative modelling) of the competition; testing and calibration of the system dynamics simulation model; conducting simulation experiments (testing the dynamic hypotheses), utilising both quantitative (mainly) and some qualitative data from the 18 projects; and conducting computer optimisation experiments aimed at improving the competition, yielding win-win long-term results for the two key project participants. Its key outputs included: a system dynamics simulation model; dynamic hypotheses test results, and provisional answers for research questions number 2 to 5 (posed in Section 1.6).

The quality and credibility of a research study are influenced by construct validity, internal validity, external validity, and reliability. Appropriate measures were taken throughout the research study to enhance each of these four key dimensions of research credibility. This research study was conducted in line with the prescripts of the University of Pretoria's 'Code of Ethics for Research' and the well-established best-practices for conducting research ethically, as captured in the reviewed literature. The next chapter critically reviews some relevant existing literature, identifying some short-comings and gaps for the current research study to focus on, in line with the research problem statement and research objectives formulated in Chapter 1.

3. Project Participants Performance and Competition, and System Dynamics Literature Review

3.1. Introduction

This chapter critically reviews some of the existing systems, project management, competition and system dynamics literature, identifying some short-comings and gaps for the current research study to focus on. It begins with a review of: the relationship between systems and projects and their life cycles; project complexity; key project participants during project execution; key challenges encountered during project execution; project management and its key knowledge areas; and the specific type of project contract considered in this research study. Next, it examines how the different key project participants measure their individual performance during project execution. It proceeds to discuss an apparent paradox: increasing demand and widespread use of project management, yet poor project performance continues to be commonplace.

It then reviews the current literature on competition, as a conflict-handling style, identifying some of the key factors that influence the competition. Subsequently, it discusses systems thinking and system dynamics, and their relevance to project management. Justification is then provided for the selection of system dynamics to model the competition between the project participants during project execution. A critical review of the application of system dynamics to project performance, business performance and competition ensues. Finally, a summary of some of the key short-comings in the reviewed literature regarding competition among project participants, and its system dynamics modelling is then provided.

3.2. Systems, Projects and Project Management

3.2.1. Systems and System Life Cycle

Systems

The International Council on Systems Engineering (INCOSE) defines a ‘system’ as an “integrated set of elements, subsystems, or assemblies that accomplish a defined objective” (Walden et al., 2015). In the reviewed literature, other scholars (Blanchard, 2008; Checkland, 2012; Monat and Gannon, 2015) defined a ‘system’ in a similar, or slightly different, manner using different words in some cases.

Regardless of the use of different words by the different scholars in defining what a ‘system’ is, there is general congruence in the reviewed literature that: a system is made up of a number of inter-related elements that, through inter-relationships and interactions, achieve a common objective; the system, as a whole, has emergent properties (created from the interactions and inter-relationships of its elements) that are greater than the sum of those of its individual elements (holism); and a system may exist within some hierarchy having different layers of systems, system of systems (SOS), in which sometimes the system is viewed as a system and sometimes as a subsystem, depending on the level of focus (Blanchard, 2008; Checkland, 2012; Monat and Gannon, 2015; Walden et al., 2015).

Blanchard (2008) indicates that the common objective achieved by a system is about "fulfilling some designated need". Monat and Gannon (2015) further highlight that the inter-relationships among the elements of a system are, at least, as important as the system's individual elements in shaping the overall behaviour and performance of the system. According to Checkland (2012), a system needs to be adaptive, in order to survive, as its surrounding environment changes and delivers some 'shocks' to it.

As highlighted by Blanchard (2008), and Monat and Gannon (2015), systems may be classified into two broad categories, namely: natural systems (such as the solar system); and human-made systems (such as a road network). Typical examples of the elements/subsystems of a human-made system include: human resources, equipment, products (hardware, software, firmware), facilities, data and information, policies, processes, documents, techniques, services, and other maintenance and support services (Blanchard, 2008; Walden et al., 2015).

The term 'engineering' refers to the professional practice of creating (conceptualising, designing and producing/constructing) and sustaining (utilising/operating, maintaining) products, services and/or systems that assist in getting things done efficiently and effectively, thereby improving the quality of life for the humankind (Walden et al., 2015). Engineered systems are human-made systems and they include: *infrastructure* (e.g., road network, water network, electricity network, commercial buildings, educational facilities, health facilities, and sports facilities); *mining and metals* (e.g., mine, crushing plant, smelting complex, refinery); *manufacturing plants and products* (e.g., cars, ships, aeroplanes, consumables); *defence* (e.g., warship, cruise missiles); and *oil and gas* (e.g., drill rigs, refinery, distribution network, filling stations); among others.

System life cycle

A system life cycle is a series of stages through which the system passes through, from the identification of the need for the system to the disposal of the system (Blanchard, 2008; Monat and Gannon, 2015; Walden et al., 2015). Typical life cycle stages of an engineered (human-made) system are: concept (identification of the need for the system, conceptual/preliminary design); development (detail design and development); production and/or construction (including integration and commissioning); operation and maintenance support; and retirement/ decommissioning and disposal (Blanchard, 2008; Walden et al., 2015). Whilst these system life cycle stages are logically sequential, in practice the stages may overlap; the activities within the different stages may be interdependent, overlap or run concurrently (Blanchard, 2008; Walden et al., 2015). The next sub-section defines projects and project life cycle in relation to systems and system life cycle.

3.2.2. Projects as Systems, and Project Life Cycle

Projects as Systems

A 'project' is a temporary (definite start and finish) endeavour that is undertaken to create a unique deliverable (product, service or result, or any combination of the three) (Project Management Institute, 2017). Pourdehnad (2007) emphasises the need to recognise projects as complex dynamic systems; a view shared by other scholars such as Locatelli et al. (2014), and Nicholas and Steyn (2012). Actually, there are two systems generally associated with any single project, namely: the *created system* (a system of project deliverables); and the *creating system* (the project itself, being a system of human resources, facilities, equipment, materials, data and information, documents, and other elements required to produce the project deliverables), according to Nicholas and Steyn (2012).

According to Daniel and Daniel (2018), the 'project system' (the *creating system*) consists of two interacting subsystems (both playing a part in generating project complexity), namely: the 'management subsystem' (representing the project management function that focusses on meeting the project performance targets); and the 'production subsystem' (representing the project implementation function that focusses on executing the project work and generating the project deliverables). However, such a view of the project system excludes other key elements or sub-systems, such as the external environment and associated stakeholders, which also interact with both the management and the production subsystems, contributing to project complexity and influencing project performance and project success.

Project life cycle

A 'project life cycle' is the series of phases that the project evolves through from its initiation to its completion (Project Management Institute, 2017). It can typically be split into three main phases, namely: conception (problem definition, user needs, and feasibility); definition (solution definition – user requirements, system objectives and system requirements); and execution (design, construct, hand-over and closeout) phases (Nicholas and Steyn, 2012). Thus, a project life cycle is basically that part of a system life cycle that involves creating or upgrading systems (Walden et al., 2015).

More recently, Cha et al. (2018) propose a six-stage project life cycle made up of concept, feasibility, definition, execution, transfer, and operations and value creation. They argued that: it is important to include the 'operations and value creation' phase as it is the stage where the project owner realises the project benefits and thus organisational transformation, the very reason the project owner launched the project; and that replacing the traditional 'project close-out' with 'transfer' signifies connectivity from 'project execution' to 'operations and value creation' (Cha et al., 2018). While the different project phases may interact and overlap, it is imperative to have 'gates' between the phases where deliverables of a preceding phase are reviewed and appropriate go/kill/hold/recycle decisions are then taken (Cooper, 2008; Project Management Institute, 2017).

Generally, for conventional engineering projects, the project execution phase often entails a number of sub-phases such as inception and detailed planning, preliminary design, detailed design, procurement, construction, commissioning, hand-over of project deliverables to the customer and project close-out (Nicholas and Steyn, 2012; Parvan, 2012; Project Management Institute, 2017). The Engineering Council of South Africa (2014) also identifies similar sub-phases of the project execution phase, but from the perspective of an engineering consultant, for a typical project that includes construction, namely: inception; concept and viability (preliminary design); design development (detailed design); documentation and procurement; contract administration and inspection (during construction); and close-out. The sub-phases of the project execution phase may differ with project type.

The current research study focusses on the project execution phase as this phase is the most challenging phase to manage in a project life cycle (Pourdehnad, 2007), yet it is one of the most crucial as its final output needs to be handed over to the client as a complete system ready for effective and efficient realisation of the intended project benefits. It also focusses on infrastructure projects, in particular raw water-related, as discussed in the next sub-section.

3.2.3. Infrastructure Projects

Infrastructure development plays a pivotal supporting role in the economic development and growth of any country, as highlighted by Ansar et al. (2016), Henckel and McKibbin (2017), and Vickerman (2018). Table 3.1 shows some of the key types of infrastructure, as is evident from the reviewed literature. While some infrastructure projects are success stories, there are many cases of poor project performance (especially time schedule delays and cost budget over-runs) as highlighted by Ansar et al. (2016), Morris (2008), and Kaliba et al. (2009). The current research study focusses only on raw-water infrastructure-related projects.

Table 3.1: Some key types of infrastructure

Type	Example sources
Buildings (residential, commercial and/or industrial)	Hwang and Ng (2013); Manu et al. (2015); Nasirzadeh and Nojedehi (2013); Nguyen et al. (2019)
Educational facilities	Manu et al. (2015); Ngacho and Das (2014); Parvan et al. (2015)
Electricity	De Marco (2006); Nguyen et al. (2019); Ogano (2016); Van Wyk, Bowen and Akintoye (2008);
Health facilities	Ngacho and Das (2014)
Internet	Henckel and McKibbin (2017)
Sport facilities	Molloy and Chetty (2015)
Telecommunications (fixed and/or mobile communications)	Henckel and McKibbin (2017); Kim et al. (2006)
Transportation (air)	Henckel and McKibbin (2017); Toor and Ogunlana (2010)
Transportation (rail)	Henckel and McKibbin (2017); Vickerman (2018)
Transportation (road)	Henckel and McKibbin (2017); Kaliba et al. (2009)
Transportation (sea)	Henckel and McKibbin (2017)
Water	Wen et al. (2018); Zarghami et al. (2018)

The next sub-section discusses 'project complexity', a key characteristic of infrastructure projects.

3.2.4. Project Complexity

In his seminal article on science and complexity, Weaver (1948) argued that there are three types of problems involving complexity facing scientists in the world, namely: "problems of simplicity" (which involve a few variables and are dealt with analytically); "problems of disorganised complexity" (which involve a very large number of variables and are dealt with statistically); and "problems of organised complexity" (which lie in the large middle region between the preceding two types, involve dealing simultaneously with a considerable number of variables which are interrelated and organised into an organic whole, and can neither be dealt with analytically or statistically). He called upon scientists to find ways of solving problems of organised complexity, and, taking cue from some of the advances that emerged from the then just ended Second World War, he also suggested/predicted that multidisciplinary teams and computers would be required to solve such problems (Weaver, 1948). As discussed later in Section 3.6, this prediction by Weaver (1948) amazingly became a reality, just over a decade later, with the dawn of system dynamics (a multidisciplinary approach that uses systems thinking, and computer modelling and simulation in solving problems of organised complexity).

Building on the work of Weaver (1948), Weinberg (1975) indicated that: organised simplicity is a characteristic of machines or mechanisms; disorganised complexity is a characteristic of populations or aggregates; and organised complexity is a characteristic of systems. He further highlighted that systems are “too complex for analysis and too organised for statistics” (Weinberg, 1975). Systems thinking assist in understanding and dealing with problems of organised complexity (i.e. systems) (Monat and Gannon, 2015; Weinberg, 1975). As projects are systems (Daniel and Daniel, 2018; Pourdehnad, 2007), they exhibit organised complexity.

According to Daniel and Daniel (2018), who also built on the work of Weaver (1948), there are three levels of complexity, namely: simple (stable), complicated (stable under fixed limits), and complex (unstable). Problems associated with the said three levels of complexity must be dealt with using algorithmic, stochastic and non-deterministic approaches, respectively (Daniel and Daniel, 2018). They also argued that there are three levels of uncertainty, namely: certainty (full predictability / no variation), risk (limited predictability / detect an error in the real-world), and uncertainty (unpredictability / detect an error in the model) (Daniel and Daniel, 2018). These three levels of uncertainty must also be dealt with using algorithmic, stochastic and non-deterministic approaches, respectively (Daniel and Daniel, 2018). Within the context of projects, complexity relates to the structure and dynamics of the project as a whole system, whereas uncertainty relates to the project management decision-making conditions (Daniel and Daniel, 2018).

According to Zhu and Mostafavi (2017), project complexity has two key dimensions: “detail complexity” (which is time-independent and arising from a large number of project variables); and “dynamic complexity” (which is time-dependent and arising from cause and effect relationships among the variables, which may be unclear and change with time). They emphasised the importance of understanding project dynamic complexity as key to enhancing project performance. Human behaviour is one of the key factors influencing project dynamic complexity, as highlighted by Lyneis and Ford (2007), Sterman (2000), and Zhu and Mostafavi (2017).

The next sub-section indicates some of the key project stakeholders whose behaviours during project execution tend to influence project dynamic complexity and, subsequently, project performance.

3.2.5. Project Participants During Project Execution

Executing a project involves the interaction of a number of project stakeholders, making decisions and taking actions largely aimed at advancing their interests (De Wit, 1988). As projects differ in types and sizes, stakeholders differ from project to project. However, project stakeholders may be classified into two main groups, namely: those actively involved in the execution of the project; and those whose interests may be affected (either positively or negatively) by the execution or completion of the project (Project Management Institute, 2017). Nicholas and Steyn (2012) refer to them as “actors” and “interested parties”, respectively. The interested parties typically include the beneficiaries, end-users, politicians, local community, general public, environmental pressure groups, as well as other project managers or functional managers that may be competing for the same resources (Davis, 2014; De Wit, 1988; Nicholas and Steyn, 2012; Project Management Institute, 2017). Nguyen et al. (2019) investigated some of the actions taken by such interested parties (external stakeholders) in a bid to try to influence the project. However, the focus of the current research study is not on the interested parties.

Project stakeholders who are actively involved in the execution of the project are, in this research study, referred to as project participants, in line with Shen et al. (2008), to differentiate them from the interested parties described in the preceding paragraph. Essentially, project participants during project execution are a subset of the project stakeholders whole set. Project participants typically include the project manager and his/her team, client (customer/owner), engineering consultant (designer), sub-consultants, construction contractor (builder), sub-contractors, suppliers, and government departments (Davis, 2014; De Wit, 1988; Ngacho and Das, 2014; Nicholas and Steyn, 2012; Pinto, Slevin and English, 2009; Project Management Institute, 2017; Shen et al., 2008; Toor and Ogunlana, 2010).

In this research study, the term ‘project participants’ (not project stakeholders) is used since the focus of this study is only on those stakeholders actively involved in the execution of the project. The key project participants during the execution of engineering projects are the client, engineering consultant and construction contractor (Ngacho and Das, 2014; Toor and Ogunlana, 2010). In this research study, only the client and the engineering consultant are considered. The next sub-section highlights some of the key challenges faced during project execution.

3.2.6. Challenges Faced During Project Execution

Table 3.2 summarises some of the key challenges encountered during project execution as identified from the reviewed literature. Such challenges (all of which are human behaviour-related) tend to worsen project dynamic complexity and, subsequently, militate against project performance and project success.

Table 3.2: Some key challenges faced during project execution

Key challenge	Example sources
Different and competing objectives and expectations of the project participants	Cha et al. (2018); De Wit (1988); Lyneis and Ford (2007); Project Management Institute (2017)
Conflict and competition among project participants	Barki and Hartwick (2001); da Silva et al. (2010); Dogbegah et al. (2011); Lyneis and Ford (2007); Meyer (2004); Mohammed et al. (2009); Sutterfield et al. (2007); Tjosvold (1998); Toor and Ogunlana (2010)
Lack of trust among project participants	da Silva et al. (2010); Pinto et al. (2009); Manu et al. (2015); Suprapto et al. (2015a); Suprapto et al. (2015b)
Lack of cooperation / collaboration among project participants	da Silva et al. (2010); Shen et al. (2008); Suprapto et al. (2015a); Suprapto et al. (2015b)
Ineffective communication among project participants	da Silva et al. (2010); Dogbegah et al. (2011); Hwang and Ng (2013); Morris (2008)
Poor knowledge management	Dogbegah et al. (2011); Sommer et al. (2014)
Language and culture barriers	da Silva et al. (2010); Rodrigues and Williams (1998)
Inadequate knowledge and skills of project team and management	Hwang and Ng (2013); Rwelamila and Purushottam (2012); Sommer et al. (2014)
Scope ambiguity and changes	da Silva et al. (2010); Hwang and Ng (2013); Lyneis and Ford (2007); Manu et al. (2015); Morris (2008); Sterman (1992)
Environmental and sustainability requirements	Dogbegah et al. (2011); Hwang and Ng (2013); Langston (2013)

The next sub-section highlights some of the key project management knowledge areas essential for project managers to successfully manage projects, handling and addressing the key challenges encountered during project execution.

3.2.7. Project Management and Key Knowledge Areas

Project management entails the application of relevant knowledge, skills, tools and techniques to project activities to ensure that the project objectives are met (Project Management Institute 2017). It is both a science (e.g., it makes use of: information and communication technology-based tools and techniques; metrics; and industry and discipline standards) and an art (e.g., it relies on and deals with human beings and their behaviour) (Pourdehnad, 2007).

The Project Management Institute (PMI) publishes what it calls "A Guide to the Project Management Body of Knowledge (PMBoK Guide)", from the first edition in 1996 to the current sixth edition released in 2017. The current PMBoK Guide identifies ten project management knowledge areas (integration, scope, schedule, cost, quality, resources, communications, risk, procurement, and stakeholder management), as shown in Table 3.3, deemed essential for a project manager to effectively and efficiently manage a project from its inception to its close-out (Project Management Institute, 2017). The International Organization for Standardization (ISO) also identified the same ten project management knowledge areas in its ISO 21500 guidance on project management standard (International Organization for Standardisation, 2012), as also shown in Table 3.3.

The different editions of the PMBoK Guide, whilst quite useful in assisting the management of project execution, have not been without some notable criticism. For instance, Dogbegah et al. (2011), and Hwang and Ng (2013) cautioned the inadequacy of the earlier versions (third and fourth, respectively) of the PMBoK Guide, and emphasised the need for project managers to extend their knowledge beyond the PMBoK Guide in order to be fully competent. They proposed additional knowledge areas essential for project managers' full understanding and competence, as shown in Table 3.3.

Morris (2013) criticised the PMBoK Guide for: focussing mainly on the, supposedly, uniqueness of project management (which it does not really do), rather than covering every knowledge area that is essential for the successful managing of projects; focussing mainly on project delivery, largely excluding the project definition (front-end) which actually has strong influence on the success or failure of a project; and insufficiently covering the unique characteristics and challenges encountered at each of the different stages of a project life cycle. He highlighted the importance of adopting what he terms the Management of Projects (MoP) framework that covers the management of the complete project context, covering both project definition (front-end) and project delivery, as well as interaction with the business and general environment, so as to ensure project stakeholders success (Morris, 2013).

Cha et al. (2018) highlighted that: a project involves two key permanent organisations (project owner and project supplier); and that a project owner launches the project with the aim of achieving organisational transformation, the benefits of which are realised after project execution during the project back-end. They criticised the PMBoK Guide for: being mainly project delivery/execution-focussed, largely ignoring both the front-end and the back-end (when the project owner realises the project benefits); and focussing mainly on the project supplier, largely ignoring the project owner (Cha et al., 2018). Subsequently, they formulated and suggested an advanced project management knowledge framework, an improvement to the MoP framework of Morris (2013), aimed at ensuring effective organisational transformation (Cha et al., 2018). Their framework proposes project management knowledge domains for both the project owner and the project supplier, namely: project definition (front-end), project governance, and project benefits realisation (back-end) (for the project owner); and project definition (front-end), and project delivery/execution (for the project supplier) (Cha et al., 2018).

Other scholars emphasised the need to recognise projects as complex dynamic systems, and accordingly employ systems thinking in the management of projects so as to enhance project performance (Morris, 2012; Nicholas and Steyn, 2012; Pourdehnad, 2007). However, all these valuable contributions and constructive criticisms of the PMBoK Guide by several scholars have been largely ignored by the PMI, as evident in the current (sixth) edition of the PMBoK Guide (Project Management Institute, 2017).

Table 3.3: Critical project management knowledge areas

Critical project management knowledge area	PMBoK Guide / ISO 21500	Supported / recommended by
Integration management	✓	Nicholas and Steyn (2012); Walden et al. (2015)
Scope management	✓	Morris (2013); Nicholas and Steyn (2012)
Time schedule management and planning	✓	Dogbegah et al. (2011); Hwang and Ng (2013); Morris (2013); Nicholas and Steyn (2012)
Cost management	✓	Dogbegah et al. (2011); Hwang and Ng (2013); Morris (2013); Nicholas and Steyn (2012)
Quality management	✓	Dogbegah et al. (2011); Morris (2013); Nicholas and Steyn (2012); Walden et al. (2015)
Human resources management	✓	Dogbegah et al. (2011); Hwang and Ng (2013); Morris (2013); Nicholas and Steyn (2012); Walden et al. (2015)
Communications management	✓	Dogbegah et al. (2011); Hwang and Ng (2013); Morris (2013); Nicholas and Steyn (2012)
Risk management	✓	Dogbegah et al. (2011); Hwang and Ng (2013); Morris (2013); Nicholas and Steyn (2012); Walden et al. (2015)
Procurement management	✓	Dogbegah et al. (2011); Morris (2013); Walden et al. (2015)
Stakeholder management	✓	Dogbegah et al. (2011); Hwang and Ng (2013); Morris (2013); Nguyen et al. (2019)
Knowledge management		Dogbegah et al. (2011); Nicholas and Steyn (2012); Walden et al. (2015)
Health and safety management		Dogbegah et al. (2011); Hwang and Ng (2013)

Critical project management knowledge area	PMBoK Guide / ISO 21500	Supported / recommended by
Environmental management		Dogbegah et al. (2011); Langston (2013)
Conflict, conflict-handling and dispute management		Dogbegah et al. (2011); Hwang and Ng (2013); Morris (2013); Nicholas and Steyn (2012)
Ethical management		Dogbegah et al. (2011)
Information technology management		Dogbegah et al. (2011); Morris (2013); Walden et al. (2015)
Materials resources management		Dogbegah et al. (2011); Hwang and Ng (2013)
Financial management		Dogbegah et al. (2011); Morris (2013)
Plant and equipment resources management		Dogbegah et al. (2011)
Claims management		Dogbegah et al. (2011); Hwang and Ng (2013)
Systems thinking		Morris (2012); Nicholas and Steyn (2012); Pourdehnad (2007)
Project definition (front-end)		Cha et al. (2018); Morris (2013)
Project governance and strategy		Cha et al. (2018); Locatelli et al. (2014); Morris (2013)
Project benefits management		Cha et al. (2018); Morris (2013)

The next sub-section indicates the type of contract between the client and the engineering consultant considered in this research study.

3.2.8. Type of Project Contract Considered

According to Turner (2004), Project Management Institute (2017), and Steyn, Carruthers, du Plessis, Kruger, Kuschke, Sparrius, van Eck and Visser (2012), there are three broad basic types of engineering project contracts (where the client does not partake in the actual doing of the project work) based on payment terms, namely: fixed-price (contractor is paid a generally fixed amount for a completely specified product); cost-reimbursable (contractor is reimbursed all costs incurred plus profit); and time and material (contractor is paid based on a fixed unit price multiplied by the actual quantities used or delivered). Turner (2004) and Steyn et al. (2012) note that engineering design contracts are often of the time and material form. In this research study, only time-based contracts are considered. The next section examines how the two key project participants (client and engineering consultant) considered in this study measure their performance during project execution.

3.3. Performance Measurement During Project Execution

Cha et al. (2018) highlighted the different mission perspectives between the project owner (the client) and the project supplier (the engineering consultant, as considered in this research study). The client launches a project with the aim of transforming his/her organisation by realising better operational benefits after the project has been successfully executed; whilst for the project supplier executing the project is part of his/her operations (Cha et al., 2018). Hence, during project execution, the client naturally focusses on minimising his/her investment into the project, and is thus particularly interested in project performance; whilst the project supplier (the engineering consultant) seeks to realise his/her benefits from the project, and is thus particularly interested in business performance. The next sub-section examines how the client measures project performance.

3.3.1. Project Performance Measures

During project execution, the client is particularly interested in project performance and its associated measures, and sets targets and priorities accordingly. The reviewed literature showed many studies and conceptual publications on project performance and how it may be measured (Anbari, 2003; Atkinson, 1999; Bryde, 2003; Chen, 2015; Cooke-Davies, 2002; De Wit, 1988; Mir and Pinnington, 2014; Ngacho and Das, 2014; Parvan, 2012; Toor and Ogunlana, 2010). However, the different researchers use different measures for project performance.

The number of key indicators used to measure project performance, in the reviewed literature, varies from two to nine. For instance, the earned value method measures project performance using time schedule and cost, as highlighted by Anbari (2003). Other researchers that also measured project performance using only time schedule and cost include Nasirzadeh and Nojedehi (2013), and Parvan et al. (2015). In his study aimed at assessing the influence of building information modelling on building project performance, Parvan (2012) also used only two key measures for project performance, namely: cost performance index (planned cost divided by actual cost); and schedule performance index (planned duration divided by actual duration).

Some scholars, such as Rahmandad and Hu (2010), used three key indicators (time schedule, cost and quality), the so-called ‘Iron Triangle’. De Wit (1988), cited by many subsequent researchers and authors, highlighted the important distinction between project success (measured against project objectives) and project management success (traditionally measured against time, cost and quality). He further made the point that good project management does not necessarily translate into project success: a project can be deemed a failure despite project management success, and vice versa (De Wit, 1988).

Subsequently, Atkinson (1999) suggested including other criteria such as organisational benefits, benefits for other stakeholders and technical strength of the project deliverable, in addition to the 'Iron Triangle', in the determination of project management success. Cooke-Davies (2002) reiterated the need to differentiate between project success and project management success: effectively, suggesting that project success needs to be determined taking into consideration stakeholders' realisation of intended projects benefits post-project completion.

Mir and Pinnington (2014) found a positive influence of project management performance and its variables on project success. They then emphasised the need to ensure that project management key performance indicators (KPIs) are formulated to cover all the project stakeholders and also to include not only the 'Iron Triangle' (time, cost, quality) but also the long-term benefits for the organisation, such as learning and continuous improvement (Mir and Pinnington, 2014).

Langston (2013) proposed six new KPIs (all derived from time, cost, scope and risk): value (scope/cost), efficiency (cost/time), speed (scope/time), innovation (risk/cost), complexity (risk/time), and impact (risk/scope). Ngacho and Das (2014) conducted a study on construction projects using face-to-face questionnaire-based survey research. Using data received from 175 respondents (comprising clients, consultants and contractors) and factor analysis, they found six KPIs for the measurement of project performance, namely: time; cost; quality (the traditional Iron Triangle); safety; site disputes; and environmental impact (Ngacho and Das, 2014).

A more recent study of Suprapto et al. (2015a) used efficiency (cost and time schedule performance), effectiveness (quality of project output, operability and safety), "perceived satisfaction, perceived owner's success, and perceived contractor's success" to define project performance.

At the far end of the scale, Toor and Ogunlana (2010) identified nine key indicators for project performance: on time; on cost budget; according to specifications; safety; efficiency; doing the right thing (effectiveness); free from defects; conformance to stakeholders' expectations; and minimised construction aggravation, disputes and conflicts. A closer look at the nine key indicators they identified, however, reveals that three of them (according to specifications; doing the right thing; and free from defects) can be combined into one key indicator called 'quality'. Furthermore, project efficiency refers to time schedule and cost performance, according to Suprapto et al. (2015a). Hence, it can be argued that the efficiency key indicator can be dropped to avoid double counting. Project performance needs to be measured throughout the project lifecycle so as to inform project control; while project success (measured against project objectives and stakeholders' expectations) can only be determined after a project has already been completed, according to Cooke-Davies (2002) and

De Wit (1988). Hence, it can be argued that the conformance to stakeholders' expectations key indicator can also be excluded from the list of criteria for project performance measurement, and rather be reserved for determining project success.

The project performance key indicators proposed by Toor and Ogunlana (2010) can, thus, essentially be reduced from nine to five: on time; on budget (cost); quality; safety; and minimised construction aggravation, disputes and conflicts. Indeed, the project performance evaluation framework proposed by Ngacho and Das (2014) is similar to that of Toor and Ogunlana (2010), amended as argued above and with the addition of the environmental impact key indicator. Interestingly, though, Toor and Ogunlana (2010) were not cited by Ngacho and Das (2014), suggesting independent studies that yielded almost identical findings. Table 3.4 summarises the different measures for project performance evident in the reviewed literature.

Table 3.4: Different measures for project performance

Variable	Used or recommended by
Time	Acebes, Pereda, Poza, Pajares and Galán (2015); Anbari (2003); Ford, Lyneis and Taylor (2007); Nasirzadeh and Nojedehi (2013); Ngacho and Das (2014); Parvan (2012); Parvan et al. (2015); Rahmandad and Hu (2010); Rodrigues and Williams (1998); Toor and Ogunlana (2010)
Cost	Acebes et al. (2015); Anbari (2003); Ford et al. (2007); Nasirzadeh and Nojedehi (2013); Ngacho and Das (2014); Parvan (2012); Parvan et al. (2015); Rahmandad and Hu (2010); Rodrigues and Williams (1998); Toor and Ogunlana (2010)
Quality	Ngacho and Das (2014); Rahmandad and Hu (2010)
Safety	Ngacho and Das (2014); Toor and Ogunlana (2010)
Efficiency	Suprapto et al. (2015a); Toor and Ogunlana (2010)
Disputes	Ngacho and Das (2014); Toor and Ogunlana (2010)
Environmental impact	Ngacho and Das (2014)
Specifications	Toor and Ogunlana (2010)
Effectiveness	Suprapto et al. (2015a); Toor and Ogunlana (2010)
Conformance to stakeholders' expectations	Toor and Ogunlana (2010)
Free from defects	Toor and Ogunlana (2010)

Unlike project success which is determined after a project has already been completed, project performance needs to be measured throughout the project life cycle to inform appropriate project control (Cooke-Davies, 2002; De Wit, 1988). The use and/or recommendation of different project performance measures by different researchers (Table 3.4) suggests little or no consensus in the reviewed literature on the manifest variables that must be used to measure project performance.

The focus of the current study is, however, not to investigate the validity and adequacy of the different project performance measures, but to investigate how competition between key project participants influences some of the measures. The next sub-section examines the different measures for business performance, which is of special interest to the engineering consultant during project execution.

3.3.2. Business Performance Measures

A review of existing literature shows a number of ways for measuring business performance. According to Goldratt and Cox (2004), and Gupta and Boyd (2008), there are three key performance indicators essential for measuring business performance, namely: net profit, return on investment and cash flow. Noteworthy is that all these are financial performance indicators. Furthermore, Goldratt and Cox (2004), and Hwee and Tiong (2002) emphasise that without a healthy cash flow, an organisation can fail to sustain itself (and effectively collapse), even when it records huge profits and high return on investment.

Jusoh (2008) advocated the use of a balanced score card, that includes both financial (profitability, income, return on investment, cash flow, economic value-added, sales growth, and cost control) and non-financial perspectives [customer focus ("customer satisfaction, customer response time, market share, and on-time-delivery"); internal business process ("manufacturing efficiency, quality, defect rate, and cycle time"); as well as learning and growth (employee "training and development, employee satisfaction, employee retention, and employee productivity")] in an organisation's performance measurement system. One of his key findings was that the use of a balanced score card (as a comprehensive business performance measure) results in better overall performance than the use of just one perspective, such as financial measures (Jusoh, 2008).

According to Tseng et al. (2009), business performance (for a high-tech manufacturing firm) has five dimensions: competition performance; financial performance; innovation capability; supply-chain relationships; and manufacturing capability. They found competition performance (with key indicators: sales growth rate and market share) to be the most important dimension, followed by financial performance (with key indicators: earnings profitability; capital structure (debt divided by assets), market value, and cash turnover ratio (net sales divided by average cash balance) (Tseng et al., 2009).

More recently, Prajogo (2016) measured business performance using three key measures ("sales, profit, and market share"); while Akter, Wamba, Gunasekaran, Dubey and Childe (2016) used four measures, namely customer retention, sales growth, profitability, and return on investment. Table 3.5 summarises the different measures for business performance evident in the reviewed literature.

Table 3.5: Different measures for business performance

Dimension	Variable	Used or recommended by
Financial performance	Revenue / sales	Jusoh (2008); Prajogo (2016)
	Cost	Jusoh (2008); Tseng et al. (2009)
	Net profit	Akter et al. (2016); Goldratt and Cox (2004); Gupta and Boyd (2008); Jusoh (2008); Prajogo (2016)
	Cash flow	Goldratt and Cox (2004); Gupta and Boyd (2008); Hwee and Tiong (2002); Jusoh (2008)
	Return on Investment	Akter et al. (2016); Goldratt and Cox (2004); Gupta and Boyd (2008); Jusoh (2008)
	Cash turnover ratio	Tseng et al. (2009)
	Market value	Tseng et al. (2009)
	Capital structure	Tseng et al. (2009)
Competition performance	Revenue / sales growth rate	Akter et al. (2016); Jusoh (2008); Tseng et al. (2009)
	Market share	Jusoh (2008); Prajogo (2016); Tseng et al. (2009)
Customer focus	Delivery time	Goetsch and Davis (2012); Goldratt and Cox (2004); Jusoh (2008)
	Customer response time	Goetsch and Davis (2012); Jusoh (2008)
	Customer satisfaction	Goetsch and Davis (2012); Goldratt and Cox (2004); Jusoh (2008)
	Customer retention	Akter et al. (2016); Goetsch and Davis (2012)
Supply-chain relationships	Upstream materials and supplies	Goetsch and Davis (2012); Tseng et al. (2009)
	Downstream tactical alliances	Goetsch and Davis (2012); Tseng et al. (2009)
Internal business process	Manufacturing / production efficiency	Goldratt and Cox (2004); Jusoh (2008); Tseng et al. (2009)
	Quality of products or services / defect rate	Goetsch and Davis (2012); Goldratt and Cox (2004); Jusoh (2008); Tseng et al. (2009)
	Lead/cycle time	Goldratt and Cox (2004); Jusoh (2008)
Innovation capability	Number of new patents	Jusoh (2008); Tseng et al. (2009)
	Research and development expenditure ratio	Tseng et al. (2009)
	Number of new product launches	Jusoh (2008)
	Time-to-market for new products	Jusoh (2008)
Learning and growth	Employee training and development	Goetsch and Davis (2012); Jusoh (2008)
	Employee satisfaction	Goetsch and Davis (2012); Jusoh (2008)
	Employee retention	Goetsch and Davis (2012); Jusoh (2008)
	Employee productivity	Goldratt and Cox (2004); Jusoh (2008); Tseng et al. (2009)

The use of different business performance measures by different researchers, as shown in Table 3.5, also suggests little or no consensus in the reviewed literature on the manifest variables that must be used to measure business performance. Nonetheless, a closer look at the above-reviewed literature sources reveals support for the key finding of Tseng et al. (2009) that the two top-ranked dimensions of business performance are competition performance and financial performance. Jusoh (2008) also noted the increasing importance of customer focus towards enhancing an organisation's business performance. In the particular case of a time-based contract (Turner, 2004) between an engineering consultant and the client, the key indicators for these three most important business performance dimensions for the engineering consultant during project execution are, arguably: competition performance (project revenue growth rate); financial performance (project revenue, profit, return on investment, cash turnover ratio, and cash flow); and customer focus (project time schedule duration, and customer satisfaction).

The next section highlights an apparent paradox: increasing demand and widespread use of project management, yet poor project performance continues to be commonplace.

3.4. The Paradox – Widespread Use of Project Management and Persistent Poor Project Performance

Project management has proven to be one of the most important forms of management due to its versatility, demand and widespread use in almost every discipline, field and organisation (Pourdehnad, 2007). Indeed, previous studies highlight the importance and use of project management in such areas as: defence (Sutterfield et al., 2007); infrastructure (Molloy and Chetty, 2015; Ngacho and Das, 2014; Toor and Ogunlana, 2010); and product development (Sommer et al., 2014), among many others. Yet, poor project performance continues to be commonplace. For instance: as many as 60% to 82% of all projects fail, according to Morris (2008); about 84% of software projects are completed late and over-budget (Standish, 2014); and whilst the South African stadiums were completed in time for the FIFA 2010 Soccer World Cup games, overall cost overrun of 72% was incurred, with the FNB Stadium having the highest cost overrun of 136% (Molloy and Chetty, 2015).

The reasons for project failure vary, but the reviewed literature on project management identified many challenges (all of which are human behaviour-related) encountered during project execution that tend to militate against project performance and project success, as already highlighted in Section 3.2.6, Table 3.2.

Poor understanding of project management (Sterman, 1992) and poor project execution (Molloy and Chetty, 2015; Morris, 2008; Standish, 2014) pervasive across disciplines, fields and organisations can be attributed, at least partly, to inadequate project management knowledge and skills (Hwang and Ng, 2013; Rwelamila and Purushottam, 2012; Sommer et al., 2014), as also shown in Table 3.2. Indeed, as discussed in Section 3.2.7, many scholars such as Dogbegah et al. (2011), Cha et al. (2018), Hwang and Ng (2013), Morris (2013) and Pourdehnad (2007) highlighted the need for project managers to extend their knowledge beyond the ten project management knowledge areas recommended by the Project Management Institute (2017) in order to be fully competent.

One of the additional project management knowledge areas proposed by Dogbegah et al. (2011), Hwang and Ng (2013), and Morris (2013) as essential for project managers' competence is "conflict, conflict-handling and dispute management". The next section examines this additional knowledge area in detail, with a particular focus on one (competition) of the five ways project participants handle conflict.

3.5. Competition Among Project Participants During Project Execution

3.5.1. Conflict Handling and Competition

Projects often have dependent activities (Project Management Institute, 2017; Zhu and Mostafavi, 2017) that are carried out by different people. Essentially, this means that the execution of projects involves project participants and other relevant stakeholders, and their interactions and interpersonal relationships (Schermerhorn et al., 2012). As a result, conflict is inevitable during project execution (Barki and Hartwick, 2001; Hwang and Ng, 2013; Morris, 2013; Project Management Institute, 2017).

There are many previous studies and publications covering organisational conflict in general. For instance, Sutterfield et al. (2007) highlighted the three types of conflict (interpersonal, task-based and process-based) acknowledged in existing literature. Schermerhorn et al. (2012) differentiated between two main categories of conflict, namely: functional/constructive conflict, which helps to expose problems so that they can be solved, thereby benefiting the parties involved; and dysfunctional/destructive conflict, which creates negative energies and hostilities, hurts team cohesion, and disadvantages the parties involved.

Of interest to the current study is the way project participants handle dysfunctional conflict. Several scholars and authors have identified some of the major sources of dysfunctional conflict as: resource constraints; incompatible goals/objectives; different perspectives; different priorities; different values; ineffective communication; role ambiguity; and schedules (da Silva et al., 2010; De Wit, 1988;

Goetsch and Davis, 2012; Nicholas and Steyn, 2012; Project Management Institute, 2017; Rodrigues and Williams, 1998; Schermerhorn et al., 2012).

The existing conflict management literature has also acknowledged and highlighted five different ways (styles/strategies) in which project participants handle dysfunctional conflict among themselves, namely through: avoidance (withdrawing); accommodation (sacrificing); collaboration (problem-solving); competition (forcing/directing/dominating); and compromising (sharing). The five conflict handling styles are summarised in Figure 3.1.

A number of factors influence the choice of which conflict-handling style to use, and these include: the situation and nature of the conflict (Goetsch and Davis, 2012; Rahim, 2002), level/intensity of the conflict (Barki and Hartwick, 2001; Project Management Institute, 2017), time pressure, and positional power or influence of the parties involved (Project Management Institute, 2017), among others.

Collaboration is basically the ideal conflict-handling style since it results in win-win solutions, benefiting all the parties involved. However, competition (aimed at win-lose results), as a conflict-handling style, has been shown by some previous researchers (Lyneis and Ford, 2007; Mohammed et al., 2009; Sutterfield et al., 2007) to be quite common among project participants during project execution. Indeed, interactions and interdependencies among project participants are unavoidable during project execution. Yet, interdependence is a necessary structural condition for dysfunctional conflict (Barki and Hartwick, 2001), which in turn leads to competition, as a conflict-handling style, among project participants.

Dysfunctional conflict has been widely researched and published in various disciplines, such as psychology (Tjosvold, 1998), organisational behaviour (Marques et al., 2015; Meyer, 2004; Rahim, 2002; Schermerhorn et al., 2012), and project management (Barki and Hartwick, 2001; Nicholas and Steyn, 2012; Project Management Institute, 2017; Sommer et al., 2014). Nonetheless, the impact of competition, as a conflict-handling style, on project performance and business performance is scarcely covered in the reviewed existing literature. Competition, as one style of handling conflict, is whereby one party seeks victory (win-lose) by exerting power, force, superior skill, aggression or domination at the expense of others (Barki and Hartwick, 2001; Marques et al., 2015; Project Management Institute, 2017; Rahim, 2002; Schermerhorn et al., 2012).

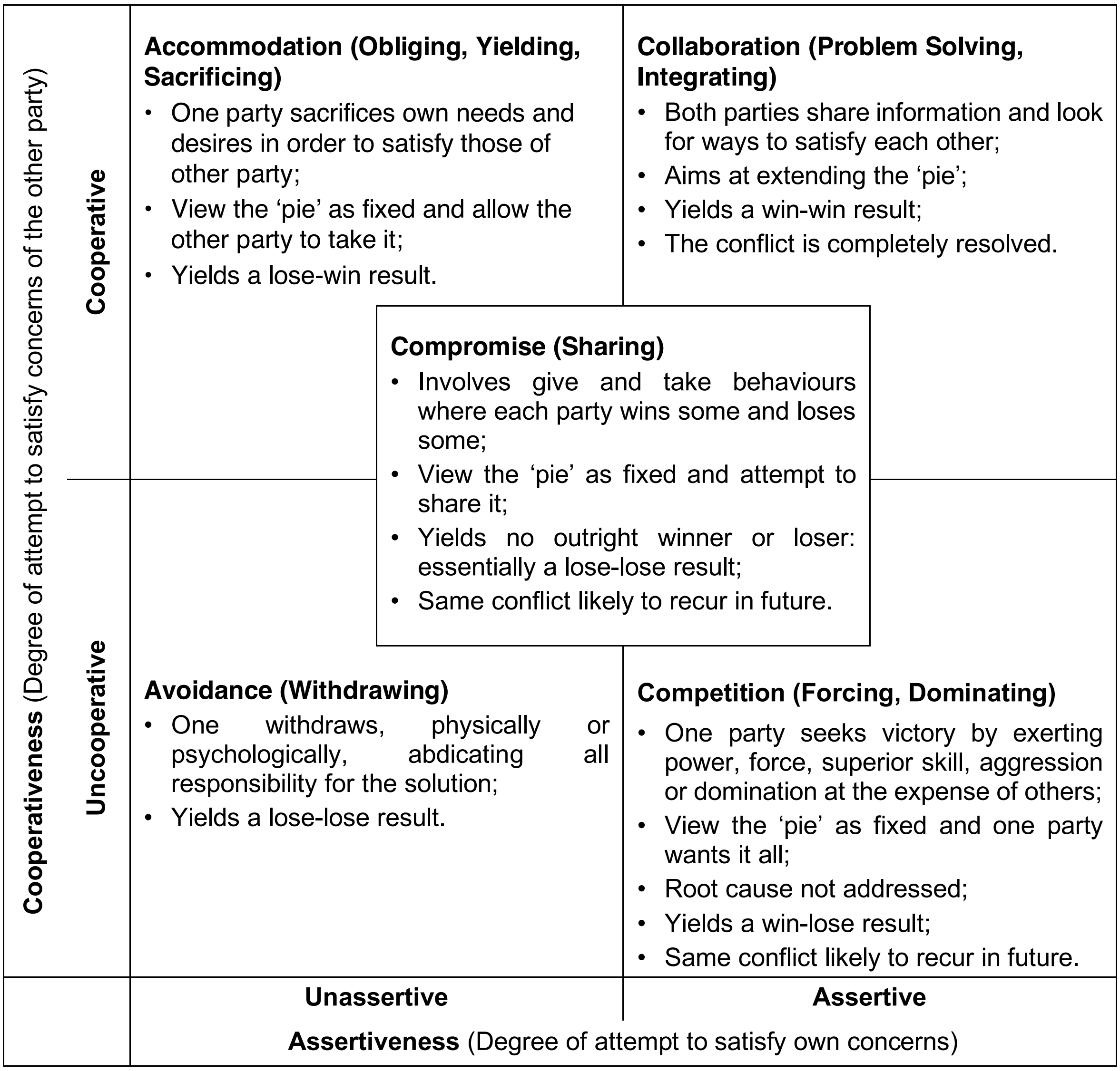


Figure 3.1: Conflict-handling styles

Sources: Adapted from Barki and Hartwick (2001), Marques et al. (2015), Nicholas and Steyn (2012), Project Management Institute (2017), Rahim (2002), Meyer (2004), Sutterfield et al. (2007), Schermerhorn et al. (2012), and Goetsch and Davis (2012).

The next four sub-sections discuss some key factors that influence competition.

3.5.2. Competing Performance Objectives and Measures

Different Performance Objectives and Measures

According to Tseng et al. (2009), financial performance is one of the key dimensions for measuring business performance. Other scholars, such as Goldratt and Cox (2004), and Gupta and Boyd (2008) echoed the same view, emphasizing that the goal of a for-profit organisation is to benefit financially from its operations. As such, each project participant needs to benefit financially from the project.

On the one hand, the 'operations' of an engineering consultant (or construction contractor), as a projectised organisation, basically entail execution of projects (Cha et al., 2018). Thus, the engineering consultant (or construction contractor) seeks to benefit financially (good financial performance, and thus good business performance) during project execution. Accordingly, the engineering consultant (or construction contractor) uses certain measures for financial performance (and thus business performance), sets certain targets, and takes appropriate controls aimed at protecting his/her business performance targets during project execution.

On the other hand, the 'operations' of a client entail making use of the project deliverables to generate intended project benefits (Cha et al., 2018). Thus, the client can generally only benefit financially after project execution since the intended benefits can only be realised during operation and maintenance of the project deliverables, assuming a sequential system life-cycle, whereby operation and maintenance of project deliverables strictly follows project execution (Blanchard, 2008; Cha et al., 2018).

Thus, during project execution, the client naturally focusses on minimising his/her investment into the project; whilst other project participants (such as engineering consultant and construction contractor) focus on generating financial benefits. Put differently, on the one hand, during project execution, the client is particularly interested in project performance and its associated measures, and sets targets and priorities accordingly. As highlighted in Section 3.3.1, existing literature is replete with many measures of project performance. For instance, the earned value method measures project performance using time and cost (Anbari, 2003); whilst Ngacho and Das (2014) proposed six key performance indicators for project performance, namely time, cost, quality, safety, site disputes, and environmental impact.

On the other hand, other project participants (e.g., the engineering consultant and construction contractor) are particularly interested in their business performance and its associated measures, and they also set their targets and priorities accordingly during project execution. Also, as highlighted in Section 3.3.2, existing literature is replete with many measures of business performance. For instance, Tseng et al. (2009) found competition performance and financial performance to be the most important key dimensions for measuring business performance of a 'for-profit' organisation; while Goldratt and Cox (2004), and Gupta and Boyd (2008) emphasise only financial performance measures (namely net profit, return on investment, and cash flow) as essential for measuring business performance.

Thus, during project execution, different project participants often have different objectives (De Wit, 1988) and competing expectations (Project Management Institute, 2017), emanating from the different ways they define and measure performance. Accordingly, different project participants tend to take different decisions and control actions, in a bid to protect their different and competing performance measures when they face a particular challenge during project execution (Lyneis and Ford, 2007). Though often intendedly rational (Sterman, 2000), such different decisions and control actions turn out to be mutually-exclusive, leading to the use of competition (aimed at win-lose end-results) as a conflict-handling style. This is quite common during project execution, as highlighted by Lyneis and Ford (2007), Mohammed et al. (2009), and Sutterfield et al. (2007).

Tjosvold (1998) defines ‘competition’ as “incompatible goals”, and proceeds to say that the different project participants in competition believe that their goals are negatively related, so that as one succeeds the other loses. Furthermore, the competitive goals lead to competition as a response to conflict (Tjosvold, 1998). However, as previously highlighted, the goals of all project participants (as organisations) are essentially the same: to generate financial benefits (Goldratt and Cox, 2004). Each participant intends to generate financial benefits from the project: the only difference is that some project participants (such as the engineering consultant and the construction contractor) need to generate financial benefits during project execution, whilst the client can only do so after project execution, assuming a sequential system life-cycle (Cha et al., 2018).

The challenge often becomes more complicated when the client tries to ‘realise’ financial benefits during project execution, and starts using some inappropriate performance measures or terminology. For instance, Chen (2015) used “project profitability” ((calculated as Project Profitability = (Revised Contract Price - Actual Cost)/Revised Contract Price)), where ‘Revised’ takes care of project scope changes) as one of the measures for the “project failure” construct. Arguably, project profitability, when used by the client, is a misleading measure that potentially leads to conflict and competition among project participants.

Firstly, in simple terms, ‘profit’ is revenue minus the costs incurred in generating the revenue. During project execution, the client invests money into the project and receives no revenue (assuming a sequential system life-cycle); so there cannot be any profit for the client to consider during this period. Secondly, if the client were to use the above-mentioned definition of “project profitability”: to maximise “project profitability” for a given “Revised Contract Price”, the client focusses on minimising the project “Actual Cost” variable. However, minimising the project “Actual Cost” means minimising the revenue (and effectively profit) of other project participants (such as the engineering consultant and the construction contractor).

As a result of such measurements, competition becomes unavoidable as different project participants take different, though intendedly rational (Sterman, 2000), decisions and control actions to protect their individual performance measures and targets. Thus, it can be argued that the different performance measures are really the underlying root cause of the competition among project participants, as the participants tend to engage in competitive behaviour (win-lose) in order to satisfy their own performance measures.

A closer analysis of the above-mentioned formula for “project profitability” shows that it is actually equivalent to the formulation of project “cost variance percentage” (cost variance percentage = cost variance / earned value), as used in the earned value method (Anbari, 2003). At project completion: cost variance = (revised contract price - actual cost); and earned value = revised contract price. Thus, the use of project cost variance percentage has potentially similar impact on the competition among project participants, as argued above for project profitability.

It can, thus, be argued that rather than the goals, what essentially differ are the performance measures of interest to the different project participants during project execution: the client focusses on project performance; whilst the other project participants (such as engineering consultant or construction contractor) focus on the business performance of their own organisations.

Asynchronous Performance Review Frequencies

The client normally reviews project performance against a baseline, milestone-based, time schedule (Project Management Institute, 2017), whilst the other project participants (such as the engineering consultant and the construction contractor), as operating businesses, tend to report and review their business performance on a quarterly basis (Gigler, Kanodia, Sapra and Venugopalan, 2014). Thus, the engineering consultant or construction contractor may end up submitting incomplete deliverables and associated invoices, and ‘pushing’ for payment just before the end of the quarter, so that they can meet their business performance targets. Often, this compromises the quality of project deliverables. Also, such behaviour erodes the trust among project participants leading to adversarial relationships (Suprapto et al., 2015b), conflicts (Pinto et al., 2009) and, in the end, competition. Thus, arguably, the different (asynchronous) performance review frequencies attached to the performance measures, targets and performance bonuses during project execution by the different project participants potentially further fuel the competition.

3.5.3. Intended Rationality

Whilst the competition among the project participants may be consciously planned and executed, it may also, arguably, be a result of intended/local rationality. Individual project participants often make locally rational decisions (Sterman, 2000) and take management control actions during project execution, in isolation of one another, as they seek to satisfy their own performance measures and targets.

However, such intendedly rational decisions and actions made in isolation (organisational silos) and treating certain variables as exogenous often lead to unintended consequences, instability and policy resistance because of the resulting dynamics (presumed exogenous variables turn out to be endogenous, time delays, unintended effects, nonlinearities and feedbacks) as the project participants interact (Sterman, 2000). Thus, intendedly rational decisions and actions can actually generate or reinforce (positive loop) the competition among the project participants.

3.5.4. Mistrust Among Project Participants

Collaboration is the ideal conflict-handling style since it results in win-win solutions for all the parties involved. Several studies have investigated trust-based collaborative relationships among project participants and their impacts on project performance (Manu et al., 2015; Pinto et al., 2009; Suprapto et al., 2015a; Suprapto et al., 2015b). Trust positively influences collaboration (Suprapto et al., 2015b) and teamworking quality (Suprapto et al., 2015a) between a client and a contractor (two key project participants). Manu et al. (2015) emphasised the need for each party to be not only trustful, but also trustworthy and ethical, so as to enable collaboration among the project participants.

Mutual trust among project participants enables them to freely share information and also minimises control mechanisms put in place and their associated costs (Pinto et al., 2009). The absence (or low levels) of trust, thus, leads to the institution of too many control mechanisms (such as procedures, meetings, reports, and approvals, among others) and too formalised relationships among project participants, killing the social relational fabric among the project participants (Suprapto et al., 2015a; Suprapto et al., 2015b).

Such unhealthy, often adversarial (Suprapto et al., 2015b), relationships emanating from mistrust among the project participants tend to generate conflicts (Pinto et al., 2009). For instance, scope changes, poor performance and delays in payments – three of the six key factors found to influence the development of trust-based collaborative relationships between a main contractor and a subcontractor by Manu et al. (2015) – tend to generate conflicts in projects, especially under adversarial relationships. Manu et al. (2015) found that if power is used to force win-lose solutions to such conflicts (implying use of competition as a conflict-handing style), it results in the erosion of trust between the main contractor and the subcontractor. They also found poor job performance to negatively influence trust among project participants (Manu et al., 2015). The net implication of all this is a reinforcing loop around mistrust, too many control mechanisms and too much formalisation, adversarial relationships, conflict, and competition.

3.5.5. Summary of Key Factors Influencing Competition

The preceding review of existing literature illuminated a number of key factors that influence the competition among project participants during project execution. Firstly, competition is one of the five typical styles for handling conflict. Thus, conflict is one of the key factors that influence competition among project participants. It was further argued in the previous sections, that other factors that can also influence competition include: different/competing performance measures; asynchronous performance review frequencies; intended rationality; as well as mistrust. It was further highlighted that some of these factors reinforce competition. Other factors that can generate/fuel competition include: client scope ambiguity/changes (Lyneis and Ford, 2007); contract buy-in from engineering consultant or construction contractor (Steyn et al., 2012); client under-budgeting the project (Lyneis and Ford, 2007); and penalties or litigation (von Branconi and Loch, 2004).

It was also argued that competing performance measures during project execution can be viewed as the underlying root cause of the competition among project participants during project execution. The reviewed existing project management literature, however, shows that the influence of the competition among project participants on project performance has largely been under-researched. The next section discusses systems thinking and system dynamics, and their relevance to project management which is the main discipline for this research study.

3.6. Systems Thinking, System Dynamics, and Project Management

3.6.1. Systems Thinking

As discussed in Section 3.2.4, Weaver (1948) highlighted that there are three types of problems involving complexity facing scientists in the world, namely: “problems of simplicity” (which involve a few variables and are dealt with analytically); “problems of disorganised complexity” (which involve a very large number of variables and are dealt with statistically); and “problems of organised complexity” (which lie in the large middle region between the preceding two types, involve dealing simultaneously with a considerable number of variables which are interrelated and organised into an organic whole, and can neither be dealt with analytically or statistically). He then called upon the scientists to find ways of solving problems of organised complexity. Subsequently, as discussed in the rest of this thesis report, systems thinking and system dynamics were invented and are very useful in dealing with problems of organised complexity.

Weinberg (1975) indicated that organised complexity is a characteristic of systems. He further highlighted that systems are “too complex for analysis and too organised for statistics”, and that systems thinking is a useful perspective in understanding and dealing with problems of organised complexity (i.e. systems) (Weinberg, 1975). This view is shared by many other scholars, such as Checkland (2012), Forrester and Senge (1980), Monat and Gannon (2015), Pourdehnad (2007), and Sterman (2000).

There is also general congruence in the reviewed literature that: a system is made up of a number of inter-related elements that, through inter-relationships and interactions, achieve a common objective; the system, as a whole, has emergent properties (created from the interactions and inter-relationships of its elements) that are greater than the sum of those of its individual elements (holism); and a system generally exists within some hierarchy having different layers of systems, system of systems, in which (depending on the layer of interest) the system may be viewed as a whole/system or as a part or subsystem of a bigger whole/system (Blanchard, 2008; Checkland, 2012; Monat and Gannon, 2015; Walden et al., 2015).

Monat and Gannon (2015) reviewed about 33 existing key systems thinking literature sources from the 1970s to 2015, identifying some common threads, and concluded that ‘systems thinking’ may be defined as “a perspective, a language, and a set of tools”. They view systems thinking as: a holistic ‘perspective’ that recognises systems as collections of inter-related components, and whose (systems’) behaviours and overall performances (emergent properties) are dominated by the inter-relationships among the systems’ components; a ‘language’ that is made up of such key terms as complexity, events, patterns of behaviour; systemic structure, mental models, feedback loops, holism, unintended consequences, and leverage points, among others; and a ‘set of tools’ that includes behaviour-over-time graphs, systemigrams, system archetypes, causal loop diagrams, and stock and flow diagrams, among others (Monat and Gannon, 2015). Indeed, such a view of what systems thinking entails is generally shared by other scholars such as Checkland (2012), Pourdehnad (2007), and Sterman (2000).

According to Monat and Gannon (2015), system dynamics/computer modelling is one of the tools for systems thinking. However, as discussed later in Section 3.6.3, according to Forrester (2007a), Sterman (2000), and Sterman (2002) system dynamics is actually systems thinking plus computer modelling and simulation.

Monat and Gannon (2015) also differentiated among three perspectives for thinking about reality, rooted on the seminal work of Weaver (1948), namely: analytical (reductionist) thinking which is concerned about details of the individual system components (that is, *organised simplicity*); statistical thinking which is concerned about populations or aggregates (that is, *unorganised complexity*); and systems thinking (holistic) which is concerned with systems as 'wholes', structural interconnectedness and inter-relationships among its constituent components and feedback loops (often associated with time delays) which influence the behaviour of the systems (that is, *organised complexity*). Each thinking perspective is important when appropriately applied, and systems thinking is not meant to replace analytical thinking or statistical thinking, but rather it is meant to complement them by helping to deepen insight into, and understanding of, the behaviours of systems (Monat and Gannon, 2015; Pourdehnad, 2007).

Checkland (2012) noted the extensive publications and talks on systems thinking, but lamented the lack of corresponding action in the real-world to solve pressing challenges. He highlighted the need to understand the emergent properties of a real-world system as the core condition required for systems thinking, and that analytical/reductionist thinking cannot assist in understanding a system's emergent properties (Checkland, 2012). The next sub-section discusses the value of systems thinking in project management.

3.6.2. Systems Thinking and Project Management

Systems thinking assists in understanding and dealing with problems of organised complexity (i.e. systems) (Monat and Gannon, 2015; Weinberg, 1975). Projects, as systems (Daniel and Daniel, 2018; Nicholas and Steyn, 2012; Pourdehnad, 2007), exhibit organised complexity which can be dealt with using systems thinking (Ackermann and Alexander, 2016; Daniel and Daniel, 2018; Nicholas and Steyn, 2012; Pourdehnad, 2007). Indeed, Nicholas and Steyn (2012) highlighted that project managers must be systems thinkers, as they are concerned with the success of the project as a whole (inclusive of its objectives, stakeholders and environment).

Checkland (2012) highlighted that systems thinking (rather than analytical/ reductionist thinking) is required in order to understand and be able to influence the emergent properties of a real-world system. Pourdehnad (2007) argued that project failure (or success) is an emergent property of a project (which is a complex dynamic system), and called for more incorporation of systems thinking into project management to ensure project success. Ackermann and Alexander (2016) demonstrated the value of causal maps, as a key systems thinking tool, in providing a systemic view and improved understanding of project dynamics, and they called for more project management studies utilising causal maps.

Daniel and Daniel (2018) highlighted the importance of incorporating systems thinking into project management in their proposed model of project management which has a 'project system' (the *creating system*) consisting of two interacting subsystems (both playing a part in generating project complexity), namely: the 'management subsystem' (representing the project management function that focusses on meeting the project performance targets); and the 'production subsystem' (representing the project implementation function that focusses on executing the project work and generating the project deliverables). In their model, they differentiated between two paradigms of project management, namely: "regulation" which is deterministic and entails a cycle of planning (management subsystem), executing (production subsystem) and monitoring and control (management subsystem); and "emergence" which is non-deterministic and entails a cycle of modelling (management subsystem), experimenting (production subsystem) and learning which helps improve the quality of the model and the resulting decisions (management subsystem).

They highlighted that the regulation paradigm is consistent with the classical project management as covered by the PMBoK Guide (Project Management Institute, 2017), whilst the emergence paradigm may be usefully achieved using system dynamics. Subsequently, they emphasised the importance of utilising both paradigms of project management so as to enhance project performance (Daniel and Daniel, 2018).

Daniel and Daniel (2018) further highlighted that complexity is associated with the whole project system (made up of two subsystems, management and production, and their interactions), whilst uncertainty is only associated with the management subsystem. Their project system, however, excludes other key elements or sub-systems, such as the external environment and associated stakeholders, which also interact with both the management and production subsystems, contributing to project complexity and influencing project performance and project success.

As discussed in Section 3.2.7, the Project Management Institute (2017) recommends ten key project management knowledge areas, including project integration management; whilst other scholars such as Cha et al. (2018), Dogbegah et al. (2011), Hwang and Ng (2013), Morris (2013), and Pourdehnad (2007) recommended some additional knowledge areas essential for project managers' full understanding and competence. In practice, all the recommended project management knowledge areas tend to influence one another. The role of the project integration management knowledge area is, to manage the interdependencies, integrating and coordinating the numerous project management processes and activities throughout project execution (Langston, 2013; Project Management Institute, 2017). Effective management of such interdependencies and complexities (often dynamic) requires systems thinking (Ackermann and Alexander, 2016; Daniel and Daniel, 2018; Nicholas and Steyn, 2012; Pourdehnad, 2007) and, as discussed later in Section 3.6.4, systems dynamics (Lyneis and Ford, 2007). The next sub-section discusses system dynamics as being more than just systems thinking.

3.6.3. System Dynamics (Systems Thinking and Modelling)

System dynamics is a multi-disciplinary approach whose goal is to assist managers improve their understanding of systems characterised by dynamic complexity, and to use such understanding to design and develop more effective, high-leverage policies and structures that solve real-world problems and improve the performance of the systems (Martinez-Moyano and Richardson, 2013; Sterman, 2000). It was founded by Jay Wright Forrester in the late 1950s and early 1960s, and publicised through his seminal *Industrial Dynamics* book that was released in 1961 (Forrester, 2007a). Since then there has been several publications about system dynamics, most notably John D. Sterman's *Business Dynamics – Systems Thinking and Modeling for a Complex World* book (Sterman, 2000), a primer for system dynamics.

Limitations of Systems Thinking and the Need for System Dynamics

Systems thinking is a useful first step towards understanding complex dynamic system problems; however, it is insufficient on its own (Forrester, 2007a). It relies on the human mind, yet the human mind is incapable of solving problems in systems characterised by dynamic complexity (Forrester, 2007b). Furthermore, experimentation in most real-world systems (such as projects, organisations, and the like) is very difficult, if not impossible, to carry out owing to the differences in time and space between causes and effects (Sterman 2002).

To fully understand complex dynamic system problems, identify the low-leverage policies and structures causing such problems, and develop more effective, high-leverage policies and structures that solve real-world problems and improve the performance of the systems, computer modelling and simulation are required (Forrester, 2007a; Forrester, 2007b; Sterman, 2000; Sterman, 2002). The founder of system dynamics emphasised this point by indicating that systems thinking contributes only about 5% towards the understanding of complex dynamic systems, with computer modelling and simulation essential in providing the remaining 95% (Forrester, 2007a). System dynamics, which is systems thinking plus computer modelling and simulation, is required for full understanding of complex dynamic systems (Forrester, 2007a; Forrester, 2007b; Sterman, 2000; Sterman, 2002).

Formal computer modelling and simulation provides fertile ground for extensive experimentation, enabling one to conduct multiple simulations and tests, identify high-leverage policies; and thus appropriately expand the boundaries of our models to include feedbacks previously not recognised, and other relevant disciplines, departments or organisations previously excluded; effectively, enhancing the overall system performance (Forrester and Senge, 1980; Sterman, 2000; Sterman, 2002).

The fact that system dynamics entails systems thinking plus computer modelling and simulation was emphasised by Sterman (2000). Sterman (2002) also highlighted the importance of the word ‘and’ in the subtitle (*Systems Thinking and Modelling for a Complex World*) of his *Business Dynamics* book (the most popular and comprehensive text book on system dynamics), basically emphasising that system dynamics is systems thinking plus computer modelling and simulation. Interestingly, way before the dawn of system dynamics, Weaver (1948) predicted that computers would be required to solve problems of organised complexity (i.e., complex dynamic systems), which can neither be solved analytically nor statistically.

Policy Resistance and Dynamic Complexity

Policy resistance is “the tendency for interventions to be defeated by the response of the system to the intervention itself”; a case where “our best efforts to solve problems often make them worse” (Sterman 2002). It arises because of our failure: to recognise that cause and effect(s) are usually distant in both time and space; and to fully comprehend and recognise all the feedbacks created by our decisions and actions in the system owing to a “narrow, event-oriented, reductionist worldview” and failure to recognise that almost everything is endogenous; all this resulting in unintended consequences and counterintuitive behaviour of systems (Sterman, 2000; Sterman, 2002). Our failure in this regard emanates from dynamic complexity of systems, which is time-dependent and arises from cause and effect relationships among the variables, which may be unclear and change with time (Sterman, 2000; Zhu and Mostafavi, 2017).

Dynamic complexity arises from the fact that systems are dynamic, tightly coupled (the system’s components are inter-related and they interact with each other and also with the external environment), governed by feedbacks (some balancing/negative, and some reinforcing/positive), nonlinear (effect is often not proportional to cause), history-dependent and self-organising (path dependence), adaptive, counterintuitive (cause and effect are usually distant in both time and space), policy resistant, and are characterised by trade-offs (time delays in the feedbacks lead to differences between short-term and long-term responses to an intervention; and low-leverage policies lead to better-before-worse behaviour, while high-leverage policies lead to worse-before-better behaviour); and all these are characteristics of dynamic complexity (Sterman, 2000).

Many systems (such as economies, transportation, cities, projects, and politics, among others) in this world are characterised by dynamic complexity (Sterman, 2000). Human behaviour is one of the key factors influencing project dynamic complexity, as highlighted by Lyneis and Ford (2007), Martinez-Moyano and Richardson (2013), Sterman (2000), and Zhu and Mostafavi (2017). System dynamics helps us to deal with dynamic complexity, identify high-leverage policies, and thus appropriately expand the boundaries of our models to include the feedbacks previously not recognised and also to include other relevant disciplines, departments or organisations previously excluded, thereby avoiding or minimising policy resistance, and enhancing the overall performance of the system (Sterman, 2000; Sterman, 2002).

System Dynamics Modelling Process

As discussed is Chapter 2 of this thesis report, a number of different versions of the system dynamics modelling process (Martinez-Moyano and Richardson, 2013; Sterman, 2000) have been suggested in the existing literature. While different scholars proposed different number of stages for the system dynamics modelling process, system dynamics basically entails developing and testing two key elements: a causal map (qualitative modelling) and a simulation model (quantitative modelling) of the system problem (Sterman, 2000; Sterman, 2001). A causal map is a diagrammatic representation of the accumulations (stocks and flows) and causal loops (positive and/or negative feedbacks) associated with the system problem (Sterman, 2000; Sterman, 2001). It is a conceptual model, and it is formulated using systems thinking tools such as causal loop diagrams and stock and flow diagrams (Sterman, 2000). Causal maps capture mental models and are insufficient for full understanding of complex dynamic systems, owing to the cognitive limitations of the human mind which makes it incapable of performing mental simulations for the dynamics of complex nonlinear systems (Sterman, 2002).

One needs to go beyond causal maps and formulate appropriate system dynamics simulation models (formal models) and conduct multiple tests and appropriate computer simulations to fully comprehend the dynamics, discover the hidden assumptions and flaws in our mental models, discover the important feedbacks previously excluded, build intuition and appropriately expand the boundaries of our mental models (Sterman, 2002). Thus, formal modelling and computer simulation, by providing full feedback regarding the effects (both intended and unintended) of our decisions and actions, assist in effective learning about and understanding of the behaviour of complex nonlinear systems (Sterman, 2002).

The causal maps are converted to system dynamics simulation models using computer software such as Vensim by: developing appropriate model structure (stocks and flows, and feedback loops); specifying mathematical equations for the relationships among the different model variables and parameters (constants), whilst ensuring dimensional consistency in all equations; specifying initial conditions, where applicable; and testing for extreme conditions, as recommended by Martinez-Moyano and Richardson (2013) and Sterman (2000). A system dynamics simulation model enables one to simulate and analyse the dynamic behaviour of the system, and to identify the root cause of the system problem (Sterman, 2000; Sterman, 2001). This enables the redesign of internal system structures and implementation of appropriate operating policies aimed at enhancing the system's performance (Forrester, 2007b; Sterman, 2000).

Systems dynamics emphasises the importance of model testing (multiple tests throughout the system dynamics modelling process) in assisting in: uncovering the hidden assumptions and flaws in our models (both mental and formal); identifying the high-leverage policies; and thus appropriately expanding the boundaries of our models to include the feedbacks previously not recognised and also to include other relevant disciplines, departments or organisations previously excluded, and thereby enhancing the overall system performance (Barlas, 1996; Forrester and Senge, 1980; Sterman, 2000; Sterman, 2002).

Applications of System Dynamics

The system dynamics approach has been widely and successfully used to model many problems in numerous disciplines and areas, enabling better understanding of the systems, formulation of high-leverage policies aimed at performance improvement. Examples of areas where system dynamics has been successfully applied include: business performance (discussed in Section 3.9); competition (discussed in Section 3.10); electricity (Ogano, 2016); innovation (Luna, 2006); inventory management (Sterman, 1989); organisational business strategy and policy evaluation (Sterman, 1992); project management (discussed in Sections 3.6.4 and 3.8); quality improvement (Van Dyk, 2013); socio-technical systems (Oosthuizen, 2014); and water sector (Zarghami et al., 2018). As highlighted by Forrester (2007a), system dynamics has also been successfully applied to economics, medicine, psychology and politics, among many other disciplines. The next sub-section discusses the value of systems dynamics in project management.

3.6.4. System Dynamics and Project Management

Systems dynamics helps managers to improve their understanding of systems characterised by dynamic complexity, and to use such understanding to design and develop more effective, high-leverage policies and structures that solve real-world problems and improve the performance of the systems (Martinez-Moyano and Richardson, 2013; Sterman, 2000). Projects, as systems (Locatelli et al., 2014; Nicholas and Steyn, 2012; Pourdehnad, 2007), are also characterised by dynamic complexity as highlighted by Daniel and Daniel (2018), and Zhu and Mostafavi (2017). Thus, systems dynamics may be usefully applied to projects and the management thereof so as to enhance project performance (Daniel and Daniel, 2018; Lyneis and Ford, 2007; Sterman, 1992). Indeed, system dynamics has been widely applied to project management (Ford et al., 2007; Ford and Sterman, 1998; Lyneis and Ford, 2007; Nasirzadeh and Nojedehi, 2013; Parvan et al., 2015; Rahmandad and Hu, 2010).

Daniel and Daniel (2018) differentiated between and emphasised the importance of utilising two paradigms of project management (namely "regulation" and "emergence") so as to enhance project performance, as discussed in Section 3.6.2. They highlighted that the regulation paradigm is consistent with the classical project management covered by the PMBoK Guide (Project Management Institute, 2017), whilst the emergence paradigm may be usefully achieved using system dynamics.

Lyneis and Ford (2007) conducted an extensive review of the applications of system dynamics to project management literature from the 1960s to 2007, focussing on models of single projects. They concluded that the application of system dynamics to project management can be classified into four main areas: post-mortem project assessments for disputes and learning; project estimating and risk assessment; change and risk management, and project control; and management training and education (Lyneis and Ford, 2007). The current research study focusses on the application of system dynamics to project control during project execution as this is a critical area that significantly impacts overall project performance. Section 3.8 discusses, in detail, application of system dynamics to project performance control. The next section discusses why systems dynamics is appropriate for modelling competition among project participants during project execution.

3.7. Dynamic Complexity of Competition and Need for System Dynamics

Projects, as systems, are characterised by dynamic complexity, as discussed in Section 3.2.4. Zhu and Mostafavi (2017) emphasised the importance of understanding project dynamic complexity as key to enhancing project performance. Human behaviour is one of the key factors influencing project dynamic complexity, according to Lyneis and Ford (2007), Martinez-Moyano and Richardson (2013), and Zhu and Mostafavi (2017).

Competition among project participants, which involves human behaviour and takes place within a project environment characterised by dynamic complexity, is thus inherently characterised by dynamic complexity. For instance: different project participants often have different objectives (Cha et al., 2018; De Wit, 1988; Lyneis and Ford, 2007) and competing expectations (Project Management Institute, 2017), and thus define and measure performance differently; there are numerous interdependencies and interactions among the different project participants; the project participants make decisions, usually intendedly rational, and take different control actions; there are often delays between the decisions/actions, their effects (some unintended and counterintuitive, as cause and effect are usually distant in both time and space) and the responses (balancing or reinforcing feedbacks) of the other project participants; and there tend to be differences between short-term and long-term results (due to time delays and the feedbacks) – all of which are characteristics of dynamic complexity (Sterman, 1992; Sterman, 2000).

Competition breeds mutual frustration and hostility among the project participants, leading to more conflict that generates more competition: a reinforcing feedback loop (Tjosvold, 1998). Interactions and interdependencies among project participants are unavoidable during project execution. Though the project participants might have different performance measures and targets, one participant often depends on other participants to achieve his/her performance measures and targets. Yet, interdependence is a necessary structural condition for dysfunctional conflict (Barki and Hartwick, 2001) which, in turn, leads to competition.

Competition (aimed at win-lose results) among project participants tends to affect the whole system (the project, including project participants). Solving problems (such as competition) affecting the whole system requires systems thinking (Monat and Gannon, 2015; Weinberg, 1975). Problems involving dynamic complexity (such as competition as highlighted above) are what Weaver (1948) referred to as "problems of organised complexity" (which involve dealing simultaneously with a considerable number of variables which are interrelated and organised into an organic whole, and can neither be dealt with analytically nor statistically).

Solving system problems involving dynamic complexity is not possible with the human mind alone; computer modelling and simulation is needed to support human decision-making and management policies, as highlighted by Forrester (2007b) and Sterman (2000). As discussed in Section 3.6, such complex dynamic system problems can be fully understood and solved using system dynamics (which is systems thinking plus computer modelling and simulation) (Forrester, 2007a; Forrester, 2007b; Sterman, 2000; Sterman, 2002). Systems dynamics helps managers to improve their understanding of systems characterised by dynamic complexity, and to use such understanding to design and develop more effective, high-leverage policies and structures that solve real-world problems and improve the performance of the systems (Martinez-Moyano and Richardson, 2013; Sterman, 2000).

Moreover, the core process of competition is essentially human behaviour, and system dynamics is ideal for modelling human behaviour (Sterman, 2000). Furthermore, in their review of the application of system dynamics to project management, Lyneis and Ford (2007) also called for research towards modelling (using system dynamics) and improvement of the competition among the different project participants. This research study seeks to take heed of their call. System dynamics was, thus, chosen in this research study to model the problem of competition between two key project participants (client and engineering consultant) during project execution. The next section highlights some of the applications of system dynamics to project performance control.

3.8. System Dynamics Applied to Project Performance Control

The Main Objective of Applying System Dynamics to Project Management

System dynamics is fundamentally aimed at improving system performance (Sterman, 2000). As projects are systems (Daniel and Daniel, 2018; Nicholas and Steyn, 2012; Pourdehnad, 2007), the main objective of applying system dynamics to project management is to improve project performance (Lyneis and Ford, 2007; Sterman, 1992). During project execution, clients are particularly interested in project performance: they set their targets and priorities, and take appropriate decisions and control actions to protect their project performance measures, as discussed in Section 3.3.1 and 3.5. The reviewed existing literature shows varying measures of project performance, as also discussed in Section 3.3.1.

Project Dynamics, Project Performance and Project Controls

Zhu and Mostafavi (2017) emphasised the importance of understanding project dynamic complexity as key to enhancing project performance. Ford et al. (2007), and Lyneis and Ford (2007) highlighted that adverse project dynamics that result in poor project performance largely emanate from four key structures: the rework cycle (discovery of errors in previously presumed completed work, prompting repetition of the work); controlling feedbacks (project controls taken by management in a bid to try and bring a poorly-performing project back on track); ripple effects (primary undesirable and unintended consequences of the management project controls); and knock-on effects (secondary and tertiary undesirable and unintended consequences of the management project controls).

The rework cycle is the main cause of many detrimental project dynamics, as highlighted by Ford et al. (2007), Lyneis and Ford (2007), and Rahmandad and Hu (2010). Ford et al. (2007) further made the point that ripple and knock-on effects (also known as policy resistance) tend to increase project work errors and/or reduce project workforce productivity. An increase in errors leads to more rework which in turn leads to more errors: a recursive cycling of tasks around the rework cycle that results in more workload, longer project duration and more resources than initially planned, as demonstrated by Ford et al. (2007), and Rahmandad and Hu (2010).

Thus, as Lyneis and Ford (2007) highlighted, minimising the rework cycle and the ripple and knock-on effects of management control actions can significantly reduce project dynamics, and enhance project performance.

To improve project performance, one needs to first measure actual project performance and compare it with the targeted project performance, and then take appropriate management decisions and actions aimed at closing the target-actual project performance gap. Essentially, there are two project controls (decisions and actions) that management can take to close the target-actual project performance gap, namely: relaxing the project performance targets; or increasing effective project resources (Ford et al., 2007; Lyneis and Ford, 2007). Both actions form negative (controlling) feedbacks aimed at closing the performance gap (Ford et al., 2007; Lyneis and Ford, 2007). In addition, the former tends to reduce ripple and knock-on effects, whilst the latter often triggers them (Lyneis and Ford, 2007).

Different project participants often have different objectives (Cha et al., 2018; De Wit, 1988; Lyneis and Ford, 2007) and competing expectations (Project Management Institute, 2017) during project execution. As such, they tend to take different project controls to try and influence the project execution in line with their objectives and expectations. Key project participants during execution of engineering projects include the client, engineering consultant and construction contractor (Ngacho and Das, 2014; Toor and Ogunlana, 2010), as discussed in Section 3.2.5.

Human behaviour is one of the key factors influencing project dynamic complexity, as highlighted by Lyneis and Ford (2007), Martinez-Moyano and Richardson (2013), Sterman (2000), and Zhu and Mostafavi (2017). Project controls essentially involve human behaviour, and are thus inherently characterised by dynamic complexity, as is evident in the studies of Ford et al. (2007), Nasirzadeh and Nojedehi (2013), and Rodrigues and Williams (1998).

When project performance is below expectation, the client typically demands that the engineering consultant (or construction contractor) increases effective resources (e.g. work overtime, add more resources, and/or increase work intensity), whilst the engineering consultant (or construction contractor) typically argues/motivates for the client to relax the targets (e.g., slip the project time schedule deadline, and/or increase the project cost budget). In some cases, the engineering consultant (or construction contractor) may also secretly ‘relax’ the targets by producing poor-quality deliverables (Ford et al., 2007). Often, the result of all this is conflict and competition among project participants, as each participant seeks to satisfy his/her own performance measures, as discussed in Section 3.5.

Project Controls by the Engineering Consultant (or Construction Contractor)

Existing project management literature is replete with discussions of controls actions taken by the engineering consultant or construction contractor to enhance project performance. A number of previous researchers modelled the 'increasing effective resources' management control aimed at improving project performance (Ford et al., 2007; Lyneis and Ford, 2007; Nasirzadeh and Nojedehi, 2013). For instance, Lyneis and Ford (2007) highlighted a typical system dynamics project model with a rework cycle and three management control actions that the project manager may take to increase the effectiveness of project human resources, and bring a project that is behind time schedule back on track, as shown in Figure 3.2. The three management control actions are: add more people to the project workforce; make the project workforce work overtime; and make the project workforce work faster by applying pressure on them.

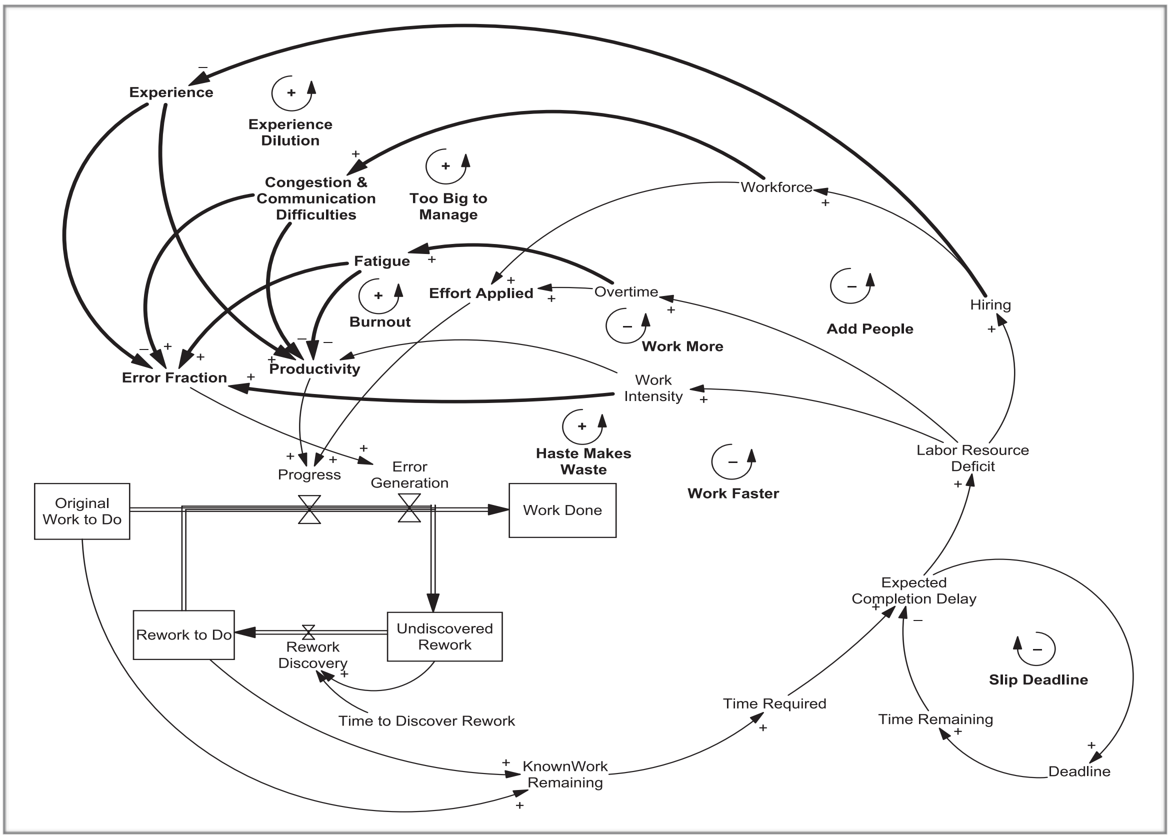


Figure 3.2: Rework cycle, controlling feedback and ripple effects for a target schedule deadline

Source: Lyneis and Ford (2007)

In system dynamics causal loop diagrams, such as Figure 3.2: the rectangles represent levels (stocks); valves represent flow rates; arrows and their polarity (+/-) indicate causal relationships (positive or negative influences) between the two variables they link; and short circular arrows (almost a circle) with polarity (+/-) at their centres show the direction (clockwise/anticlockwise) and polarity (positive/reinforcing or negative/balancing) of the causal loop (Sterman, 2000). In Figure 3.2, the thin arrows indicate negative/balancing loops (controlling feedbacks), and the thick arrows indicate positive/reinforcing loops (ripple effects).

Each set consisting of two variables linked by an arrow with a positive or negative sign, on a system dynamics model, represents a dynamic hypothesis. Dynamic hypotheses are read following the direction of the arrows and loops. For instance, in Figure 3.2, in the “Work More” loop: the longer the project is behind schedule (*Expected Completion Delay*), the more labour resources are required to bring the project back on schedule (*Labour Resource Deficit*); the larger the *Labour Resource Deficit*, the longer the available resources need to work (*Overtime*); the higher the *Overtime*, the higher the *Effort Applied*; applying more effort increases the work *Progress* rate, leading to less *Known Work Remaining*, less *Time Required* to complete the project and reduced *Expected Completion Delay*. Sustained *Overtime*, however, tends to generate unintended and undesirable consequences (ripple effects): it leads to *Fatigue*, which increases *Error Fraction* and reduces labour *Productivity*, resulting in reduced *Progress* rate (the “Burnout” reinforcing loop).

Some errors and short-comings evident in the model of Lyneis and Ford (2007) shown in Figure 3.2 include: the “Error Generation” flow is wrongly placed, it must be on the pipe feeding the “Undiscovered Rework” only; and the rework cycle does not explicitly capture testing or quality assurance.

Ford et al. (2007) formulated another system dynamics project model with similar project time schedule controls, but using a more detailed rework cycle that explicitly captured quality assurance. However, the rework cycle on their model assumed that quality assurance is perfect and no tasks with defects are approved and released to the next project phase. Yet, in practice it is quite common for defects in design stage deliverables to propagate to (and sometimes be picked up during) the construction stage (Ford and Sterman, 1998; Parvan et al., 2015).

Furthermore, both models of Ford et al. (2007), and Lyneis and Ford (2007) have other short-comings, notably:

- only the management controls taken by the project manager (belonging to only one project participant) are included. It is not clearly stated to which project participant (client, engineering consultant or contractor) this project manager belongs. However, considering that the client normally does not have direct control over the project workforce, it can be argued (and thus assumed in this research study) that the project manager in the models of Ford et al. (2007) and Lyneis and Ford (2007) is that of the engineering consultant or construction contractor. Thus, the system dynamics models of Ford et al. (2007), and Lyneis and Ford (2007) exclude client project time schedule controls (and associated ripple and knock-on effects), yet they are, arguably, key to project dynamics and project performance;

- scope changes (increase/decrease in *Original Work to Do*) which are common during project execution are excluded;
- the control actions shown are only for achieving a target time schedule deadline (only one measure of project performance), yet project performance may be measured by as many as six (or more) measures: time, cost, quality, safety, site disputes, and environmental impact (Ngacho and Das, 2014);
- the rework cycle is based on the assumption that a task can only have a maximum of one defect, yet in reality it is possible to have more than one defect per task as shown by Rahmandad and Hu (2010); and
- the rework cycle is limited to only one phase of a project as it does not capture any defects/errors generated in the current phase but discovered in subsequent phases (Ford and Sterman, 1998; Parvan et al., 2015).

Rahmandad and Hu (2010) challenged the assumption made on the rework cycle by many researchers that a task can only have a maximum of one defect as too simplistic. They argued that in practice a project task can have more than one defects, and that a task with more defects requires more rework than a task with only one defect (Rahmandad and Hu, 2010). They then formulated an improved system dynamics project rework cycle model that captures multiple defects and makes use of separate stock and flow chains for tasks and defects in a co-flow structure. By capturing multiple defects per task, their refined rework cycle enables a more accurate accounting of the magnitude of rework in a project (Rahmandad and Hu, 2010). They demonstrated a tendency of rework escalation due to the capturing of multiple defects on some tasks, and pronounced slowing down of progress towards the end of the project: providing an alternative explanation for the causes of the so-called ‘90% syndrome’ (Rahmandad and Hu, 2010).

Some short-comings are, however, noticeable in the refined rework cycle of Rahmandad and Hu (2010), and these are:

- scope changes are excluded;
- no project control actions, and associated ripple and knock-on effects, of any project participant are included;
- the rework cycle is also limited to only one phase of a project as it does not capture any defects/errors generated in the current phase that are discovered in subsequent phases; and
- whilst capturing multiple defects per task may yield a more accurate picture of project dynamics as discussed, there may be challenges in getting the

relevant project data disaggregated down to task details, especially for an academic research study, as experienced by Parvan et al. (2015).

Earlier, Ford and Sterman (1998) formulated a system dynamics project development model incorporating: the project workflow (and rework cycle); interdependencies among development tasks within a project phase; as well as inter-phase workflow dependencies and rework/changes coordination. More recently, Parvan et al. (2015) developed an improved system dynamics project model capturing three inter-phase feedbacks between the design and construction project phases in design-bid-build construction projects. The three design-construction inter-phase feedbacks considered by Parvan et al. (2015) are: "Error Domino Effect" (undiscovered design stage rework increases construction stage errors); "Slowdown Effect" (undiscovered design stage errors/rework slows down construction stage progress); and "Reality Check Effect" (construction stage progress increases the detection rate of undiscovered design stage errors/rework).

Parvan et al. (2015) found that the three inter-phase feedback effects negatively impacted project performance, causing 20% variation (increase) in total project costs and 6% variation (delay) in project time schedule. The following limitations, however, are noteworthy regarding their model:

- the design and construction phases are sequential and non-overlapping, yet in practice overlaps are common between project phases (Cooper, 2008);
- the rework cycle does not capture testing or quality assurance;
- intra-phase feedbacks and dynamics (such as burnout and corner-cutting, among others) are excluded;
- no project control actions, and associated ripple and knock-on effects, of any project participant are included;
- project scope deductions are captured, but scope additions are not; and
- project performance is measured using only time schedule duration and cost.

Nasirzadeh and Nojedehi (2013) developed a system dynamics simulation model of labour productivity in a construction project. Their model shows how labour productivity influence the work done and, subsequently, project performance, in terms of project cost and time duration (Nasirzadeh and Nojedehi, 2013). Their model includes two project control actions taken by the contractor's project manager, namely: increasing/reducing the project workforce; and making the project workforce work overtime (Nasirzadeh and Nojedehi, 2013). However, their model does not include scope changes and management control actions (and associated ripple and knock-on effects) taken by other project participants, such as the client.

Project Controls by the Client

When a project is behind time schedule, the client has basically three options to take, namely: extend the project time schedule deadline; or take some control actions aimed at bringing the project back on track; or both (Rodrigues and Williams, 1998). Consistent with previous studies such as those of Lyneis and Ford (2007), and Ford et al. (2007), the current study is aimed at advancing project management effectiveness and is, thus, focussed on investigating client project controls aimed at bringing a poorly-performing project back on track. System dynamics has been widely applied to project controls, particularly with regard to project time schedule controls, taken by engineering consultant or construction contractor, as the preceding discussion highlights. However, project controls taken by the client and their system dynamics modelling were sparingly covered in the reviewed literature.

Rodrigues and Williams (1998) developed a system dynamics model that indicated that poor project time schedule performance makes the client lose trust in the contractor; resulting in the client taking some control actions in a bid to try and bring the project back on time schedule, such as: demanding more progress reports from the contractor (or engineering consultant); and not tolerating any delays in attainment of project milestones. Their model further showed that such client controls (negative feedbacks), however, tend to generate some ripple effects. For instance, an increase in progress reports results in a decrease in productivity, and consequently a decrease in project work completion rate and an increase in the project time schedule delay (Rodrigues and Williams, 1998). However, their study did not specify how the intolerance in project milestones delays is manifested.

One study by von Branconi and Loch (2004) highlighted that when a project is delayed, the client may institute liquidated damages penalty against the construction contractor. They, however, warn that the contractor often makes trade-off analysis between the delay damages and the cost of accelerating the project, and may even decide to stop executing the project if acceleration costs exceed the delay damages (von Branconi and Loch, 2004). Effectively, in system dynamics terminology, this suggests a primary undesirable and unintended effect (ripple effect) of the delay damages penalty. The study of von Branconi and Loch (2004), however, did not include any system dynamics modelling and simulation to demonstrate the impact of schedule delay damages penalty (as a project time schedule control) on project completion, and a ripple effect on contractor (or engineering consultant) productivity. The next section highlights some of the applications of system dynamics to business performance control, as evident in the reviewed literature.

3.9. System Dynamics Applied to Business Performance Control

System dynamics is fundamentally aimed at improving system performance (Sterman, 2000). Thus, the main objective of applying system dynamics to a project-based going concern (such as engineering consultant or construction contractor), which is a system, during project execution is to improve its business performance.

During project execution, some key project participants (such as the engineering consultant and the construction contractor) are particularly interested in their own business performance: they set their targets and priorities, and take appropriate decisions and control actions to protect their business performance measures, as discussed in Sections 3.3.2 and 3.5. The reviewed literature shows varying measures for business performance, as also discussed in Section 3.3.2. There are many applications of system dynamics, in existing literature, to a number of business performance measures, resulting in better understanding of systems, formulation of high-leverage policies and internal system structures that lead to performance improvement (Gilkinson and Dangerfield, 2013; Kim and Reinschmidt, 2006; Sterman, 1989; Sterman, 2000).

Sterman (1989) modelled, using system dynamics, the stock management problem in a supply chain, from ordering raw materials, through factory production/ manufacturing inventory, distributor inventory, wholesaler inventory, retailer inventory to the placing and fulfilment of orders by clients. He found that the decision-makers in the supply chain, in their efforts to control the stock levels, were underestimating or disregarding delays in the supply chain, resulting in oscillations and amplifications of stock levels (Sterman, 1989; Sterman, 2000).

Kim and Reinschmidt (2006) modelled, using system dynamics, competition among different construction firms during contract acquisition in a competitive bidding process. They measured business performance of a construction firm using cumulative net profit and market share (Kim and Reinschmidt, 2006), which are financial performance and competition performance measures, respectively, according to Tseng et al. (2009).

More recently, Gilkinson and Dangerfield (2013) formulated a system dynamics simulation model of the competitiveness of a construction firm, from the time new contracts are advertised, through award to project execution completion. Their model measured financial performance of the construction firm in terms of cash flow and profit/loss (project revenue minus costs) (Gilkinson and Dangerfield, 2013). They further highlighted that cash flow is one of the key factors that define the competitiveness of a company (Gilkinson and Dangerfield, 2013). Nonetheless, their model did not include return on investment which, according to some scholars

(Akter et al., 2016; Goldratt and Cox, 2004; Gupta and Boyd, 2008), is one of the key measures of business performance. The next section reviews some of the applications of system dynamics to competition performance.

3.10. System Dynamics Applied to Competition

A number of previous studies modelled competition using system dynamics. For instance: competition between or among technology products/services in the market (Kim et al., 2006; Pretorius and Benade, 2011; Pretorius et al., 2015); competitive bidding for projects (Kim and Reinschmidt, 2006); and competitiveness of project construction firms (Gilkinson and Dangerfield, 2013).

Kim et al. (2006) modelled the competition among mobile phone providers in South Korea using the Lotka-Volterra equations. They found the Lotka-Volterra competitive diffusion model to more accurately estimate the market demand (mobile phone subscription) than the monopolistic logistic model (Kim et al., 2006). They also highlighted the six possible types of competitive relationships between any two parties, namely: pure competition (lose-lose); predator-prey (win-lose); mutualism (win-win); commensalism (win-no effect); amensalism (lose-no effect); and neutralism (no impact on both parties due to the absence of interaction between the parties) (Kim et al., 2006). Subsequently, Pretorius and Benade (2011) used the Lotka-Volterra system of differential equations and system dynamics to model the predator-prey competition between two competing technologies (computer-aided design and manual design).

More recently, Pretorius et al. (2015) formulated a model of three competing technologies, using Lotka-Volterra differential equations and system dynamics, that showed cyclic behaviour of technology diffusion. They evaluated their model using real data, gathered through bibliometrics, from two cases (industrial robot technology and laser technology in manufacturing) that exhibited the cyclic behaviour (Pretorius et al., 2015).

As highlighted in the preceding section: Kim and Reinschmidt (2006) modelled, using system dynamics, competition among different construction firms during contract acquisition in a competitive bidding process; and Gilkinson and Dangerfield (2013) modelled, also using system dynamics, the competitiveness of a firm in the construction industry, from the time new contracts are advertised, through award to execution completion.

In another study, Mikulskiene and Pitrenaite-Zileniene (2013), using qualitative data gathered through semi-structured interviews, formulated a system dynamics conceptual model for a participatory policy-making process. Their model:

incorporates different policy actors (stakeholders), i.e. politicians, public administrators, researchers, and the public (non-governmental organisations, communities, individuals, and businesses, among others); promotes competition of different stakeholder interests, interest alignment and in the end formulation of policy that encapsulates a balance of the interests; and, thus, preventing policy makers from formulating policy that only captures the interests of one stakeholder (typically ignoring public interests) (Mikulskiene and Pitrenaite-Zileniene, 2013). In addition, their model shows that the level of operational knowledge of the public administrators influences stakeholder competition, which in turn influences interest representation (Mikulskiene and Pitrenaite-Zileniene, 2013). However, their model does not explicitly capture the competition of interests among the different stakeholders, and how such competition influences the quality of the resulting policy. Furthermore, their model is purely conceptual and was not further developed into a simulation model, empirically calibrated and validated.

While competition has been widely modelled using system dynamics by previous researchers, the focus has been mainly on technologies competing in the market, competitive bidding and organisational competitiveness. The reviewed literature could not reveal an appropriate system dynamics model that considers competition among key project participants during project execution. The next section summarises the key gaps identified in the reviewed literature, and thus, the need for the current research study.

3.11. Summary of Key Literature Gaps and the Need for this Research Study

System dynamics has been widely applied to project management in general and project performance in particular, as the preceding review of some existing literature highlighted. Nonetheless, while many previous researchers modelled task interdependencies within a project phase, and workflow and coordination interdependencies across phases, few studies have considered the resulting interdependencies, particularly the inherent competition, among the project participants during project execution. Firstly, no appropriate system dynamics project model could be identified that considers competition among project participants, with their different and competing performance measures and targets during project execution. Yet, some previous researchers highlighted that such competition is a common challenge during project execution (Lyneis and Ford, 2007; Mohammed et al., 2009; Sutterfield et al., 2007). Indeed, Lyneis and Ford (2007) called for research towards modelling and improvement of the competition among the different project participants.

Secondly, no appropriate study could be identified that specifically investigated the influence of the competition among key project participants (such as the client, the engineering consultant and/or the construction contractor) on project performance and on the business performance of the engineering consultant (or construction contractor) during project execution.

Thirdly, current project dynamics models are limited to project performance control actions of mainly the project manager (Ford et al., 2007; Lyneis and Ford, 2007; Nasirzadeh and Nojedehi, 2013). Very few studies consider the control actions (and ripple and knock-on effects thereof) taken by other key project participants to protect their individual performance measures and targets during project execution. For instance, control actions taken by the client to protect project performance; and control actions taken by the engineering consultant and construction contractor to protect the business performance (of their own organisations), are sparingly covered in the reviewed existing literature.

Finally, current project performance controls seem to be only aimed at achieving project time schedule target. Yet, time schedule is just one of the many measures of project performance. For instance, according to Ngacho and Das (2014) key measures of project performance include time, cost, quality, safety, site disputes, and environmental impact. Indeed, Ford et al. (2007) called for controls that are also driven by cost (budget) performance. The current research study, thus, seeks to make an attempt towards the filling of the above-mentioned gaps in existing project management and system dynamics literature, as indicated in Chapter 1.

3.12. Conclusion

A project is basically a system of human resources, facilities, equipment, materials, data and information, documents, and other elements required to produce the required project deliverables. A ‘project life cycle’ is the series of phases that the project evolves through from its initiation to its completion. It is basically that part of a system life cycle that involves the creation or upgrading of systems. The project execution phase is the most challenging phase to manage in a project life cycle, yet it is one of the most crucial as its final output needs to be handed over to the client as a complete system ready for effective and efficient realisation of the intended project benefits. While there are many types of engineering projects, this research study focusses only on raw water infrastructure-related projects.

Project participants are those project stakeholders who are actively involved in the execution of the project. The term ‘project participants’ (not project stakeholders) is used since the focus of this study is only on those stakeholders actively involved in the execution of the project. The key project participants during the execution of engineering projects are client, engineering consultant and construction contractor.

During project execution, different project participants often have different objectives and competing expectations, and they accordingly tend to define and measure performance differently. On the one hand, during project execution, clients are particularly interested in project performance: they set their targets and priorities, and take appropriate decisions and control actions to protect their project performance measures. The reviewed existing literature shows varying measures of project performance – from only two measures (project time schedule and cost) through six (time, cost, quality, safety, site disputes, and environmental impact) to as many as nine.

On the other hand, other project participants (such as the engineering consultant and the construction contractor), as project-based going concerns, are particularly interested in business performance (of their own organisations) and its associated measures, and they also set their targets and priorities during project execution accordingly. The reviewed existing literature also shows varying measures for business performance. For instance, some suggested that business performance has five key dimensions: competition performance; financial performance; innovation capability; supply-chain relationships; and manufacturing capability (for a manufacturing firm); with competition performance and financial performance being the most important key dimensions. Other scholars emphasise three key measures for financial performance of a ‘for-profit’ organisation, namely: net profit; return on investment; and cash flow.

Projects, as systems, are characterised by dynamic complexity. Their execution revolves around project participants and other relevant stakeholders (with their different objectives, expectations, and performance measures and targets) and their interactions and interpersonal relationships. As a result, conflict is inevitable during project execution as highlighted by several scholars. Competition, is one style of handling conflict, whereby one party seeks victory (win-lose) by exerting power, force, superior skill, aggression or domination at the expense of others. Competition among project participants has also been highlighted by some previous researchers as one of the key challenges encountered during project execution.

Some of the key factors influencing competition, evident in the reviewed literature, include: dysfunctional conflict; different/competing performance measures; asynchronous performance review frequencies; intended rationality; as well as mistrust. Other factors, as identified in the reviewed literature, that can generate/fuel competition include: client scope ambiguity/changes; contract buy-in from engineering consultant or construction contractor; client under-budgeting the project; and penalties and/or litigation.

Competition among project participants, which essentially involves human behaviour and takes places within a project environment characterised by dynamic complexity, is thus inherently characterised by dynamic complexity. Competition (aimed at win-lose results) among project participants tends to affect the whole system (the project, including project participants). Solving problems (such as competition) affecting the whole system requires systems thinking, as highlighted by previous scholars. Furthermore, solving system problems (such as competition) involving dynamic complexity is not possible with the human mind alone. However, such complex dynamic system problems can be fully understood and solved using system dynamics (which is systems thinking plus computer modelling and simulation). Hence, system dynamics was, accordingly, chosen in this research study to model the problem of competition between two key project participants (the client and the engineering consultant) during project execution.

While there are many applications of system dynamics to project performance control, business performance control and competition in the reviewed literature, some notable gaps still exist. Firstly, no appropriate system dynamics project model could be identified that considers competition among project participants, with their different and competing performance measures and targets during project execution. Yet, some previous researchers highlighted that such competition is a common challenge during project execution; with some, subsequently, calling for research towards modelling and improvement of such competition.

Secondly, no appropriate study could be identified that specifically investigated the influence of such competition on project performance and on the business performance of the engineering consultant (or construction contractor) during project execution. Thirdly, current project dynamics models are limited to project performance control actions of mainly one project participant (the engineering consultant or construction contractor). Control actions taken by the client to protect project performance; and control actions taken by the engineering consultant and construction contractor to protect their business performance are sparingly covered in the reviewed existing literature.

Finally, current project performance controls seem to be only aimed at achieving project time schedule target. Yet, time schedule is just one of the many measures of project performance. The current research study, thus, seeks to address some of the above-mentioned gaps in existing project management and system dynamics literature, as indicated in Chapter 1. In the next chapter, a system dynamics conceptual model of the competition between the two key project participants (the client and the engineering consultant) during project execution is formulated.

4. Project Participants Competition System Dynamics Conceptual Model (Qualitative Modelling)

4.1. Introduction

This chapter focusses on the problem identification and definition, and system conceptualisation stages of the system dynamics modelling process recommended in the reviewed existing literature (Martinez-Moyano and Richardson, 2013; Sterman, 2000). It begins by briefly highlighting the research problem described in Chapter 1, outlining the purpose of the modelling effort. It then presents an overview of the system dynamics conceptual model formulation process followed. Next, it highlights the boundary as well as the key subsystems of the system dynamics conceptual model of the competition between the two key project participants (client and engineering consultant) during project execution. Then, the conceptual model is formulated and presented, subsystem by subsystem. Accordingly, the following research question, posed in Section 1.6, is addressed in this chapter:

1. *How can competition between two key project participants (client and engineering consultant) during project execution be conceptually modelled using systems thinking?*

4.2. System Problem Identification and Definition

The challenge of competition, as a conflict-handling style aimed at win-lose results, has been highlighted by some previous scholars (Lyneis and Ford, 2007; Mohammed et al., 2009; Sutterfield et al., 2007) to be quite prevalent among project participants during project execution. Yet, no appropriate study could be identified, in the reviewed existing literature, that specifically investigated the influence of such competition on project performance and on the business performance of the engineering consultant (or construction contractor) during project execution.

Competition by its nature has inherently high levels of dynamic complexity, and solving system problems involving dynamic complexity (such as competition) is not possible with the human mind alone; system dynamics (which is systems thinking plus computer modelling and simulation) is quite useful in solving such system problems as it supports human decision making and management policies (Forrester, 2007b; Sterman, 1992; Sterman, 2000), as discussed in Chapter 3. Yet, no appropriate system dynamics project model could be identified, in the reviewed literature, that considers competition among project participants, with their different and competing performance measures and targets during project execution. Hence, the *system problem* to be modelled using system dynamics, in this research study, is the competition between two key project participants (the client and the engineering consultant) during project execution.

The *purpose of the modelling effort,* in the current research study, is aligned to the research objectives outlined in Chapter 1. Firstly, to investigate, from a combination of existing literature, empirical study and using system dynamics, how competition develops between two key project participants (the client and the engineering consultant) during project execution. This is done through the formulation of an appropriate system dynamics conceptual model of the competition (in this Chapter 4), and associated simulation model (in Chapter 5). Secondly, to investigate how the competition influences both the project performance and the business performance of the engineering consultant during project execution. This is done in Chapter 6 through appropriate simulation experiments on the system dynamics simulation model formulated in Chapter 5. Thirdly, to investigate how the competition may be improved so as to enhance both the project performance and the business performance of the engineering consultant, yielding 'win-win' long-term results for the two key project participants. This is also done in Chapter 6 through appropriate policy optimisation experiments

The *system problem owners* are the two key project participants (the client and the engineering consultant): it is in their mutual interest that the above-mentioned system problem, its influence on both project performance and the business performance of the engineering consultant, and how it may be improved, are fully understood.

4.3. System Conceptualisation Overview

The system dynamics conceptual model of the competition between the two key project participants (the client and the engineering consultant) during project execution was formulated from a combination of: existing literature; key findings from an embedded multiple-case study that captured the relevant mental models of the client and engineering consultant project managers; as well as making use of causal loop diagrams (system dynamics systems thinking tool). This helped to strengthen the validity of the formulated dynamic hypotheses and conceptual model, as recommended by Barlas (1996), Luna-Reyes and Andersen (2003), Martinez-Moyano and Richardson (2013), and Sterman (2000).

System dynamics best-practices were followed, as far as possible, in the formulation of all the system dynamics conceptual models presented in this chapter. These included, among others:

- General graphical representation/visualization guidelines for causal loop diagrams, and stock and flow diagrams (Rahmandad and Sterman, 2012; Sterman, 2000);
- Variables naming convention, where variable names are formulated as "nouns or noun phrases", with the actions (verbs) being captured by the

causal links that connect the different variables (Sterman, 2000). Furthermore, “descriptive names or phrases” (“not acronyms or symbols” are used for the variable names (Sterman, 2000);

- Each negative feedback loop aims at closing a particular performance gap/discrepancy between the performance goal/target (the “desired state of the system”) and the actual/forecasted performance (the “state of the system”) (Sterman, 2000); and
- Each positive feedback loop widens the performance gap (acting against the associated negative feedback loop), as an unintended effect (Ford et al., 2007; Lyneis and Ford, 2007).

The system dynamics conceptual models presented in this chapter were formulated using Vensim DSS for Macintosh Version 6.4E software installed on an Apple MacBook Pro 13-inch 2014 laptop with an Intel Core i5 CPU at 2.6 GHz with a 64-bit macOS High Sierra Version 10.13.6 operating system and 8 GB of RAM.

This research study assumes a time-based contract with a ceiling price (Turner, 2004) between the client and the engineering consultant.

4.4. System Dynamics Conceptual Model Boundary

A model boundary chart (which indicates which key variables are: endogenous; exogenous; and excluded) assists in clearly defining the scope of a conceptual model (Sterman, 2000). Table 4.1 shows the model boundary chart for the system dynamics conceptual model formulated in this research study.

Table 4.1: Project participants competition conceptual model boundary chart

Endogenous	Exogenous	Excluded
Client project time schedule control actions	project time schedule deadline	
Unintended effects of client project time schedule control actions	Client project time schedule control actions policies	
	Client project time schedule control actions adjustment delays	
Client project cost control actions	client project cost variance % at completion target	
Unintended effects of client project cost control actions	Client project cost control actions policies	
	Client project cost control actions adjustment delays	
Engineering consultant project revenue control actions	engineering consultant project contract ceiling price % target	

Endogenous	Exogenous	Excluded
Unintended effects of engineering consultant project revenue control actions	engineering consultant project revenue control actions policies	
	engineering consultant project revenue control actions adjustment delays	
Engineering consultant project cash flow control actions	engineering consultant project cash flow target	
Unintended effects of engineering consultant project cash flow control actions	engineering consultant project cash flow control actions policies	
	engineering consultant project cash flow control actions adjustment delays	
engineering consultant project time schedule control (only work intensity)		Other engineering consultant project time schedule controls (such as overtime; adding more people)
	initial project contract ceiling price	Other project stakeholders (other than client and engineering consultant) control actions and unintended effects thereof
	additional project contract price (data series)	
	initially planned project time schedule duration	
	additional project time schedule duration (data series)	
	initial project scope	
	additional project scope (data series)	
	Actual Project Time Schedule Duration	
	Actual Project Cost	
	actual engineering consultant project revenue (data series)	
	actual engineering consultant project cash inflow (data series)	
	base error fraction	
	normal productivity	
	average workforce unit cost	

Table 4.2 shows the sub-systems for the system dynamics conceptual model formulated in this research study. The overall project participants competition system dynamics conceptual model is formulated in Section 4.9 of this chapter.

Table 4.2: Project participants competition conceptual model sub-systems

Sub-system	Purpose	Applicable section of this thesis
Client project time schedule controls and unintended effects	Captures the different corrective control actions (and unintended effects thereof) taken by client project managers when a project is, or is forecasted to be, behind time schedule during project execution.	4.5
Client project cost controls and unintended effects	Captures the different corrective control actions (and unintended effects thereof) taken by client project managers when a project is, or is forecasted to be, above cost budget during project execution.	4.6
Engineering consultant project revenue controls and unintended effects	Captures the different corrective control actions (and unintended effects thereof) taken by engineering consultant project managers when they experience or forecast a project revenue shortfall during project execution.	4.7
Engineering consultant project cash flow controls and unintended effects	Captures the different corrective control actions (and unintended effects thereof) taken by engineering consultant project managers when they experience or forecast insufficient project operating cash flow during project execution.	4.8
Engineering consultant project time schedule control	Captures one corrective control action (work intensity) and its unintended effect (both adapted from existing literature) taken by engineering consultant project managers when a project is, or is forecasted to be, behind time schedule during project execution.	4.9

Sections 4.5 to 4.8: firstly, present key findings from the embedded multiple-case study; proceed to discuss the findings in relation to existing literature; and then formulate the different parts of the overall system dynamics conceptual model (presented in Section 4.9).

4.5. Client Project Time Schedule Controls and their Unintended Effects

4.5.1. Controls (Results and Discussions)

Findings

In this research study, it was found that when a project is currently (or is forecasted to be) behind time schedule during project execution, the client’s trust in the engineering consultant diminishes: the higher the project time schedule delay, the less the client’s trust. One of the client project managers interviewed quipped:

> *"… the more the project is behind time schedule, the less I trust the engineering consultant. You just cannot trust a non-performer!” [Client Project Manager, Questionnaire Reference Number: C01].*

Further analysis of the gathered empirical data showed that, as the client's trust in the engineering consultant decreases due to poor time schedule performance, the client takes some corrective control actions. Table 4.3 summarises the time schedule controls usually taken by the interviewed client project managers.

Table 4.3: Client project time schedule controls (interviewee results)

Client project time schedule control usually taken by the interviewees	Interviewees (Client project manager questionnaire reference number)
Demanding more project progress reports	C01; C02; C03; C04; C05
Conducting more project progress meetings	C01; C02; C03; C04; C05
Conducting more progress inspections	C02; C03
Applying delay-damages penalties	C01; C02; C03; C05
Delaying approval and payment of engineering consultant's invoices	C01; C02; C03; C04; C05

Figure 4.1 is a causal network display (generated using the network view tool in ATLAS.ti), in line with Miles et al. (2014), showing the five client project time schedule controls presented in Table 4.3.

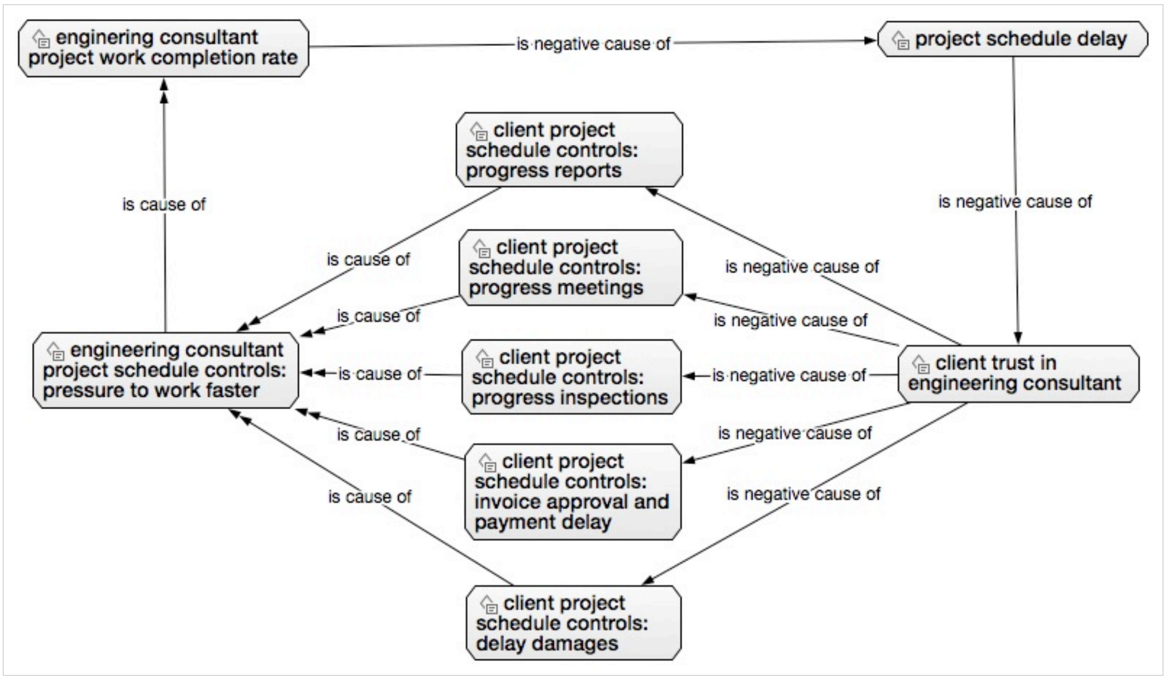


Figure 4.1: Client project time schedule controls

As shown in Figure 4.1, the client project managers interviewed in this research study indicated that the above-mentioned client project time schedule controls are aimed at exerting pressure on the engineering consultant to work faster and, consequently, speed up project work completion. One of the client project managers interviewed highlighted this as follows:

> *"I take these control actions not as punitive measures, but to try and apply some pressure on the engineering consultant to work faster. … sometimes the engineering consultant tends to 'relax', so they need some pressure to deliver on time." [Client Project Manager, Questionnaire Reference Number: C03].*

In an ATLAS.ti network view, such as that in Figure 4.1, the relationship between two codes (variables, constructs, or concepts) is indicated by an arrow (showing the direction of the relationship) as well as a name in the middle of the arrow indicating the type of the relationship (ATLAS.ti, 2016). ATLAS.ti software has standard relations, such as "isa" (is a) and "is cause of" (one variable causes another variable), and also allows the creation of user-defined relations (ATLAS.ti, 2016). The 'is negative cause of' (one variable negatively causes another variable) relation was specifically created for this research study. In Figure 4.1, the 'is cause of' (causes) and the 'is negative cause of' (negatively causes) relations indicate the type of relationship between the associated two variables, as identified from the gathered empirical data during data analysis in ATLAS.ti.

Figure 4.1 is interpreted as follows, using the top route for illustration: 'project schedule delay' negatively causes 'client trust in engineering consultant', which in turn negatively causes 'progress reports'; 'progress reports' causes 'pressure to work faster', which in turn causes 'work completion rate'; 'work completion rate' negatively causes 'project schedule delay'.

Put differently, the higher the 'project schedule delay', the lower the 'client trust in engineering consultant'; the higher the 'client trust in engineering consultant', the lower the client demand for 'progress reports' from the engineering consultant; the higher the client demand for 'progress reports' from the engineering consultant, the higher the 'pressure to work faster' on the engineering consultant; the higher the 'pressure to work faster' on the engineering consultant, the greater the project 'work completion rate'; and, the greater the project 'work completion rate', the lower the 'project schedule delay'.

In brief, it was found in this research study that the higher the current (or forecasted) project time schedule delay: the less the client's trust in the engineering consultant; and the more stringent the client project time schedule control action(s): demanding more project reports; conducting more progress meetings; conducting more progress inspections; delaying approval and payment of engineering consultant's invoices; applying delay damages penalties. All such control actions being aimed at applying pressure on the engineering consultant to work faster, speed up project work completion, and reduce project schedule delay.

Discussion

In this research study, a client's trust in the engineering consultant was found to decrease with increasing project time schedule delay. This corroborated the findings of Manu et al. (2015), and Rodrigues and Williams (1998). It was further found in this study that, as the client's trust in the engineering consultant diminishes due to poor project time schedule performance, the client implements one or more controls (i.e., demanding more project progress reports; conducting more progress meetings; conducting more progress inspections; delaying approval and payment of engineering consultant's invoices; and applying delay-damages penalties) aimed at putting pressure on the engineering consultant to work faster and increase project work completion.

Some of these client project time schedule controls corroborated the works of previous scholars. For instance, demanding more project reports is in line with Rodrigues and Williams (1998), and applying delay-damages penalties is in line with von Branconi and Loch (2004). For client delays in payment of the engineering consultant's invoices, Manu et al. (2015) found a similar tendency, with the main contractors often delaying making payments to their subcontractors during construction.

The 'is cause of' and 'is negative cause of' relations used in ATLAS.ti, as shown in Figure 4.1, effectively express what system dynamics call 'dynamic hypotheses' and are represented on causal loop diagrams using arrows with (+/-) signs (Sterman, 2000). Indeed, causal networks (such as that in Figure 4.1) are used to illuminate causal relationships between variables/constructs, according to Miles et al. (2014). This means that the causal network display shown in Figure 4.1 can be easily converted to a causal loop diagram, a useful systems thinking tool used in system dynamics (Martinez-Moyano and Richardson, 2013; Sterman, 2000).

Evident in the models of Ford et al. (2007), Lyneis and Ford (2007), and Nasirzadeh and Nojedehi (2013) is that a higher project work completion rate leads to a lower expected project time duration. Combining this dynamic hypothesis with Figure 4.1, effectively, forms a negative (balancing) feedback loop around 'project time schedule delay', 'client trust in engineering consultant', 'client project time schedule controls', 'engineering consultant project schedule controls: pressure to work faster'; 'project work completion', and 'estimated project time duration'. Ford et al. (2007), and Lyneis and Ford (2007) refer to the 'pressure to work faster' as 'work intensity'. The resulting negative feedback loop formed by integrating the findings of this research study with previous research studies is shown as a system dynamics causal loop diagram in Figure 4.2; where 'client project time schedule controls' refers to the five client project time schedule controls shown in Figure 4.1.

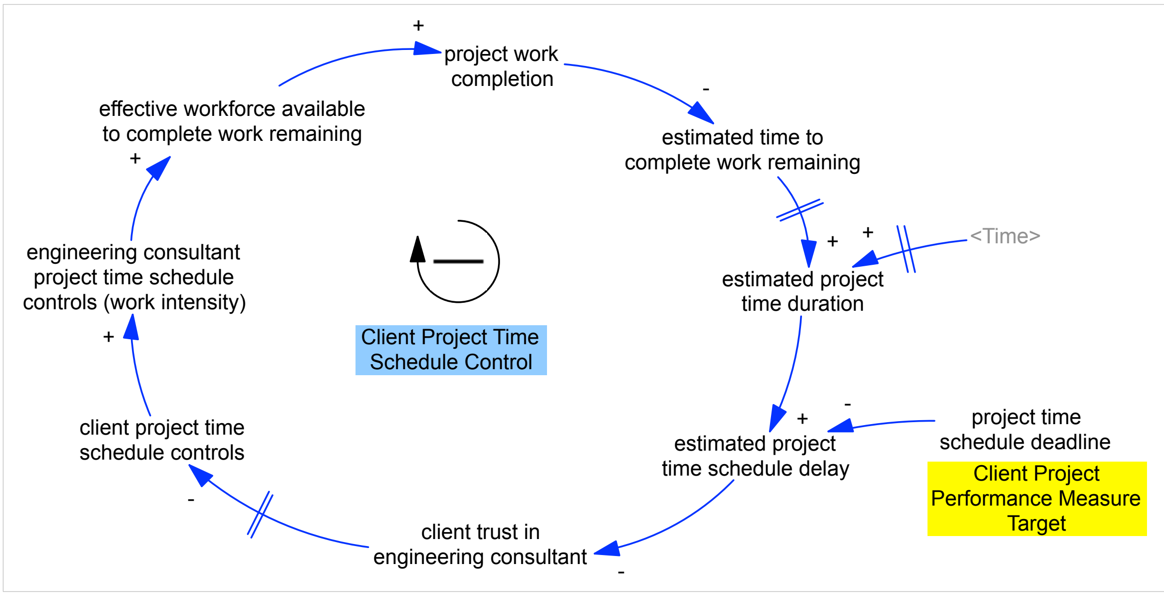


Figure 4.2: Client project time schedule controlling feedback

Source: Adapted from this research study (Figure 4.1), Ford et al. (2007), and Rodrigues and Williams (1998).

Every negative feedback loop must aim at eliminating/closing the performance gap between the performance target and the current/forecasted performance state (Sterman, 2000). In the negative feedback loop in Figure 4.2: the target is the 'project time schedule deadline'; the forecasted state is the 'estimated project time duration'; and the gap to be eliminated is the 'estimated project time schedule delay'.

Sterman (2000) highlighted that in system dynamics causal loop diagrams (e.g., Figure 4.2): arrows and their polarity (+/-) indicate causal relationships (positive or negative influences); and short circular arrows (almost a circle) with polarity (+/-) at their centres show the direction (clockwise or anticlockwise) and polarity (positive/reinforcing or negative/balancing) of loop. Each set consisting of two variables linked by an arrow with a positive or negative sign represents a dynamic hypothesis. Dynamic hypotheses are read following the direction of the arrows and loops. For example, in Figure 4.2, the higher the 'estimated project schedule delay', the lower the 'client trust in engineering consultant'.

As discussed in Chapter 3, the reviewed existing literature showed that while system dynamics has been widely applied to project controls (particularly project time schedule controls) taken by the engineering consultant or construction contractor, project controls taken by other project stakeholders (such as the client) and their system dynamics modelling were sparingly covered in the reviewed literature. For instance, the models of Ford et al. (2007), and Lyneis and Ford (2007) effectively focussed on project time schedule controls taken by the engineering consultant (or construction contractor); as such, they did not include the 'client trust in engineering consultant', and 'client project time schedule controls' shown in Figure 4.2. The model of Rodrigues and Williams (1998) effectively (though using some different but similar words) included only the 'project time schedule delay', 'client trust in engineering consultant', and one client project time schedule control (demand for more progress reports) causal relationships shown in Figure 4.2. Thus, the full client project time schedule control negative feedback loop shown in Figure 4.2, and all the causal loop diagrams subsequently formulated in this section, help towards the filling of the abovementioned gap in the existing literature on project performance controls. The next sub-section discusses some unintended effects of the client project time schedule controls shown in Figure 4.1.

4.5.2. Unintended Effects (Results and Discussions)

Findings

Further analysis of the empirical data gathered in this study revealed that the client project time schedule controls, described in the preceding section, generate some undesirable and unintended consequences (ripple effects). Table 4.4 summarises the ripple effects of the client project time schedule controls, as evident from the responses of the interviewed client and engineering consultant project managers.

Table 4.4: Unintended effects of client project time schedule controls (interviewee results)

Client project time schedule control usually taken by the interviewees	Unintended effect evident from the responses of the interviewees	Interviewees	
		Client project manager questionnaire reference number	Engineering consultant project manager questionnaire reference number
Demanding more project progress reports	Less time available for the engineering consultant to carry out real project work, thereby reducing the engineering consultant's productivity, resulting in a decrease in project work completion.	C01; C03; C04	EC01; EC02; EC03; EC05; EC06
Conducting more project progress meetings.		C01; C03; C04	EC01; EC02; EC03; EC04; EC05; EC06
Conducting more progress inspections		C02; C03	EC02; EC04; EC05
Applying delay-damages penalties	Insufficient project operating cash flow for the engineering consultant, resulting in reduced engineering consultant project workforce, leading to a decrease in project work completion.	C02; C03; C05	EC01; EC02; EC03; EC06
Delaying approval and payment of engineering consultant's invoices		C03; C04	EC01; EC02; EC03; EC04; EC05; EC06

Firstly, as shown in Table 4.4, the interviewees indicated that producing more project progress reports, holding more progress meetings, and conducting more progress inspections consume a significant amount of time, resulting in less time being available for the engineering consultant to carry out real project work (e.g., producing design calculations, specifications, and drawings), thus reducing the engineering consultant's productivity, which in turn decreases project work completion. Secondly, as also shown in Table 4.4, it was found that instituting delay-damages penalties or delaying approval and payment of the engineering consultant's invoices sometimes leads to insufficient project operating cash flow for the engineering consultant. This makes it difficult for the engineering consultant to resource the project fully, thus putting more strain on the engineering consultant's work completion rate.

Figure 4.3 shows the above-mentioned two unintended effects of client project time schedule controls in the form of a causal network, in line with Miles et al. (2014), generated using ATLAS.ti. It is interpreted in a similar way to that described for Figure 4.1 in the preceding section.

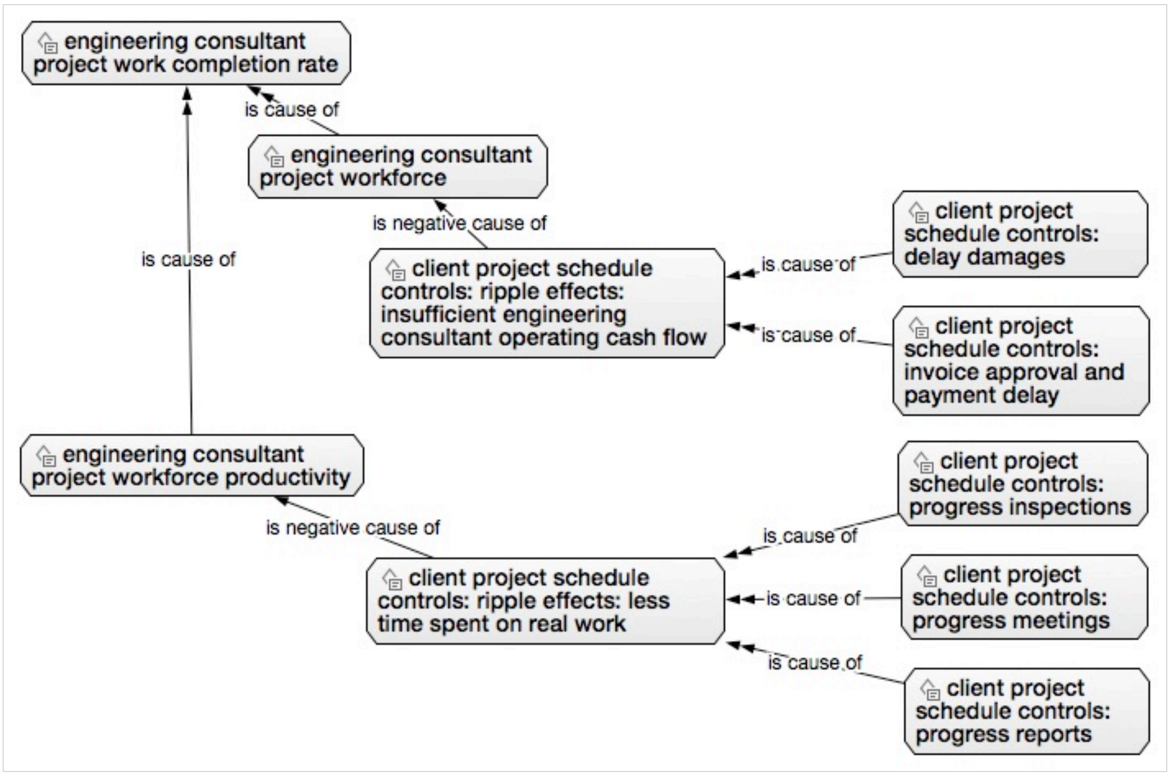


Figure 4.3: Unintended effects of client project time schedule controls

Discussion

Two key unintended effects of the client project time schedule controls were found in this research study, as shown in Figure 4.3. Firstly, demanding more progress reports was found to lead to less time spent on carrying out real project work (e.g.

producing design drawings) by the engineering consultant; effectively decreasing project workforce productivity, and resulting in a decrease in the project work completion rate. This finding corroborates the work of Rodrigues and Williams (1998). It was also revealed in this study that conducting more progress meetings and/or inspections yields a similar ripple effect. This unintended effect forms a positive (reinforcing) feedback loop (Sterman, 2000), 'Less Time Spent On Real Work', that opposes the well-intentioned client project time schedule control. Integrating this unintended into the client project time schedule controlling (negative) feedback loop presented in Figure 4.2 yields the system dynamics causal loop diagram shown in Figure 4.4, for one of the client project time schedule controls (conducting more progress meetings).

Other scholars, such as Ford et al. (2007), Lyneis and Ford (2007), and Nasirzadeh and Nojedehi (2013), also highlighted that the lower the workforce productivity, the less the work completion rate, and the higher the project schedule delay. However, as discussed in Chapter 3 and highlighted in Section 4.5.1, the models of these previous scholars effectively only focussed on project time schedule controls taken by the engineering consultant (or construction contractor) and their unintended effects. Thus, the client project time schedule control negative feedback loop and its associated unintended effect shown in Figure 4.4 help to build on the existing literature on the application of system dynamics to project performance control.

Two other client project time schedule controls (demand for more progress reports from the engineering consultant; and conducting more progress inspections with the engineering consultant) yield loops similar to those shown in Figure 4.4.

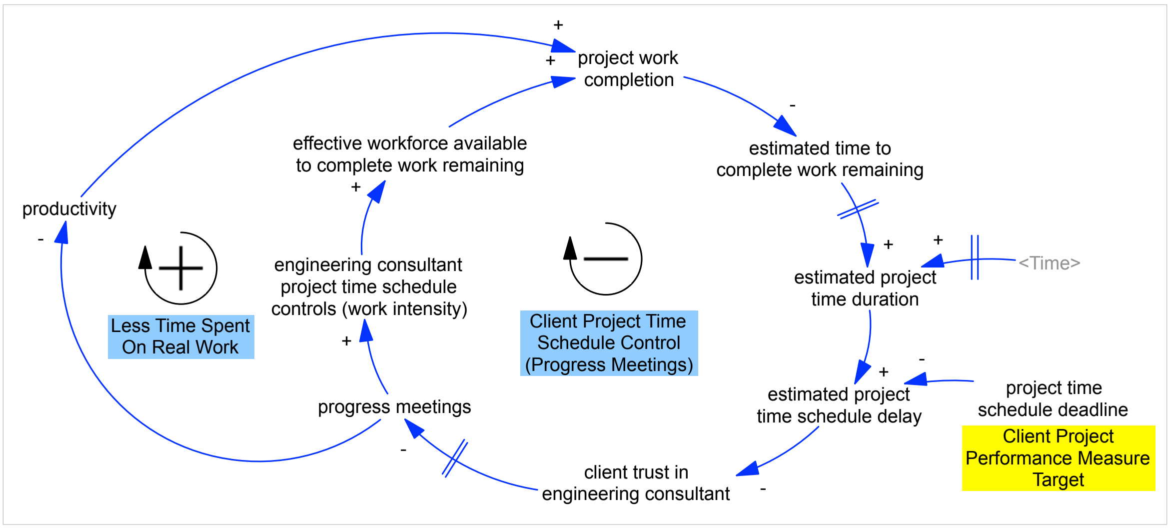


Figure 4.4: Client project time schedule control (progress meetings) and its unintended effect

Source: Adapted from this research study (Figures 4.1 to 4.3), Ford et al. (2007), and Rodrigues and Williams (1998).

The second unintended effect of client project time schedule controls, found in this study, was that instituting delay-damages penalty or delaying approval and payment of engineering consultant's invoices sometimes leads to insufficient project operating cash flow for the engineering consultant. This makes it difficult for the engineering consultant to resource the project fully, thus degrading the engineering consultant’s project work completion rate. Figure 4.5 shows the controlling (negative) feedback loop (from Figure 4.2) and its unintended effect (positive loop) for client delay in approving and paying the engineering consultant’s invoices. Applying a delay-damages penalty yields loops similar to those shown in Figure 4.5.

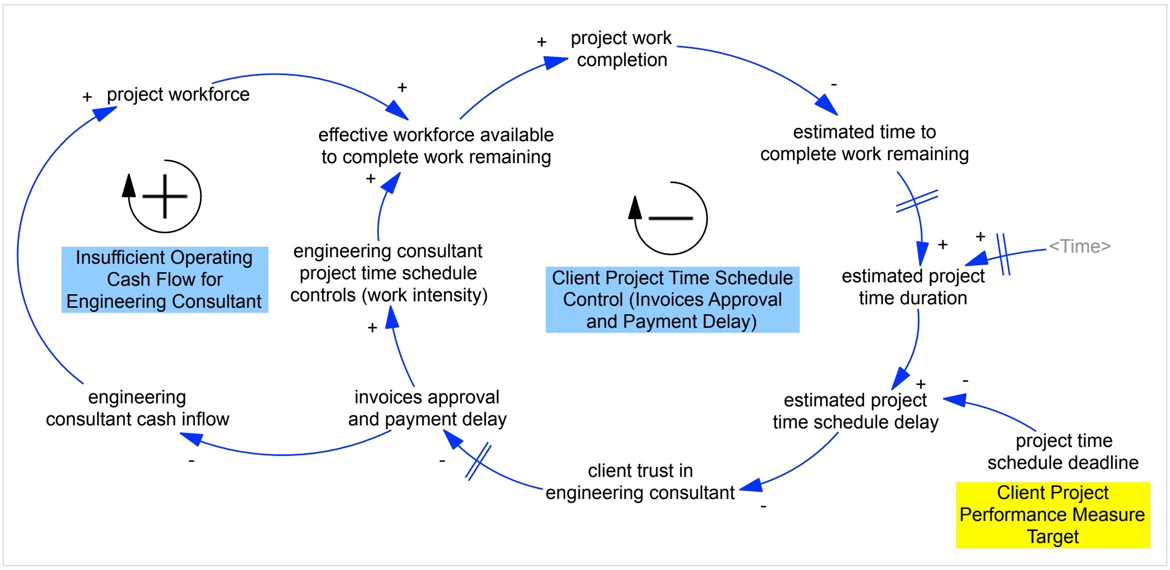


Figure 4.5: Client project time schedule control (invoice approval and payment delay) and its unintended effect

Source: Adapted from this research study (Figures 4.1 to 4.3), Ford et al. (2007), and Rodrigues and Williams (1998).

4.5.3. System Dynamics Conceptual Model

Applying pressure on project workforce to work faster (work intensity) yields an unintended effect of increasing errors on project deliverables (lowering the quality of deliverables), thereby decreasing project work completion rate, according to Ford et al. (2007), and Lyneis and Ford (2007). Integrating this with the causal loop diagrams shown in Figure 4.4 and Figure 4.5, and including all the five client project time schedule controls (Figure 4.1) and their associated unintended effects (Figure 4.3) found in this research study, yield the overall system dynamics conceptual model of client project time schedule controls and their associated unintended effects shown in Figure 4.6.

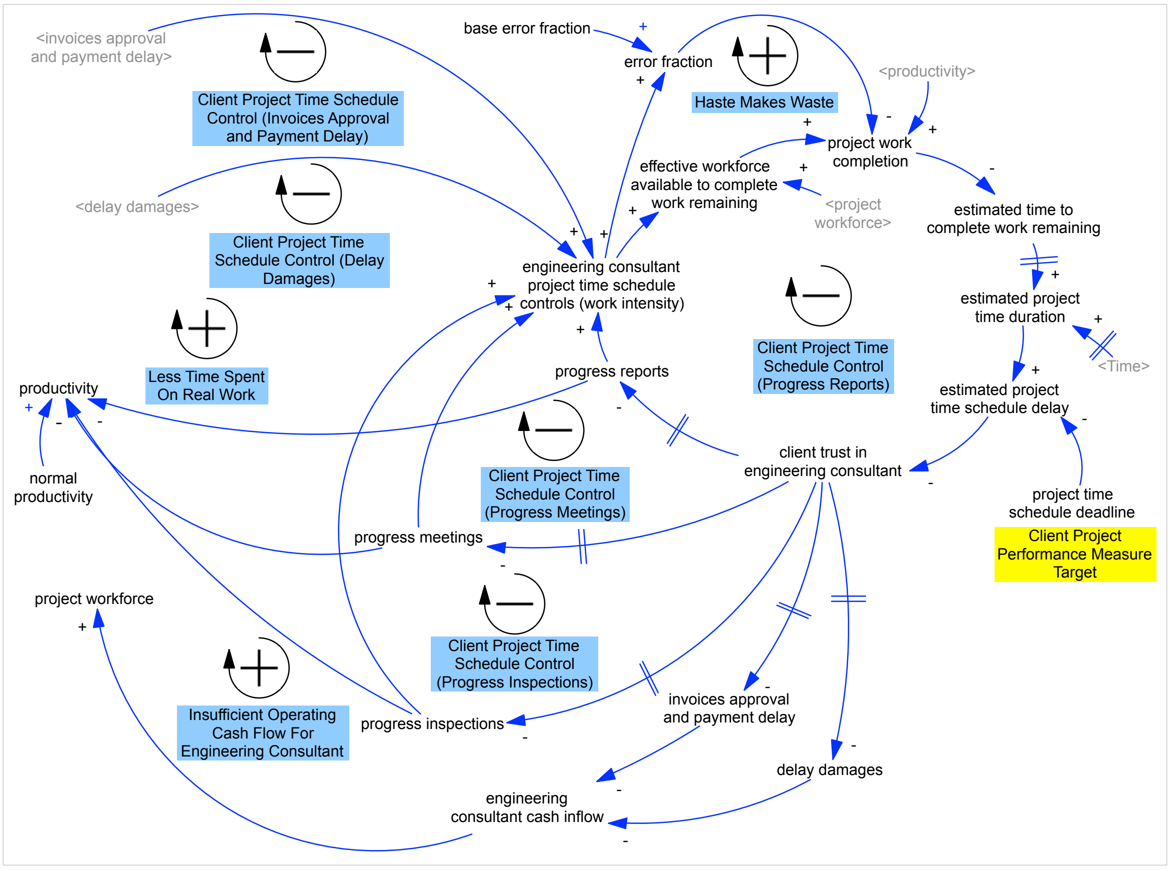


Figure 4.6: Client project time schedule controls and associated unintended effects

Source: Adapted from this research study (Figures 4.1 to 4.5), Ford et al. (2007), and Rodrigues and Williams (1998).

In Figure 4.6, the five negative feedback loops represent the five client project time schedule controls found in this study (some of which corroborated existing literature, as discussed in the preceding sub-sections). The positive feedback loops represent the unintended effects of the client project time schedule controls. As shown in Figure 4.6, the positive/reinforcing feedback loops militate against the intended negative/balancing feedback loops, degrading project time schedule performance. Put differently, *the client project time schedule controls, which are aimed at increasing the project work completion rate and reducing/eliminating the project time schedule delay, tend to generate some unintended and counteractive consequences (unintended effects) that reduce the project work completion rate and increase the project time schedule delay.* This counterintuitive key finding is effectively the main dynamic hypothesis presented in Figure 4.6.

As evident throughout this Section 4.5, the system dynamics conceptual model of client project time schedule controls and their associated unintended effects, shown in Figure 4.6, was formulated from a combination of: the existing literature; the key findings from an empirical research study that captured relevant mental models of the client's and the engineering consultant's project managers; and one of system dynamics' systems thinking tools (the causal loop diagram). This helped to strengthen the validity of the dynamic hypotheses and conceptual model presented in Figure 4.6, as recommended by Barlas (1996), Luna-Reyes and Andersen (2003), Martinez-Moyano and Richardson (2013), and Sterman (2000). All the system dynamics conceptual models of the project participants' controls presented in the rest of this chapter were formulated in a similar manner.

The reviewed existing literature, as discussed in Chapter 3, showed that: while system dynamics has been widely applied to project controls (particularly project time schedule controls) taken by the engineering consultant or construction contractor, project controls taken by other project stakeholders (such as the client) and their system dynamics modelling were sparingly covered in the reviewed literature; and no appropriate system dynamics conceptual model similar to that shown in Figure 4.6 could be identified in the reviewed literature. For instance, the models of Ford et al. (2007), and Lyneis and Ford (2007) effectively focussed on project time schedule controls taken by the engineering consultant (or construction contractor); as such, they did not include the 'client trust in engineering consultant', and the five client project time schedule controls shown in Figure 4.6. The model of Rodrigues and Williams (1998) effectively (though using some different but similar words) included only the 'project time schedule delay', 'client trust in engineering consultant', and one client project time schedule control (demand for more progress reports) causal relationships shown in Figure 4.6.

The system dynamics causal loop diagram of client project time schedule controls and their associated unintended effects shown in Figure 4.6, and the associated main counterintuitive dynamic hypothesis (as formulated in this study), thus help towards the filling of the abovementioned gap in the existing literature on project controls and the application of system dynamics to project performance control.

4.6. Client Project Cost Controls and their Unintended Effects

4.6.1. Controls (Results and Discussions)

Findings

The control actions often taken by the interviewed client project managers to try and bring back a project that is forecasted to be above cost budget back within budget, as found in this study, are similar to four of the client project time schedule controls discussed in Section 4.5. This seems logical considering that this research study focussed only on time-based contracts. The four client project cost controls are: demanding more project progress reports; conducting more project progress meetings; conducting more project progress inspections; and delaying approval and payment of the engineering consultant's invoices, as shown in Table 4.5.

Table 4.5: Client project cost controls (interviewee results)

Client project cost control usually taken by the interviewees	Interviewees (Client project manager questionnaire reference number)
Demanding more project progress reports	C01; C02; C03; C04; C05
Conducting more project progress meetings	C01; C02; C03; C04; C05
Conducting more progress inspections	C02; C03
Delaying approval and payment of engineering consultant's invoices	C01; C02; C03; C04; C05

Figure 4.7 is a causal network display (generated using the network view tool in ATLAS.ti), in line with Miles et al. (2014), showing the four client project cost controls in Table 4.5, in the particular case of time-based contracts. It is interpreted in a similar way to that described for Figure 4.1.

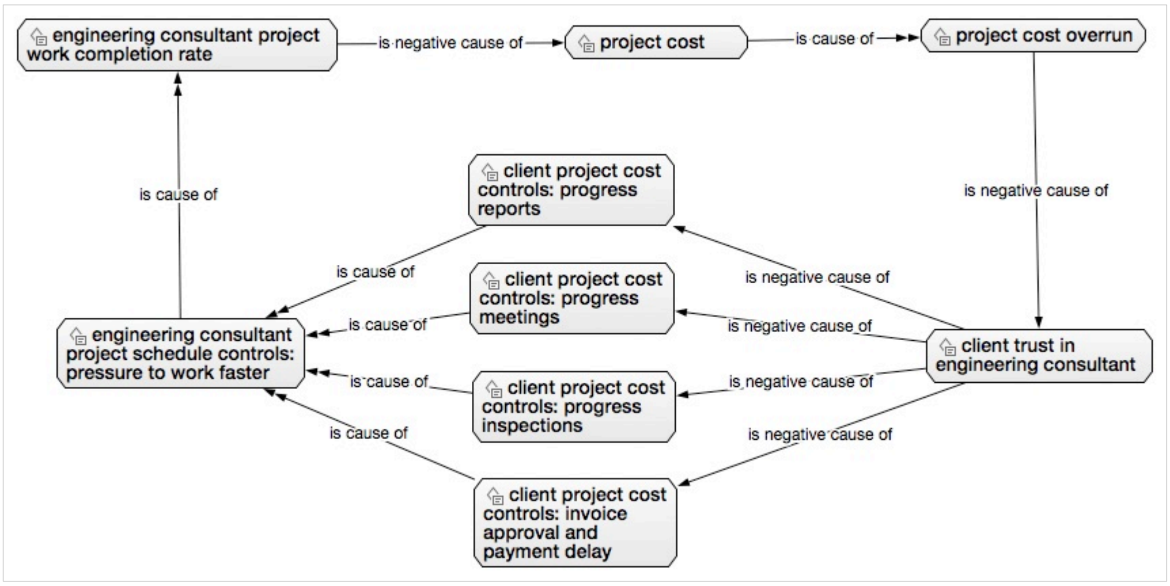


Figure 4.7: Client project cost controls

Discussion

The four client project cost control actions found in this study, and shown in Figure 4.7, do corroborate some findings from previous studies, similar to the corresponding client project time schedule controls discussed in Section 4.5. In his discussion of the earned value method, Anbari (2003) highlighted that: ‘cost variance’ is the difference between the ‘earned value’ (budgeted cost of work performed) and the ‘actual cost’ (of work performed); ‘cost variance percentage’ is the cost variance divided by the earned value, expressed as a percentage; a negative project cost variance (project cost overrun) is an indication of poor project performance; and that ‘estimated cost at completion’ can be determined by the sum of the ‘actual cost’ of work done to date and the ‘estimated cost to complete’ the remaining project work. He further indicated that the earned value is determined, at any given time during project execution, by multiplying the completed project proportion by the total project budget (Anbari, 2003). Thus, the earned value at project completion equals the budget at completion (or the contract ceiling price). This seminal work of Anbari (2003) was incorporated into the PMBoK Guide since 2004 (Project Management Institute, 2017), and is widely cited by subsequent researchers on the earned value method, including Acebes et al. (2015).

Combining the findings of the current research study (Figure 4.7) with: previous studies as discussed in the preceding section for client project time schedule controls (Figure 4.2); the work of Anbari (2003); and considering a time-based contract with a ceiling price (Turner, 2004) between the client and the engineering consultant, yields the negative feedback loop shown as a system dynamics causal loop diagram in Figure 4.8.

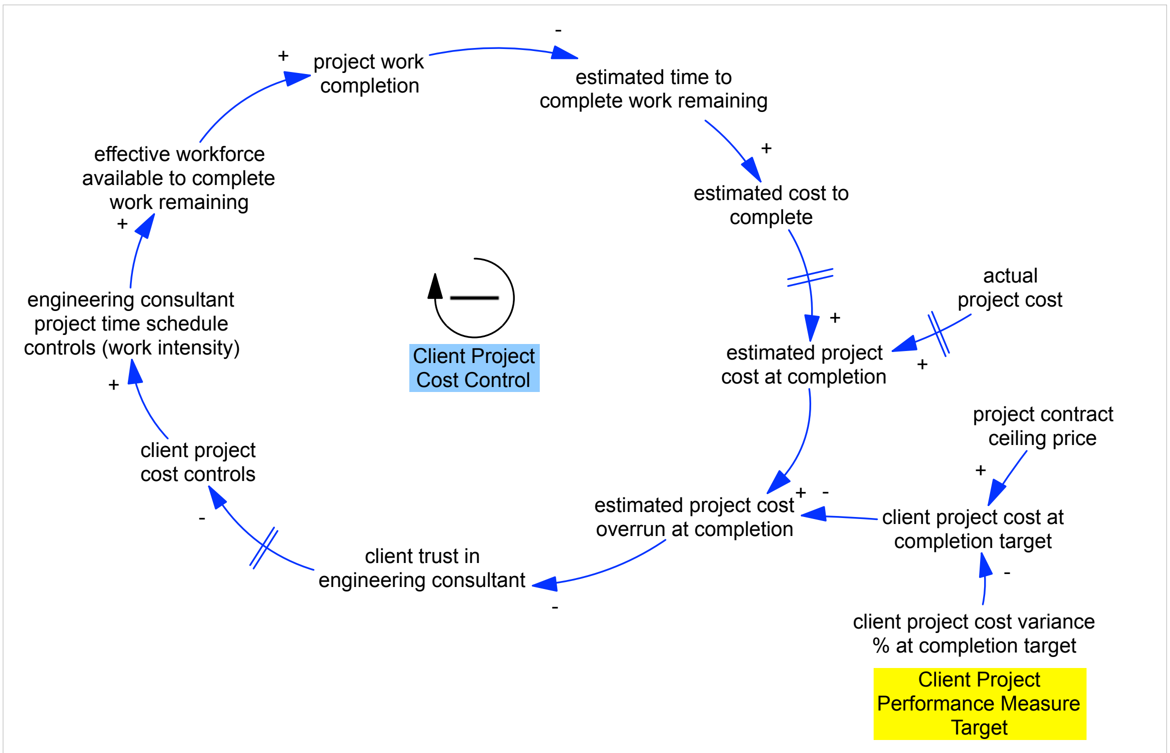


Figure 4.8: Client project cost controlling feedback

Source: Adapted from this study (Figures 4.2 and 4.7), Anbari (2003), and Ford et al. (2007).

Every negative feedback loop must aim at eliminating/closing the performance gap between the performance target and the current/forecasted performance state (Sterman, 2000). In the negative feedback loop in Figure 4.8: the target is the 'client project cost at completion target' (which is influenced by the 'project contract ceiling price' and the 'client project cost variance % at completion target'); the forecasted state is the 'estimated project cost at completion'; and the gap to be eliminated (balanced out) is the 'estimated project cost overrun at completion').

In Figure 4.8, the causal relationships shown for 'estimated cost to complete', 'actual project cost', and 'estimated project cost at completion' were adopted from a formula presented by Anbari (2003), who did not formulate any system dynamics model. The causal relationships from 'engineering consultant project time schedule controls (work intensity)' to 'estimated time to complete work remaining' are the same as those in Figure 4.2, and are in line with Ford et al. (2007) as discussed in Section 4.5. Ford et al. (2007) only focussed on project time schedule controls taken by the engineering consultant (or construction contractor), and did not include the 'client trust in engineering consultant', and 'client project cost controls' shown in Figure 4.8.

As discussed in Chapter 3 and in Section 4.5, the reviewed literature showed that while system dynamics has been widely applied to project controls (particularly project time schedule controls) taken by the engineering consultant or construction contractor, project controls taken by other project stakeholders (e.g., the client) and their system dynamics modelling are sparingly covered. It also showed that current project performance controls are only aimed at achieving project time schedule target. Yet, there are many other key measures of project performance, including cost, as discussed in Section 3.3.1. Thus, the full client project cost control negative feedback loop formulated in this study and shown in Figure 4.8, and all the causal loop diagrams subsequently formulated in this section, help towards the filling of the abovementioned gaps in existing literature on project controls and the application of system dynamics to project performance control. The next sub-section discusses some key unintended effects of the four client project cost controls in Figure 4.7.

4.6.2. Unintended Effects (Results and Discussions)

Findings

Further analysis of the empirical data gathered in this study revealed that the client project cost controls, described in the preceding sub-section, typically generate two undesirable and unintended effects, similar to those of client project time schedule controls (Section 4.5.2). These are: less time spent on real project work, resulting in a decrease in the engineering consultant's project workforce productivity; and insufficient project operating cash flow for the engineering consultant, resulting in a decrease in engineering consultant's project workforce size, as shown in Table 4.6.

A third unintended effect of all the client project cost controls, emerging from the current research study, is engineering consultant project revenue control, as also shown in Table 4.6. Project cost is the sum of all the costs incurred by the client throughout the project life cycle (Project Management Institute, 2017). Thus, the project cost for executing a typical engineering project is the sum of all the costs incurred by the client during project execution, and it includes the costs for project management services, engineering consultant services, and construction contractor works (including labour, material, equipment, and sub-contractors), among others. However, in this research study, only time-based contracts with a ceiling price (Turner, 2004) between the client and the engineering consultant were considered, and only the time-based costs for the engineering consultant services were considered for the project cost. Thus, a decrease in project cost (resulting from the client project cost controls, as shown in Figure 4.8) leads to an increase in the engineering consultant's project revenue shortfall, which in turn leads to a decrease in the engineering consultant's trust in the client, prompting engineering consultant project revenue controls (as discussed further in Section 4.7).

Table 4.6: Unintended effects of client project cost controls (interviewee results)

Client project cost control usually taken by the interviewees	Unintended effect evident from the responses of the interviewees	Interviewees	
		Client project manager questionnaire reference number	Engineering consultant project manager questionnaire reference number
Demanding more project progress reports	Less time available for the engineering consultant to carry out real project work, thereby reducing the engineering consultant's productivity, resulting in a decrease in project work completion.	C01; C03; C04	EC01; EC02; EC03; EC05; EC06
Conducting more project progress meetings.		C01; C03; C04	EC01; EC02; EC03; EC04; EC05; EC06
Conducting more progress inspections		C02; C03	EC02; EC04; EC05
Delaying approval and payment of engineering consultant's invoices	Insufficient project operating cash flow for the engineering consultant, resulting in reduced engineering consultant workforce size, leading to a decrease in project work completion.	C03; C04	EC01; EC02; EC03; EC04; EC05; EC06
Any of the above four controls	A decrease in project cost, resulting from the client project cost controls, leads to an increase in the engineering consultant's project revenue shortfall; which in turn leads to a decrease in the engineering consultant's trust in the client, prompting engineering consultant project revenue controls.	C01; C03; C04	EC01; EC02; EC03; EC04; EC05; EC06

Figure 4.9 shows the three unintended effects of client project cost controls in the form of a causal network, in line with Miles et al. (2014), generated using ATLAS.ti. It is interpreted in a similar way to that described for Figure 4.1 in Section 4.5.

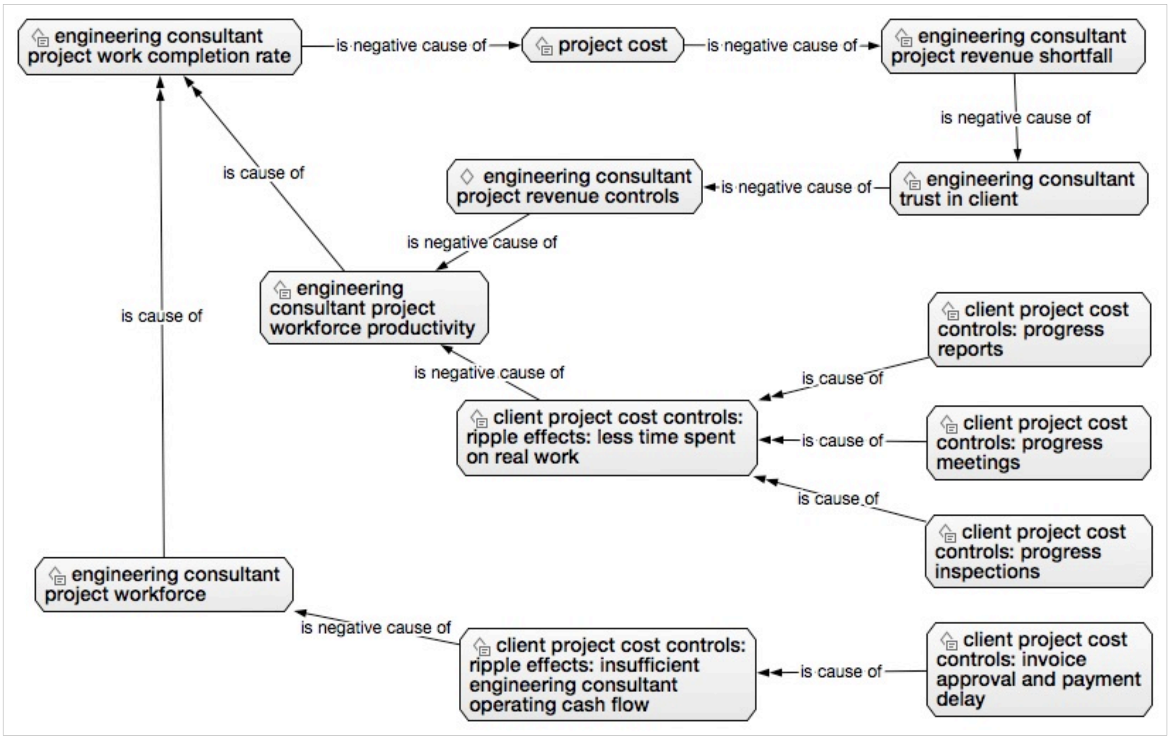


Figure 4.9: Unintended effects of client project cost controls

Discussion

One of the unintended effects of client project cost control actions, found in this research study as shown in Figure 4.9, was that less time available for the engineering consultant to carry out real project work, thereby reducing the engineering consultant's workforce productivity, resulting in a decrease in project work completion. It is similar to the corresponding unintended effect of client project time schedule controls discussed in Section 4.5.3 and shown in Figure 4.4. Integrating the client project cost control negative feedback loop shown in Figure 4.8 with the associated unintended effects shown in Figure 4.9 yields a system dynamics causal loop diagram such as that shown in Figure 4.10. In particular, Figure 4.10 shows the controlling (negative) feedback loop and its associated unintended effect (positive loop) for one of the client project cost controls (demanding more progress reports). Two other client project cost controls (conducting more progress meetings, and conducting more progress inspections with the engineering consultant) yield loops similar to those shown in Figure 4.10.

Another unintended effect of the client project cost controls, found in this research study as shown in Figure 4.9, was that delaying approval and payment of engineering consultant's invoices sometimes leads to insufficient project operating cash flow for the engineering consultant. This makes it difficult for the engineering consultant to resource the project fully, resulting in a decrease in project work completion. It is also similar to the corresponding unintended effect of client project time schedule controls discussed in Section 4.5.3 and shown in Figure 4.5. Integrating this unintended effect into the client project cost control negative feedback loop shown in Figure 4.8 yields the controlling (negative) feedback loop and its associated unintended effect (positive loop) for client delay in approval and payment of the engineering consultant's invoices shown in Figure 4.11.

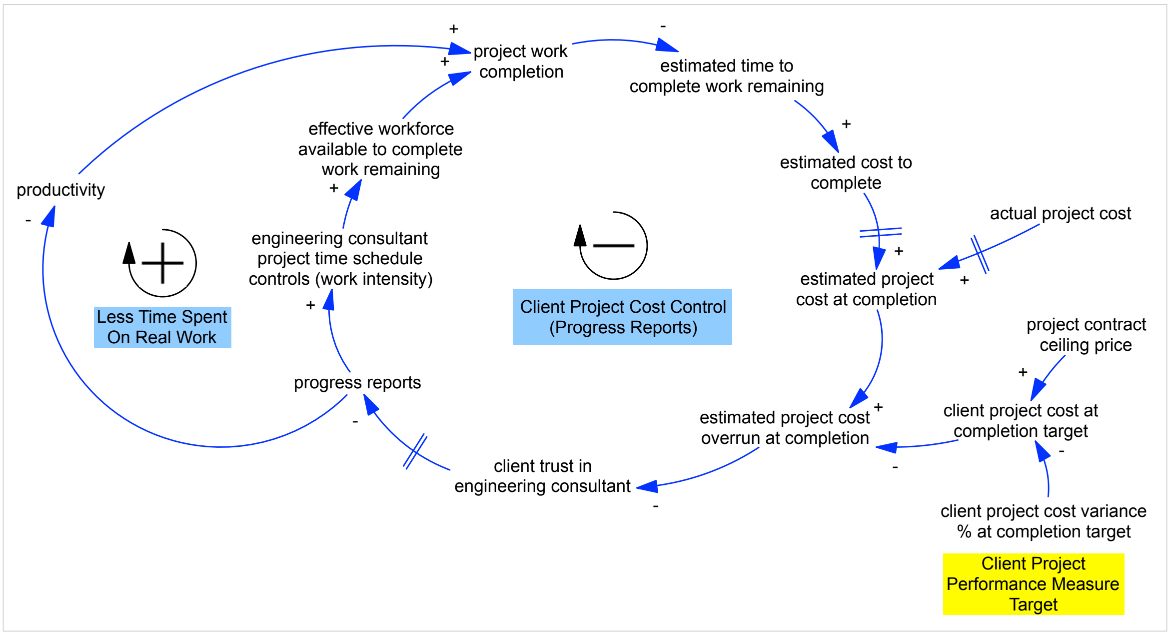


Figure 4.10: Client project cost control (progress reports) and its unintended effects

Source: Adapted from this research study (Figures 4.7 to 4.9), Anbari (2003), Ford et al. (2007), and Rodrigues and Williams (1998).

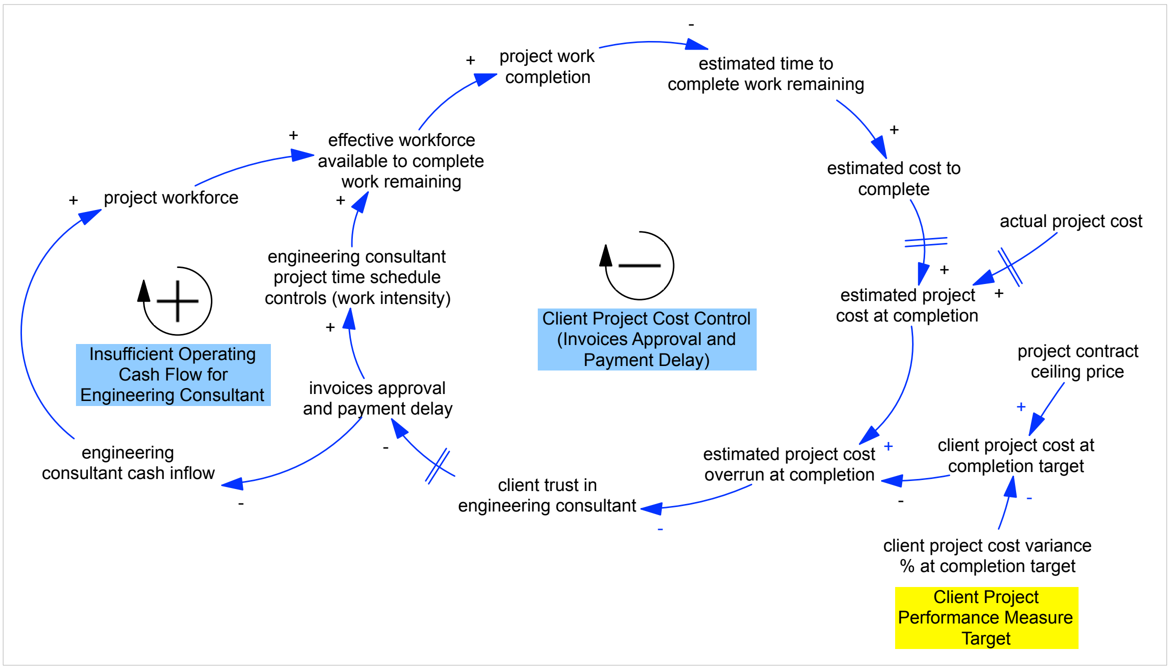


Figure 4.11: Client project cost control (invoices approval and payment delay) and its unintended effect

Source: Adapted from this study (Figures 4.7 to 4.9), Anbari (2003), Ford et al. (2007).

4.6.3. System Dynamics Conceptual Model

Integrating the causal loop diagrams shown in Figures 4.10 and 4.11, and including all the four client project cost controls (Figure 4.7) and their associated unintended effects (Figure 4.9) found in this research study, yield the overall system dynamics conceptual model of client project cost controls and their associated unintended effects shown in Figure 4.12.

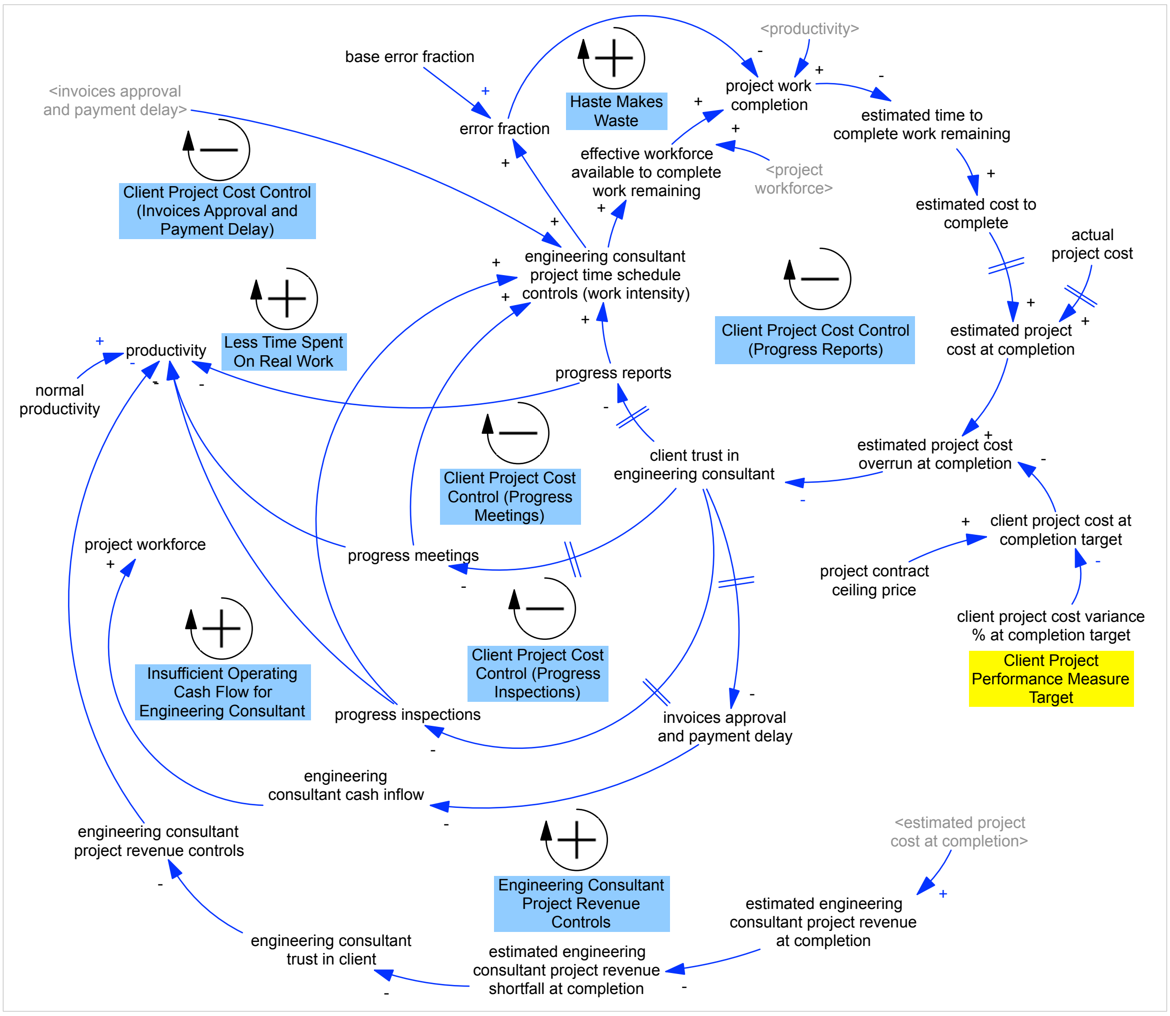


Figure 4.12: Client project cost controls and their unintended effects

Source: Adapted from this research study (Figures 4.7 to 4.11), Anbari (2003), Ford et al. (2007), and Rodrigues and Williams (1998).

In Figure 4.12, the four negative feedback loops represent the four client project cost controls found in this research study (some of which corroborated the existing literature, as discussed in the preceding sub-sections). The positive feedback loops represent the unintended effects of the client project cost controls. Effectively, as shown in Figure 4.12, the positive/reinforcing feedback loops militate against the intended negative/balancing feedback loops, degrading the project cost performance. Put differently, *the client project cost controls, which are aimed at reducing/eliminating the 'project cost overrun' by reducing the 'estimated project* *cost at completion', tend to generate some unintended and counteractive consequences (unintended effects) that increase the 'estimated project cost at completion' and the 'project cost overrun'.* This counterintuitive key finding is effectively the main dynamic hypothesis presented in Figure 4.12.

As evident throughout this Section 4.6, the system dynamics conceptual model of client project cost controls and their associated unintended effects, shown in Figure 4.12, was formulated from a combination of: existing literature; key findings from an empirical research study that captured relevant mental models of the client's and the engineering consultant's project managers; and one of system dynamics' systems thinking tools (causal loop diagram).

In Figure 4.12, the causal relationships shown for 'estimated cost to complete', 'actual project cost', and 'estimated project cost at completion' were adopted from a formula presented by Anbari (2003), who did not formulate any system dynamics causal loop diagrams. The causal relationships from 'engineering consultant project time schedule controls (work intensity)' to 'estimated time to complete work remaining' are the same as those in Figure 4.6 (client project time schedule controls), and are in line with Ford et al. (2007) as discussed in Section 4.5. The system dynamics model of Ford et al. (2007) only focussed on project time schedule controls taken by the engineering consultant (or construction contractor), and did not include the 'client trust in engineering consultant', and the four client project cost controls shown in Figure 4.12. The model of Rodrigues and Williams (1998) included (though using some different but similar words) only the 'client trust in engineering consultant', and demand for more progress reports (though as a client project time schedule control) causal relationships shown in Figure 4.12.

The reviewed existing literature, as discussed in Chapter 3 and highlighted in Section 4.5, showed that: while system dynamics has been widely applied to project controls (particularly project time schedule controls) taken by the engineering consultant or construction contractor, project controls taken by other project stakeholders (e.g. the client) and their system dynamics modelling were sparingly covered; and no appropriate system dynamics conceptual model similar to that shown in Figure 4.12 could be identified in the reviewed literature. It also showed that current project performance controls seem to be only aimed at achieving project time schedule target. Yet, there are many other key measures of project performance, including cost, as discussed in Section 3.3.1. Thus, the system dynamics causal loop diagram of client project cost controls and their associated unintended effects shown in Figure 4.12, formulated in this study, helps towards the filling of the abovementioned gaps in existing literature on project controls and application of system dynamics to project performance control.

4.7. Engineering Consultant Project Revenue Controls and their Unintended Effects

4.7.1. Controls (Results and Discussions)

Findings

The interviewed engineering consultant project managers indicated that their trust in the client diminishes when they forecast a project revenue shortfall. For instance, one of the interviewees indicated that:

> *"A revenue shortfall really makes it a bit difficult to trust the client, hence motivation for variation orders" [Engineering Consultant Project Manager, Questionnaire Reference Number: EC04].*

The interviewees indicated that, as a result, they usually motivate for project scope variations, capitalising on the 'grey' areas in the project scope statements, and/or resort to effort adjustment (reduction in productivity, thereby decreasing project work completion rate) so as to increase their project revenue, in the particular case of time-based contracts, as summarised in Table 4.7.

Table 4.7: Engineering consultant project revenue controls (interviewee results)

Engineering consultant project revenue control usually taken by the interviewees	Interviewees (Engineering consultant project manager questionnaire reference number)
Project scope variation motivations	EC01; EC02; EC03; EC04; EC05; EC06
Effort adjustment	EC01; EC02; EC04; EC05; EC06

Figure 4.13 is a causal network display (generated using the network view tool in ATLAS.ti), in line with Miles et al. (2014), showing the two engineering consultant project revenue controls presented in Table 4.7.

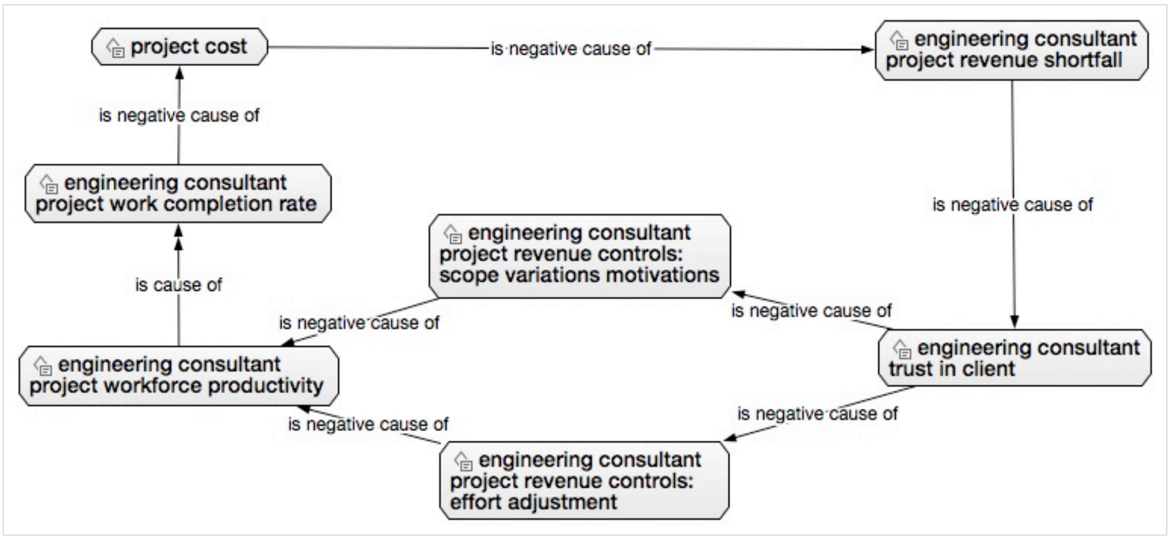


Figure 4.13: Engineering consultant project revenue controls

Figure 4.13 is interpreted in a similar way to that described for Figure 4.1.

Discussion

Turner (2004) highlighted that a ceiling contract price is often specified in time-based contracts by the client to minimise engineering consultant / contractor opportunism. Project cost is the sum of all costs incurred by the client throughout the project life cycle (Project Management Institute, 2017). Thus, the project cost for executing a typical engineering project is the sum of all costs incurred by the client during project execution, and it includes the costs for project management services, engineering consultant services, and construction contractor works (including labour, material, equipment, and sub-contractors), among others. However, in this research study: only time-based contracts with a ceiling price (Turner, 2004) between the client and the engineering consultant were considered; and only the time-based costs for the engineering consultant services were considered for the project cost. Hence, in this research study, the estimated project revenue to be realised by the engineering consultant at project completion was assumed to be equal to the estimated project cost to be incurred by the client at completion of the same project.

Anbari (2003) discussed different ways of estimating project cost at completion, one of which is by determining the sum of the actual project cost to date and the estimated cost to complete the remaining project work; which was also incorporated into the PMBoK Guide (Project Management Institute, 2017). Combining the above-mentioned existing literature and assumptions with the findings presented in Figure 4.13 yields the system dynamics causal loop diagram shown in Figure 4.14.

Every negative feedback loop must aim at eliminating/closing the performance gap between the performance target and the current/forecasted performance state (Sterman, 2000). In the negative feedback loop in Figure 4.14: the target is the ‘engineering consultant project revenue at completion target’ (which is influenced by the ‘project contract ceiling price’ and the ‘engineering consultant project contract ceiling price % target’); the forecasted state is the ‘estimated engineering consultant project revenue at completion’; and the gap to be eliminated (balanced out) is the ‘estimated engineering consultant project revenue shortfall at completion’).

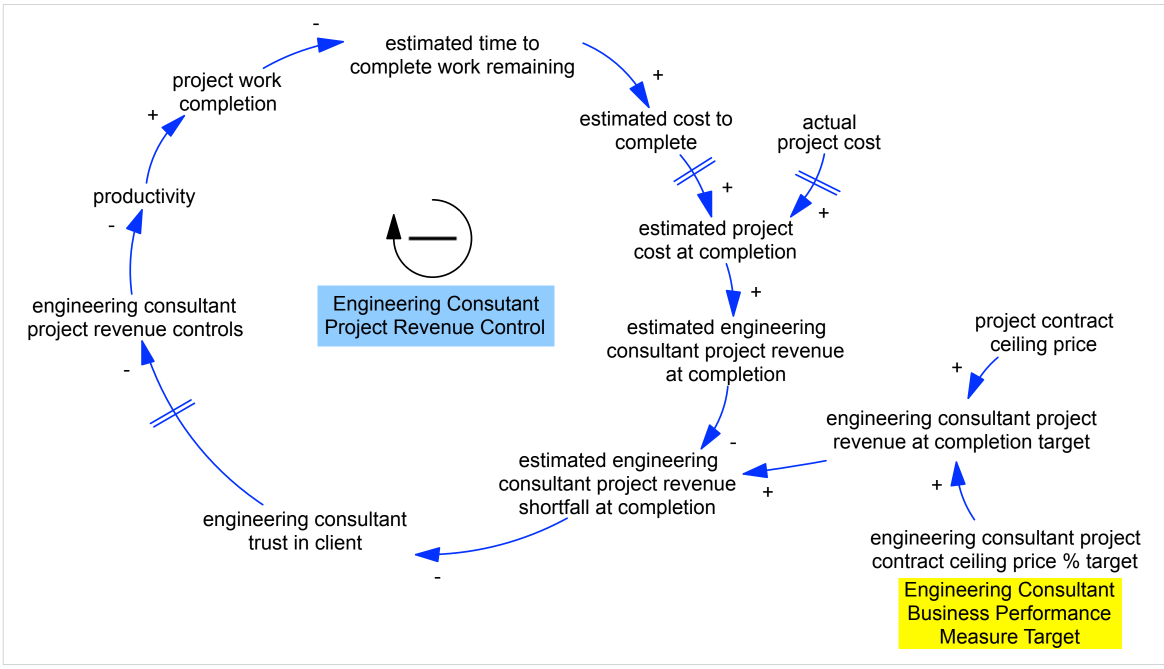


Figure 4.14: Engineering consultant project revenue controlling feedback

Source: Adapted from this research study (Figure 4.13), Anbari (2003) and Turner (2004).

As discussed in Chapter 3, the reviewed literature showed that: current project dynamics models are limited to project performance control actions taken mainly by the engineering consultant or construction contractor; and control actions taken by other key project participants to protect their individual performance measures and targets during project execution (e.g., control actions taken by the engineering consultant to protect his/her business performance) are sparingly covered. Revenue is one of the many key measures of business performance, as discussed in Section 3.3.2. Thus, the system dynamics causal loop diagram of engineering consultant project revenue controls formulated in this research study and shown in Figure 4.14, and all the causal loop diagrams subsequently formulated in this section, help towards the filling of the above-mentioned gap in existing literature on project controls and application of system dynamics to business performance control. The next sub-section discusses some key unintended effects of the two engineering consultant project revenue controls presented in Figure 4.13.

4.7.2. Unintended Effects (Results and Discussions)

Findings

Further analysis of the empirical data gathered in this study revealed that the two engineering consultant project revenue controls, described in the preceding sub-section, generate some undesirable and unintended effect: an increase in project cost overrun, which in turn decreases the client’s trust in the engineering consultant, leading to more intensified client project cost controls, as shown in Table 4.8.

Table 4.8: Unintended effects of engineering consultant project revenue controls (interviewee results)

Engineering consultant project revenue control usually taken by the interviewees	Unintended effect evident from the responses of the interviewees	Interviewees	
		Client project manager questionnaire reference number	Engineering consultant project manager questionnaire reference number
Project scope variation motivations	An increase in project cost leads to an increase in the project cost overrun, which in turn decreases the client's trust in the engineering consultant, leading to more intensified client project cost controls.	C01; C02; C03; C04; C05	EC01; EC02; EC03; EC06
Effort adjustment		C01; C02; C03; C04; C05	EC01; EC02; EC03; EC06

Figure 4.15 shows the above-mentioned three unintended effects of engineering consultant project revenue controls in the form of a causal network (generated using ATLAS.ti), in line with Miles et al. (2014). It is interpreted in a similar way to that described for Figure 4.1 in Section 4.5.

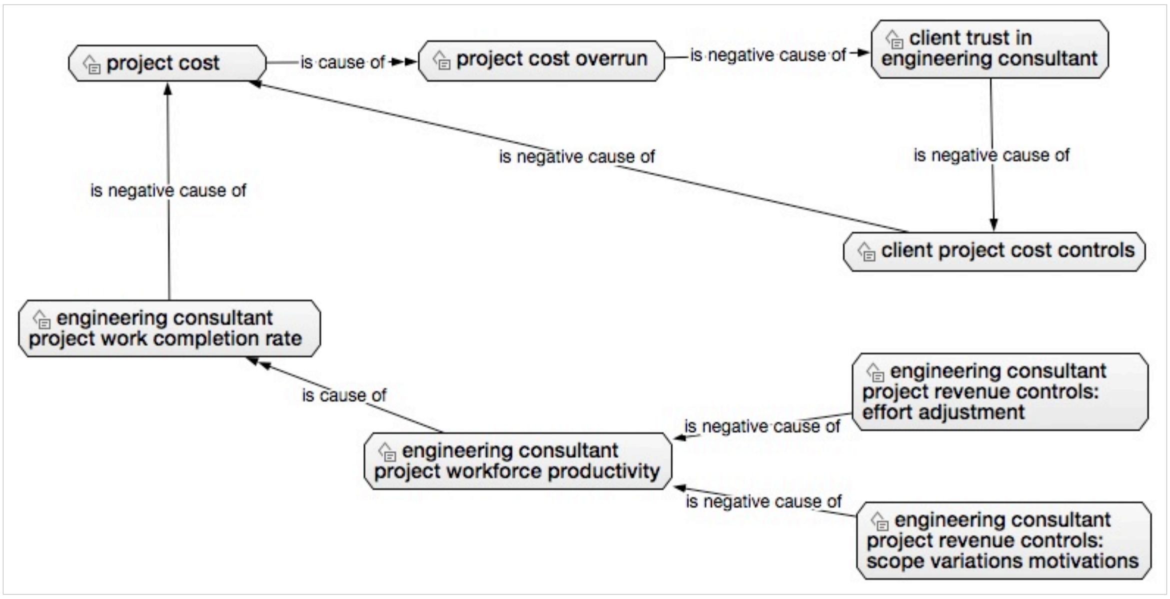


Figure 4.15: Unintended effect of engineering consultant project revenue controls

Discussion

Combining the engineering consultant project revenue controls negative feedback loop (Figure 4.14) with the associated unintended effect (Figure 4.15) yields the system dynamics causal loop diagram shown in Figure 4.16. In particular, Figure 4.16 shows the controlling (negative) feedback loop and its associated unintended effect (positive loop) for one of the two engineering consultant project revenue controls (effort adjustment). The other engineering consultant project revenue control (scope variation motivations) yields loops similar to those in Figure 4.16.

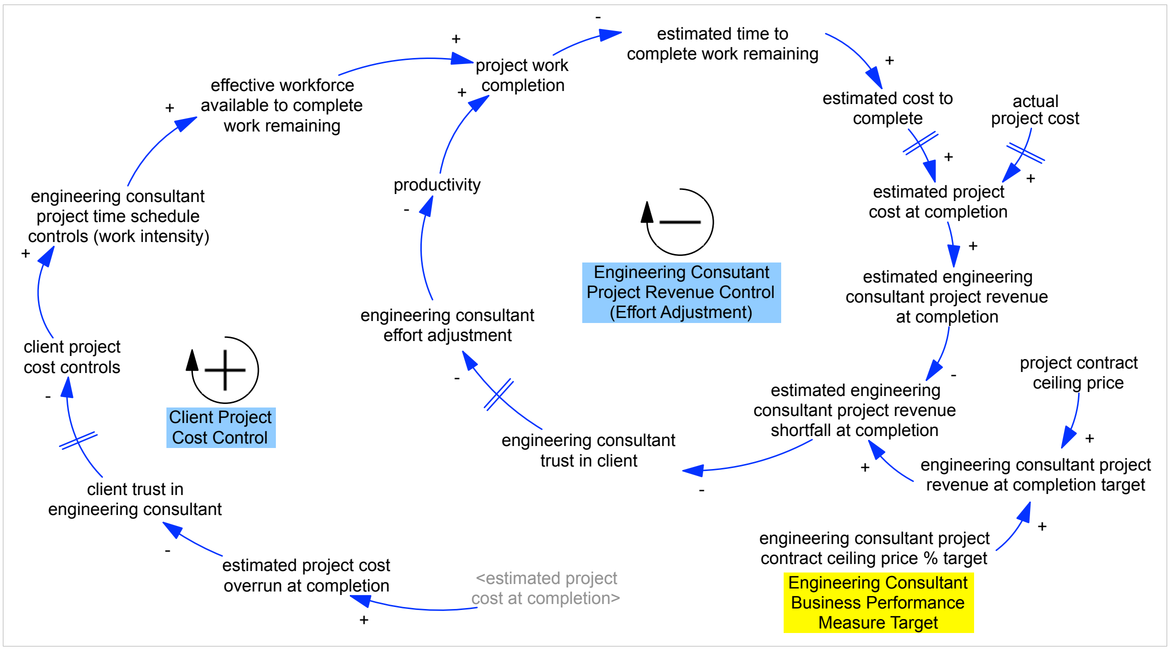


Figure 4.16: Engineering consultant project revenue control (effort adjustment) and its unintended effect

Sources: Adapted from this study (Figures 4.13 to 4.15), Anbari (2003) and Turner (2004).

4.7.3. System Dynamics Conceptual Model

Integrating the causal loop diagrams shown in Figure 4.14 and Figure 4.16, and including both engineering consultant project revenue controls (Figure 4.13) and their associated unintended effect (Figure 4.15), yield the overall system dynamics conceptual model of engineering consultant project revenue controls and their associated unintended effect shown in Figure 4.17. The two negative feedback loops represent the two engineering consultant project revenue controls found in this research study, while the positive feedback loop represents their unintended effect. As shown in Figure 4.17, the positive/reinforcing feedback loop militates against the intended negative/balancing feedback loops, degrading the engineering consultant's project revenue performance.

Put differently, *the engineering consultant project revenue controls, which are aimed at reducing/eliminating the 'project revenue shortfall' by increasing the 'estimated project cost at completion', tend to generate some unintended and counteractive consequence (unintended effect) that decreases the 'estimated project cost at completion' and increases the 'project revenue shortfall'.* This counterintuitive key finding is effectively the main dynamic hypothesis presented in Figure 4.17.

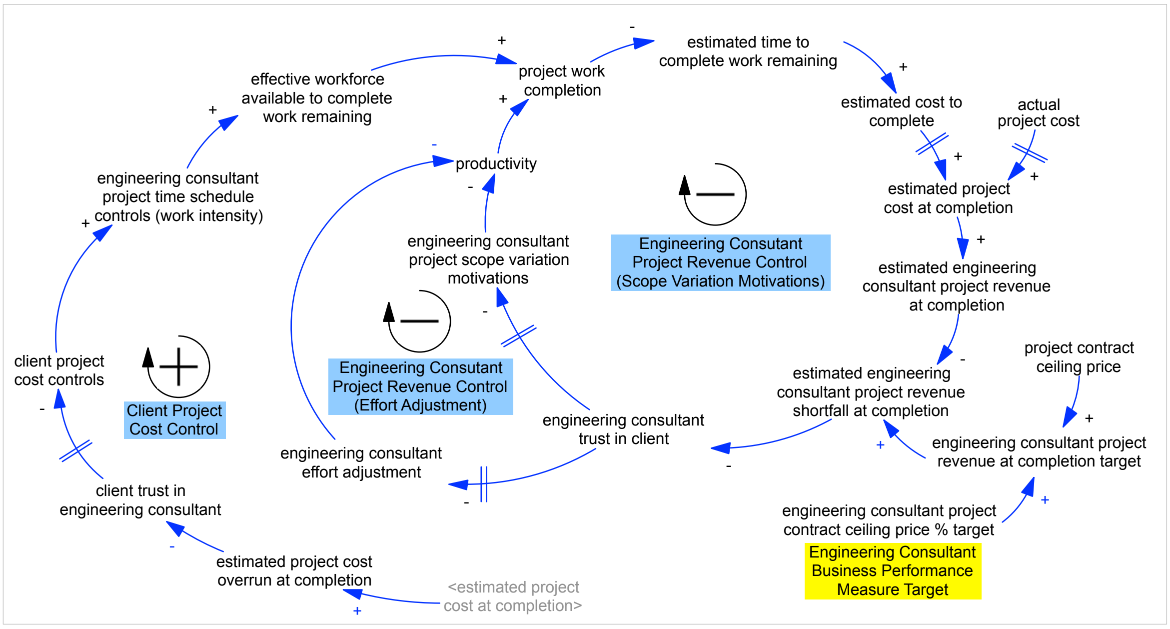


Figure 4.17: Engineering consultant project revenue controls and their unintended effects

Sources: Adapted from this study (Figures 4.13 to 4.16), Anbari (2003) and Turner (2004).

In Figure 4.17, similar to Figure 4.12, the causal relationships shown for 'estimated cost to complete', 'actual project cost', and 'estimated project cost at completion' were adopted from the formulae presented by Anbari (2003), who did not formulate any system dynamics causal loop diagrams. The reviewed existing literature, as discussed in Chapter 3 and highlighted in Section 4.7.1, showed that: current project dynamics models are limited to project performance control actions taken mainly by the engineering consultant or construction contractor; control actions (and their unintended effects) taken by other key project participants to protect their individual performance measures and targets during project execution (such as control actions taken by the engineering consultant to protect his/her business performance are sparingly covered; and no appropriate system dynamics conceptual model similar to that shown in Figure 4.17 could be identified in the reviewed literature.

Revenue is one of the many key measures of business performance, as discussed in Section 3.3.2. Thus, the system dynamics conceptual model of engineering consultant project revenue controls and their associated unintended effect shown in Figure 4.17, as formulated in this research study, helps towards the filling of the abovementioned gap in existing literature on project controls and the application of system dynamics to business performance control.

4.8. Engineering Consultant Project Cash Flow Controls and their Unintended Effects

4.8.1. Controls (Results and Discussions)

Findings

The interviewed engineering consultant project managers indicated that some of the control actions they usually take when they forecast a cash flow shortfall during project execution include: workforce reduction; overtime reduction; applying pressure on project workforce to work faster; and expediting submitted invoices, as shown in Table 4.9. This was, for instance, highlighted by one of the interviewed engineering consultant project managers who indicated that when he forecasts a cash flow shortfall during project execution he usually takes the following actions:

> *"… reduce workforce; reduce overtime; make the project workforce work faster by applying pressure on them; … and expedite invoices (making follow-ups on submitted invoices until they are paid)". [Engineering Consultant Project Manager, Questionnaire Reference Number: EC01].*

Table 4.9: Engineering consultant project cash flow controls (interviewee results)

Engineering consultant project cash flow control usually taken by the interviewees	Interviewees (Engineering consultant project manager questionnaire reference number)
Reducing project workforce size	EC01; EC02; EC04; EC05; EC06
Reducing project workforce paid overtime	EC01; EC02; EC05;
Applying pressure on project workforce to work faster	EC01; EC02; EC04; EC05; EC06
Invoice payment expediting	EC01; EC02; EC04; EC05; EC06

The indicated control actions usually taken by the engineering consultant project managers are aimed at increasing the engineering consultant's project cash flow (by increasing the project cash inflows and/or reducing the project cash outflows), thereby reducing the engineering consultant's project cash flow shortfall. This was, for instance, evident in the response of one of the interviewees who highlighted that:

> *"… These actions are aimed at improving [the project] cash inflows and reducing cash outflows." [Engineering Consultant Project Manager, Questionnaire Reference Number: EC05].*

Figure 4.18 is a causal network display (generated using the network view tool in ATLAS.ti), in line with Miles et al. (2014), showing the four engineering consultant project cash flow controls presented in Table 4.9. It is interpreted in a similar way to that described for Figure 4.1 in Section 4.5.

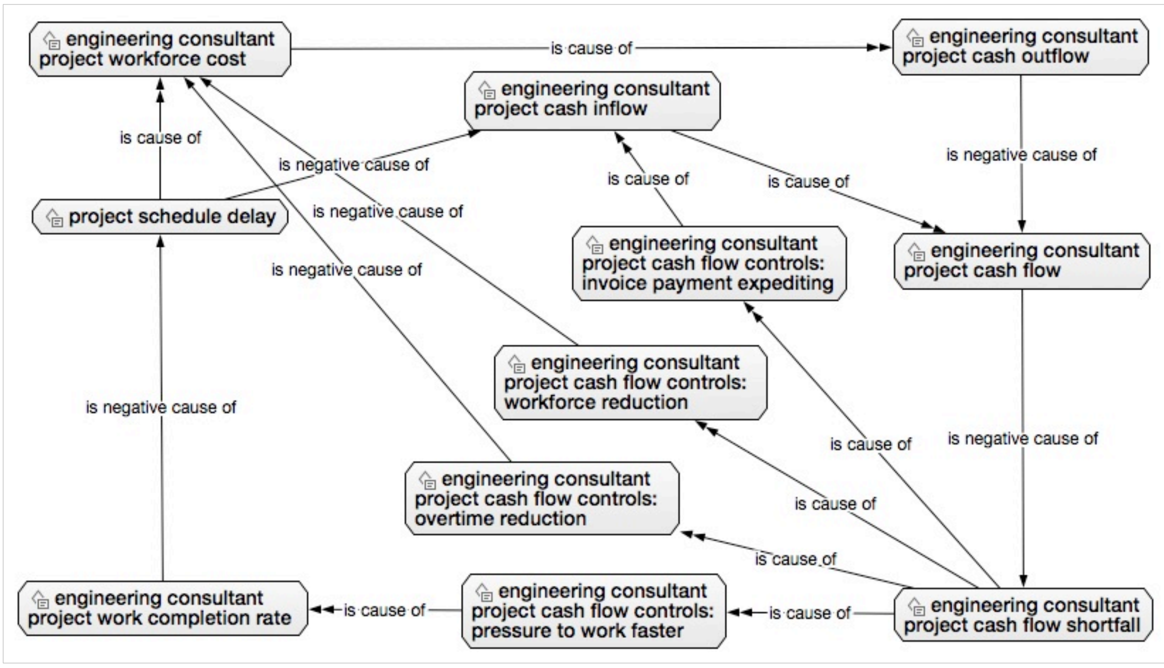


Figure 4.18: Engineering consultant project cash flow controls

Discussion

Poor subcontractor cash flow, due to late invoice payments, diminishes the subcontractor's trust in the main contractors (client) (Manu et al., 2015). According to Gupta and Boyd (2008), cash flow is one of the key business performance measures essential for the sustenance of any organisation (e.g., the engineering consultant). Thus, when the engineering consultant project managers forecast a cash flow shortfall (poor business performance) during project execution, their trust in the client diminishes. As a result, they take certain control actions (applying pressure on project workforce to work faster, reducing project workforce size, reducing project workforce paid overtime, and/or invoice payment expediting, as shown in Table 4.9) aimed at increasing the engineering consultant's project cash flow (by increasing project cash inflow and/or reducing the project cash outflow), thereby reducing the engineering consultant's project cash flow shortfall.

'Applying pressure on project workforce to work faster' is also referred to as "work intensity" by such previous researchers as Lyneis and Ford (2007), and Ford et al. (2007). According to Lyneis and Ford (2007), and Ford et al. (2007), the higher the work intensity, the greater the project work completion rate, and consequently, the lower the project time schedule delay. Arguably, the higher the project time schedule delay: the longer the invoicing delay (assuming one can only invoice for the work done); and also, the greater the engineering consultant's project workforce salaries (the more time the project workforce spends on the project, the greater their salaries cost, assuming they are paid on a fixed hourly/monthly rate). Work intensity, thus, improves the engineering consultant's project cash flow in two ways, namely by increasing project cash inflow and reducing project cash outflow.

The use of work intensity for project cash inflow improvement is shown in the system dynamics causal loop diagram (negative feedback loop) in Figure 4.19 that was formulated in line with the findings of this research study (Figure 4.18) as well as taking into consideration the discussed findings from Ford et al. (2007), and Manu et al. (2015). In Figure 4.19, the causal relationships from 'engineering consultant project cash flow controls (work intensity)' to 'estimated project time schedule delay' are in line with Ford et al. (2007), as discussed in Section 4.5. The causal relationship between the 'estimated engineering consultant project cash flow shortfall' and 'client trust in engineering consultant' is in line with the findings of Manu et al. (2015), who, however, did not include any system dynamics model.

According to Sterman (2000), every negative feedback loop must aim at eliminating/ closing the performance gap between the performance target and the current/ forecasted performance state. In the negative feedback loop in Figure 4.19: the performance target is the 'engineering consultant project cash flow projection target'; the forecasted performance state is the 'estimated engineering consultant project cash flow'; and the performance gap to be eliminated (balanced out) is the 'engineering consultant project cash flow shortfall'.

As discussed in Chapter 3 and highlighted in Section 4.7, the reviewed literature showed that: current project dynamics models are limited to project performance control actions taken mainly by the engineering consultant or construction contractor; and control actions taken by other key project participants to protect their individual performance measures and targets during project execution (e.g., control actions taken by the engineering consultant to protect his/her business performance) are sparingly covered.

Cash flow is one of the many key measures of business performance, as discussed in Section 3.3.2. Thus, the system dynamics causal loop diagram of engineering consultant project cash flow control (work intensity improving cash inflow) formulated in this study and shown in Figure 4.19, and all the causal loop diagrams subsequently formulated in this section, help towards the filling of the abovementioned gap in existing literature on project controls and application of system dynamics to business performance control.

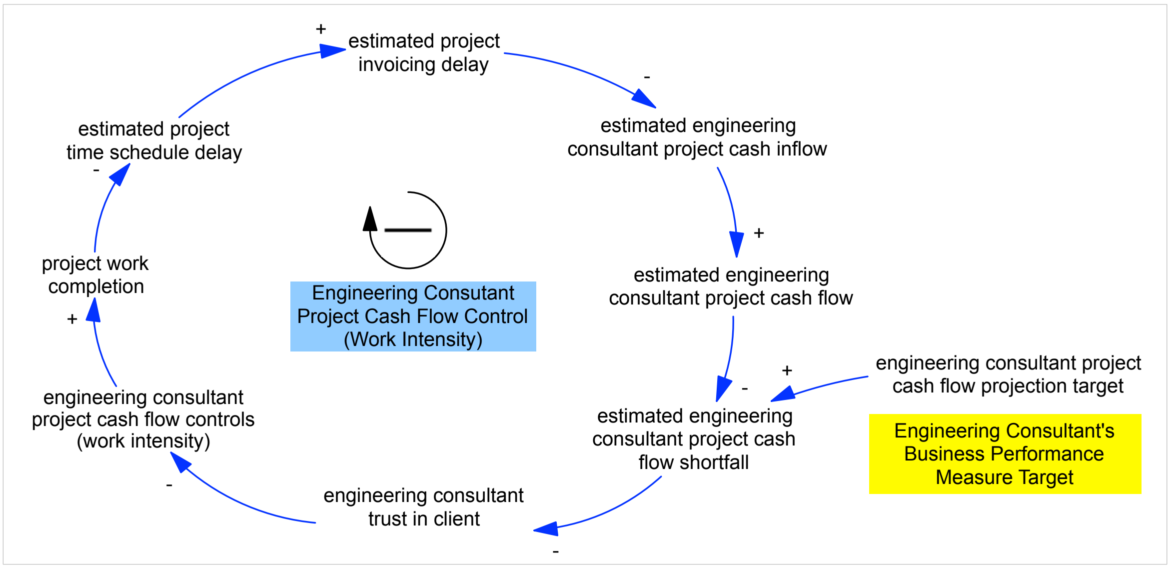


Figure 4.19: Engineering consultant project cash flow control (work intensity improves cash inflow)

Sources: Adapted from this study (Figure 4.18), Ford et al. (2007), and Manu et al. (2015).

The use of work intensity for project cash outflow minimisation yields the causal loop diagram shown in Figure 4.20, formulated in line with Figures 4.18 and 4.19.

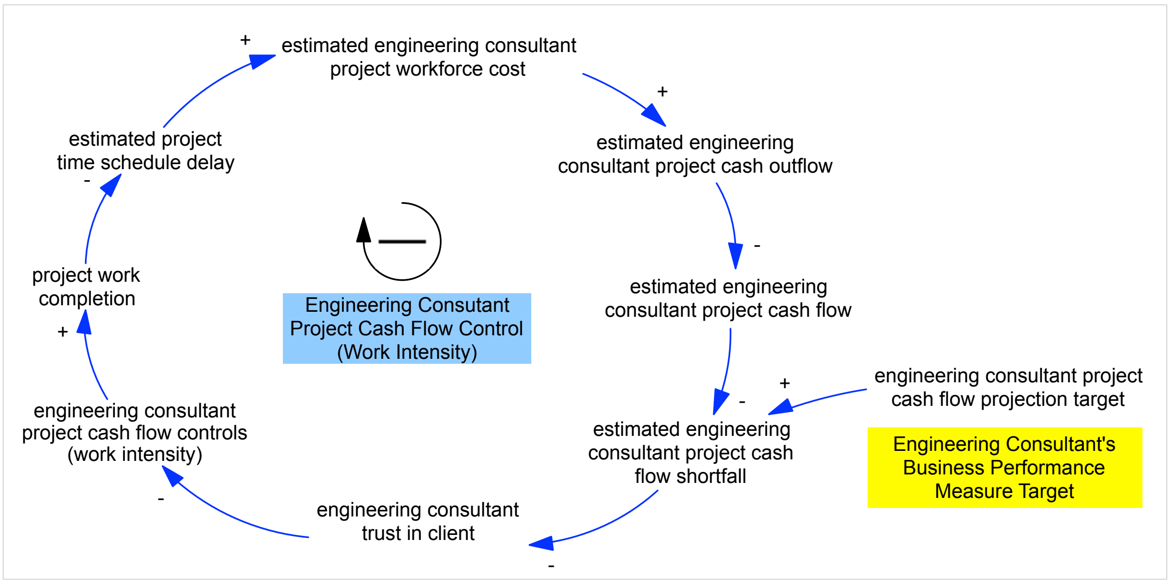


Figure 4.20: Engineering consultant project cash flow control (work intensity reduces cash outflow)

Sources: Adapted from this study (Figures 4.18 and 4.19), Ford et al. (2007) and Manu et al. (2015).

Invoice payment expediting (regular follow-ups on submitted invoices until they are paid), as an engineering consultant project cash flow control, helps to reduce the client invoices approval and payment delay, yielding the system dynamics causal loop diagram shown in Figure 4.21, formulated in line with Figures 4.18 and 4.19.

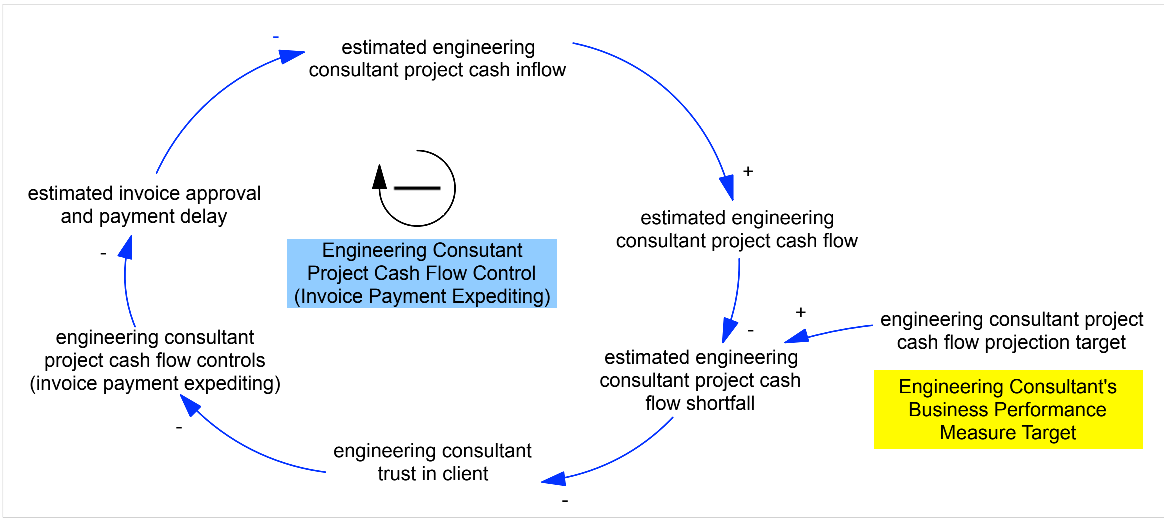


Figure 4.21: Engineering consultant project cash flow control (invoice payment expediting improving cash inflow)

Sources: Adapted from this study (Figures 4.18 and 4.19), and Manu et al. (2015).

The other two engineering consultant project cash flow controls (reducing project workforce size and reducing paid overtime), as shown in Figure 4.18, reduce the effective project workforce size available to complete project work and the project workforce cost (Ford et al., 2007), thereby reducing the engineering consultant's project cash outflow, and improving the engineering consultant's project cash flow. Figure 4.22, formulated in line with Figures 4.18 and 4.20, shows the resulting system dynamics causal loop diagram for reducing the project workforce size.

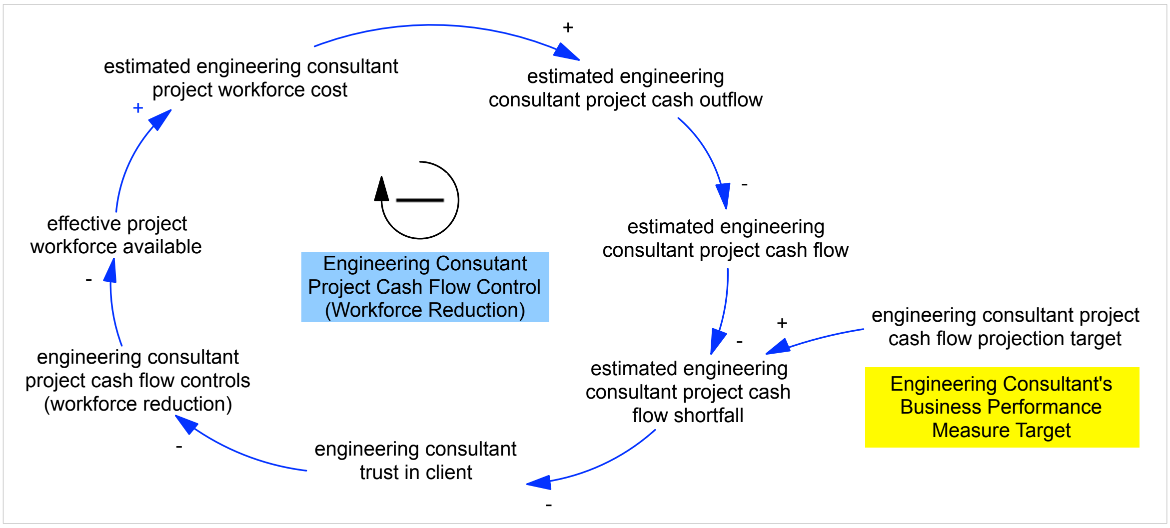


Figure 4.22: Engineering consultant project cash flow control (workforce reducing cash outflow)

Sources: Adapted from this study (Figures 4.18 and 4.20), Ford et al. (2007), and Manu et al. (2015).

4.8.2. Unintended Effects (Results and Discussions)

Findings

Further analysis of the empirical data gathered in this research study revealed that the engineering consultant project cashflow controls generate some unintended effects, as shown in Table 4.10.

Table 4.10: Unintended effects of engineering consultant project cash flow controls (interviewee results)

Engineering consultant project cash flow control usually taken by the interviewees	Unintended effect evident from the responses of the interviewees	Interviewees	
		Client project manager questionnaire reference number	Engineering consultant project manager questionnaire reference number
Reducing project workforce size	Inadequate project workforce, resulting in a decrease in project work completion (which in turn increases project time schedule delay leading to invoice submission delays and delays in approval and payment of submitted invoices by the client, thereby reducing project cash inflow).	C03; C04	EC01; EC02; EC04; EC05; EC06
Reducing project workforce paid overtime		C03; C04	EC01; EC02; EC04; EC05; EC06
Applying pressure on project workforce to work faster	Decrease in the quality of the project deliverables (resulting in reworks and a decrease in project work completion, which in turn increases project time schedule delay leading to invoice submission delays and delays in approval and payment of submitted invoices by the client, thereby reducing project cash inflow).	C02; C03; C04; C05	EC02; EC04; EC06
Invoice payment expediting	Less time available for the engineering consultant to carry out real project work, thereby reducing the engineering consultant's productivity (resulting in a decrease in project work completion, which in turn increases project time schedule delay leading to invoice submission delays and delays in approval and payment of submitted invoices by the client, thereby reducing project cash inflow).	C03; C04	EC02; EC05; EC06

An increase in project schedule delay sometimes leads to delays in approval and payment of submitted invoices by the client, as one interviewee highlighted:

> *"The client sometimes delays paying our invoices especially if the project is behind schedule ..." [Engineering Consultant Project Manager, Questionnaire Reference Number: EC02].*

Figure 4.23 shows the engineering consultant project cash flow controls' unintended effects, presented in Table 4.10, in the form of a causal network (generated using ATLAS.ti), in line with Miles et al. (2014). It is interpreted in a similar way to that described for Figure 4.1 in Section 4.5.

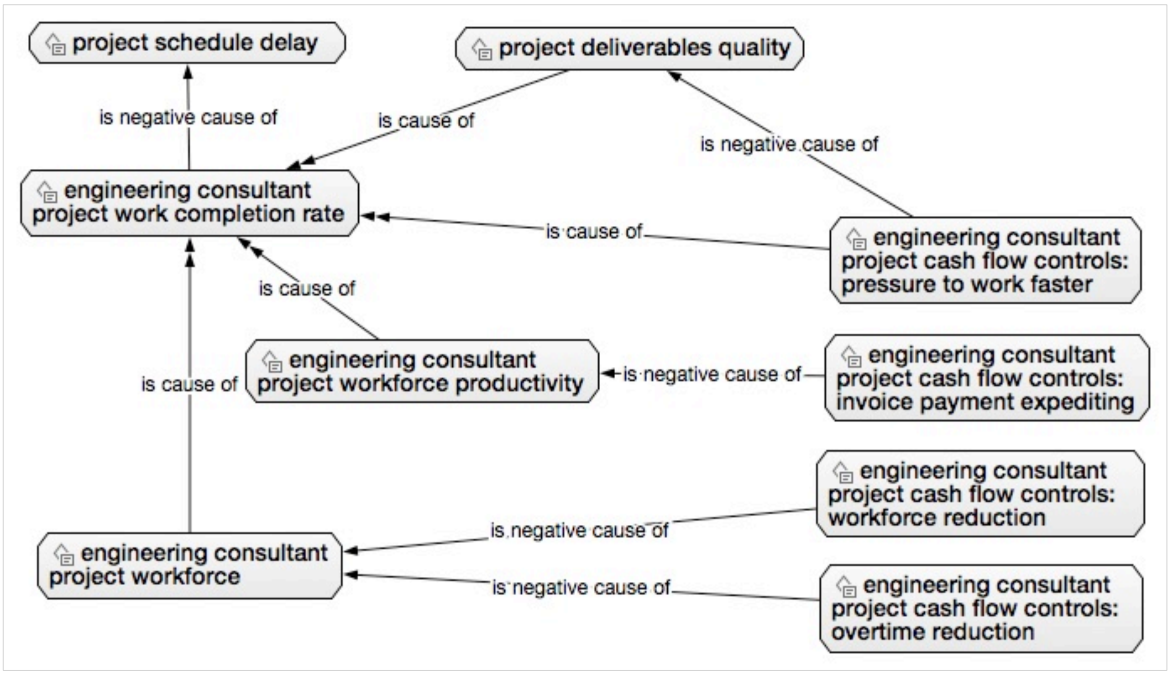


Figure 4.23: Unintended effects of engineering consultant project cash flow controls

Discussion

One of the unintended effects of engineering consultant project cash flow controls presented in Table 4.10 and Figure 4.23 is that reducing either project workforce size or project workforce overtime results in inadequate effective project workforce size, slowing down project work completion and increasing the project time schedule delay, corroborating Lyneis and Ford (2007), and Ford et al. (2007).

Project time schedule delay leads to some undesirable effects on the engineering consultant's project cash flow. Firstly, it leads to a delay in the engineering consultant submitting invoices and getting paid, thereby reducing the engineering consultant's project cash inflow and reducing his/her project cash flow (where project cash flow is equal to project cash inflow minus project cash outflow). Secondly, it results in an increase in the engineering consultant's project workforce cost, consistent with Ford et al. (2007), which increases the engineering consultant's project cash outflow, and reduces his/her project cash flow.

Thirdly, it may lead to the institution of delay damages by the client (von Branconi and Loch, 2004), thereby reducing the engineering consultant's project cash inflow and project cash flow. Integrating these unintended effects of the engineering consultant project cash flow control (workforce reduction) into the negative feedback loop shown in Figure 4.22 yields the system dynamics causal loop diagram (balancing and reinforcing loops) shown in Figure 4.24. The engineering consultant project cash flow control (overtime reduction) and its associated unintended effects yield a similar system dynamics causal loop diagram to that shown in Figure 4.24.

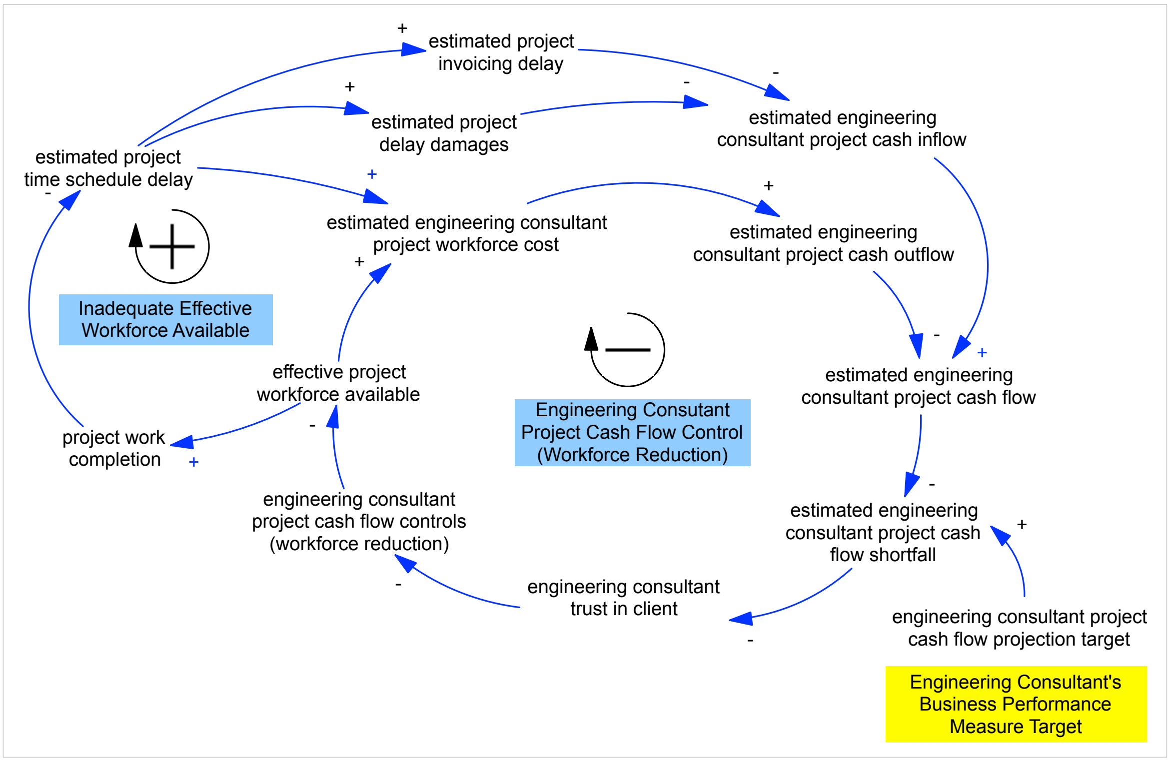


Figure 4.24: Engineering consultant project cash flow control (workforce reduction) and its unintended effects

Sources: Adapted from this research study (Figures 4.18, 4.22 and 4.23), Ford et al. (2007), Manu et al. (2015), and von Branconi and Loch (2004).

In Figure 4.24, the causal relationships from 'engineering consultant project cash flow controls (workforce reduction)' to 'estimated engineering consultant project workforce cost' are in line with Ford et al. (2007), who, however, only focussed on project time schedule controls as discussed in Section 4.5. The causal relationship between 'estimated engineering consultant project cash flow shortfall' and 'client trust in engineering consultant' is in line with Manu et al. (2015), who, however, did not formulate any system dynamics model. The causal relationship between the 'estimated project time schedule delay' and 'estimated project delay damages' is in line with von Branconi and Loch (2004), who also did not formulate any system dynamics model.

As discussed in Chapter 3 and highlighted in Sections 4.7 and 4.8.1, the reviewed literature showed that: current project dynamics models are limited to project performance control actions taken mainly by the engineering consultant or construction contractor; control actions taken by other key project participants to protect their individual performance measures and targets during project execution (e.g., control actions taken by the engineering consultant to protect his/her business performance) are sparingly covered; and no appropriate system dynamics conceptual model similar to that shown in Figure 4.24 was identified in the reviewed literature.

Cash flow is one of the many key measures of business performance, as discussed in Section 3.3.2. Thus, the system dynamics causal loop diagram of engineering consultant project cash flow control (workforce reduction) and its unintended effect, formulated in this research study (from a combination of existing literature, embedded multiple-case study and systems thinking) and shown in Figure 4.24, helps towards the filling of the above-mentioned gap in existing literature on project controls and application of system dynamics to business performance control. The same applies to all the causal loop diagrams subsequently formulated in this section.

The second unintended effect of engineering consultant project cash flow controls presented in Table 4.10 and Figure 4.23 is that applying pressure on the project workforce to work faster (also referred to as work intensity by some previous researchers) results in a decrease in the quality of the project deliverables. This finding corroborates Ford et al. (2007), and Lyneis and Ford (2007) who highlighted that an increase in project workforce work intensity leads to an increase in work errors in the project deliverables resulting in rework, reduction in project work completion, and increase in project time schedule delay. This results in delayed project invoicing. Integrating this unintended effect into the negative feedback loop shown in Figure 4.19 yields the system dynamics causal loop diagram (balancing and reinforcing loops) for the engineering consultant project cash flow control (work intensity improving cash inflow) and its associated unintended effect shown in Figure 4.25.

The reinforcing loop for the engineering consultant project cash flow control (work intensity reducing cash outflow) loop (Figure 4.20) is similar to that shown in Figure 4.25.

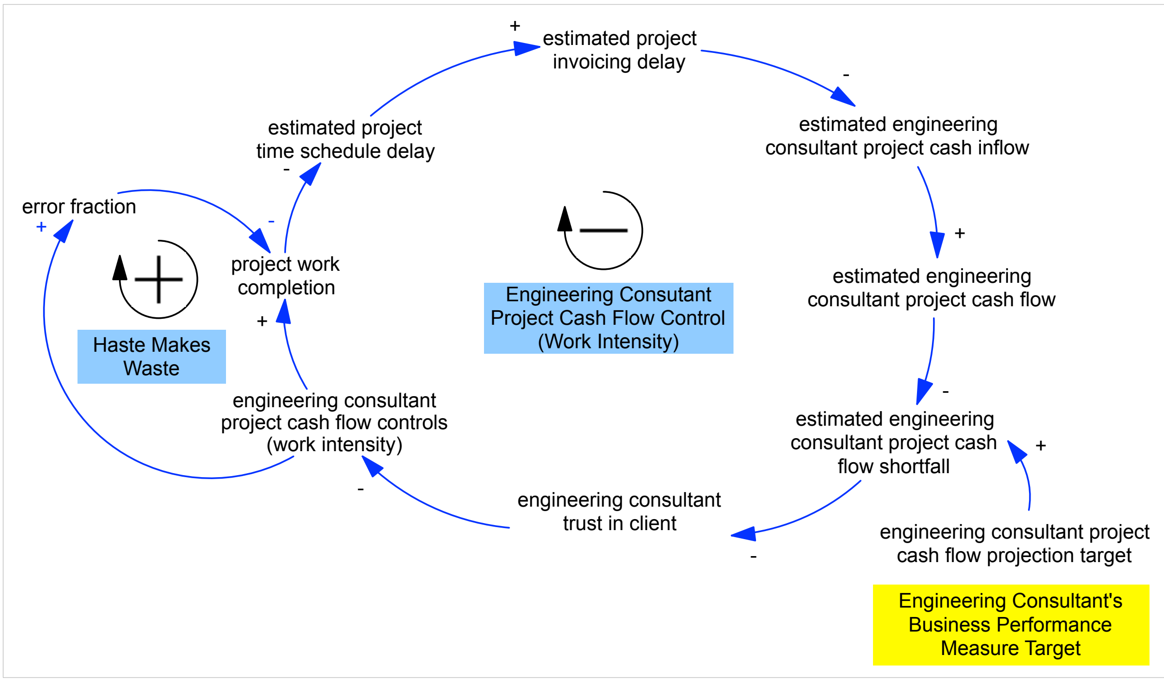


Figure 4.25: Engineering consultant project cash flow control (work intensity improving cash inflow) and its unintended effects

Sources: Adapted from this research study (Figures 4.18, 4.19 and 4.23), Ford et al. (2007), and Manu et al. (2015).

The third unintended effect of the engineering consultant project cash flow controls presented in Table 4.10 and Figure 4.23 is that invoice expediting (making regular follow-ups on submitted invoices until they are paid) consumes the engineering consultant's productive time resulting in less time being spent on producing real project deliverables, lowering productivity and project work completion rate, and increasing project time schedule delay. This finding corroborates the findings of some previous studies. For instance, Manu et al. (2015) highlighted that invoice expediting lowers productivity. Also, the project models of Ford et al. (2007), Lyneis and Ford (2007), and Nasirzadeh and Nojedehi (2013) show that a decrease in project workforce productivity leads to a decrease in project work completion rate and an increase in project time schedule delay.

Another finding of this study was that an increase in project time schedule delay leads to client delays in approval and payment of submitted invoices. Integrating these undesirable effects into the negative feedback loop shown in Figure 4.21 yields the system dynamics causal loop diagram (balancing and reinforcing loops) for the engineering consultant project cash flow control (invoice payment expediting) and its associated unintended effect shown in shown in Figure 4.26.

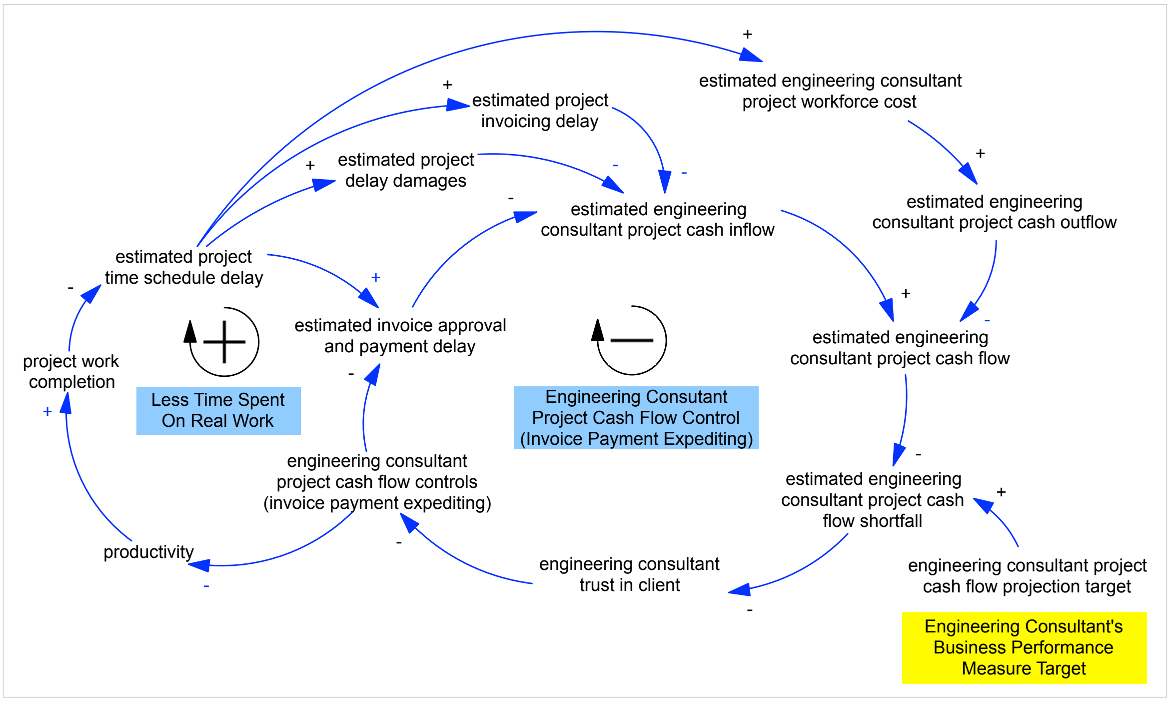


Figure 4.26: Engineering consultant project cash flow control (invoice payment expediting) and its unintended effects

Sources: Adapted from this research study (Figures 4.18, 4.21 and 4.23), Ford et al. (2007), Manu et al. (2015), and von Branconi and Loch (2004).

4.8.3. System Dynamics Conceptual Model

Integrating the system dynamics causal loop diagrams shown in Figures 4.24 to 4.26, and incorporating all the engineering consultant project cash flow controls (Figure 4.18) and their associated unintended effects (Figure 4.23), yield the overall system dynamics conceptual model of the engineering consultant project cash flow controls and their associated unintended effects shown in Figure 4.27. The four negative feedback loops represent the four engineering consultant project cash flow controls found in this research study, while the positive feedback loops represent their unintended effects. As shown in Figure 4.27, the positive/reinforcing feedback loops militate against the intended negative/balancing feedback loops, degrading the engineering consultant's project cash flow performance.

Put differently, *the engineering consultant project cash flow controls, which are aimed at reducing/eliminating the 'engineering consultant project cash flow shortfall' by increasing the 'estimated engineering consultant project cash flow', tend to generate some unintended and counteractive consequence (unintended effect) that decreases the 'estimated engineering consultant project cash flow'' and increases the 'engineering consultant project cash flow shortfall'.* This counterintuitive key finding is effectively the main dynamic hypothesis presented in Figure 4.27.

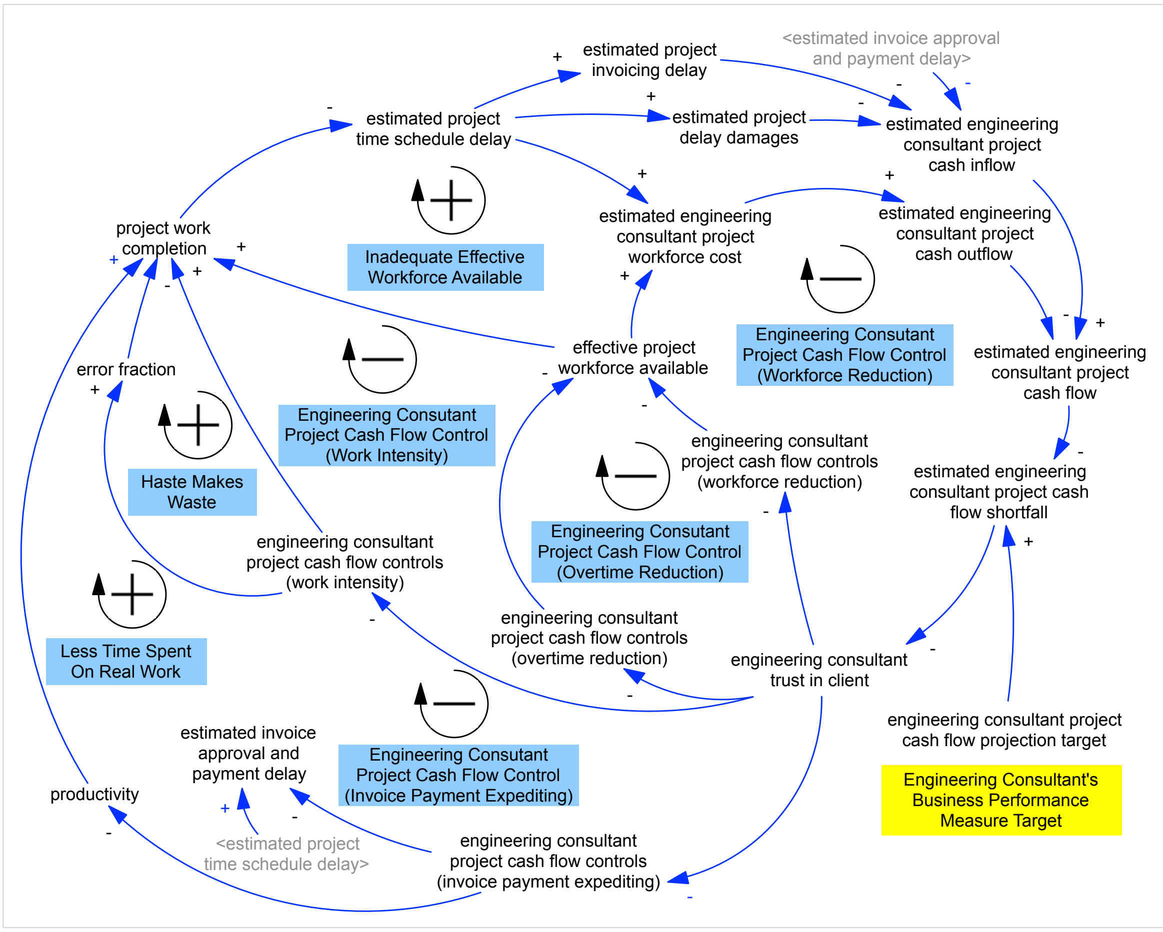


Figure 4.27: Engineering consultant project cash flow controls and their unintended effects

Sources: Adapted from this research study (Figures 4.18 to 4.26), Ford et al. (2007), Manu et al. (2015), and von Branconi and Loch (2004).

In Figure 4.27, the causal relationships from workforce reduction, overtime reduction and work intensity to 'estimated engineering consultant project workforce cost' are in line with Ford et al. (2007), who, however, only focussed on project time schedule controls as discussed in Section 4.5. The causal relationship between 'estimated engineering consultant project cash flow shortfall' and 'client trust in engineering consultant' is in line with Manu et al. (2015), who, however, did not formulate any system dynamics model. The causal relationship between the 'estimated project time schedule delay' and 'estimated project delay damages' is in line with von Branconi and Loch (2004), who also did not formulate any system dynamics model.

The reviewed existing literature, as discussed in Chapter 3 and highlighted in Sections 4.8.1 and 4.8.2, showed that: current project dynamics models are limited to project performance control actions taken mainly by the engineering consultant or construction contractor; control actions taken by other key project participants to protect their individual performance measures and targets during project execution (e.g., control actions taken by the engineering consultant to protect his/her business performance) are sparingly covered; and no appropriate system dynamics conceptual model similar to that shown in Figure 4.27 could be identified in the reviewed literature.

Cash flow is one of the many key measures of business performance, as discussed in Section 3.3.2. Thus, the system dynamics causal conceptual model of engineering consultant project cash flow controls and their unintended effects, formulated in this study (from a combination of existing literature, embedded multiple-case study and systems thinking) and shown in Figure 4.27, helps towards the filling of the abovementioned gap in existing literature on project controls and application of system dynamics to business performance control.

The next section integrates the system dynamics conceptual models formulated in the preceding Sections 4.5 to 5.8, and formulates a system dynamics conceptual model of the competition between two key project participants (the client and the engineering consultant) during project execution

4.9. Project Participants Competition System Dynamics Conceptual Model

4.9.1. Integrated Client and Engineering Consultant Performance Controls

Integrating the client project performance control (time schedule and cost) negative feedback loops and the engineering consultant project business performance control (revenue and cash flow) negative feedback loops (in Figures 4.6, 4.12, 4.17 and 4.27), formulated in the preceding Sections 4.5 to 4.8, yields the integrated client and engineering consultant performance control system dynamics causal loop diagram shown in Figure 4.28.

In Figure 4.28, the causal relationships from ‘engineering consultant project time schedule controls (work intensity)’ to ‘estimated time to complete work remaining’ are in line with Ford et al. (2007), who only focussed on project time schedule controls taken by the engineering consultant (or construction contractor). The causal relationships shown for ‘estimated cost to complete’, ‘actual project cost’, and ‘estimated project cost at completion (W)’ were adopted from a formula presented by Anbari (2003), who did not formulate any system dynamics causal loop diagrams. The causal relationships between 'estimated project time schedule delay', ‘client trust in engineering consultant’, and one client project time schedule control (demand for more progress reports) are in line with Rodrigues and Williams (1998), though they used some different but similar variable names. The causal relationship between the ‘estimated engineering consultant project cash flow shortfall’ and ‘client trust in engineering consultant’ is in line with the findings of Manu et al. (2015), who, however, did not include any system dynamics model.

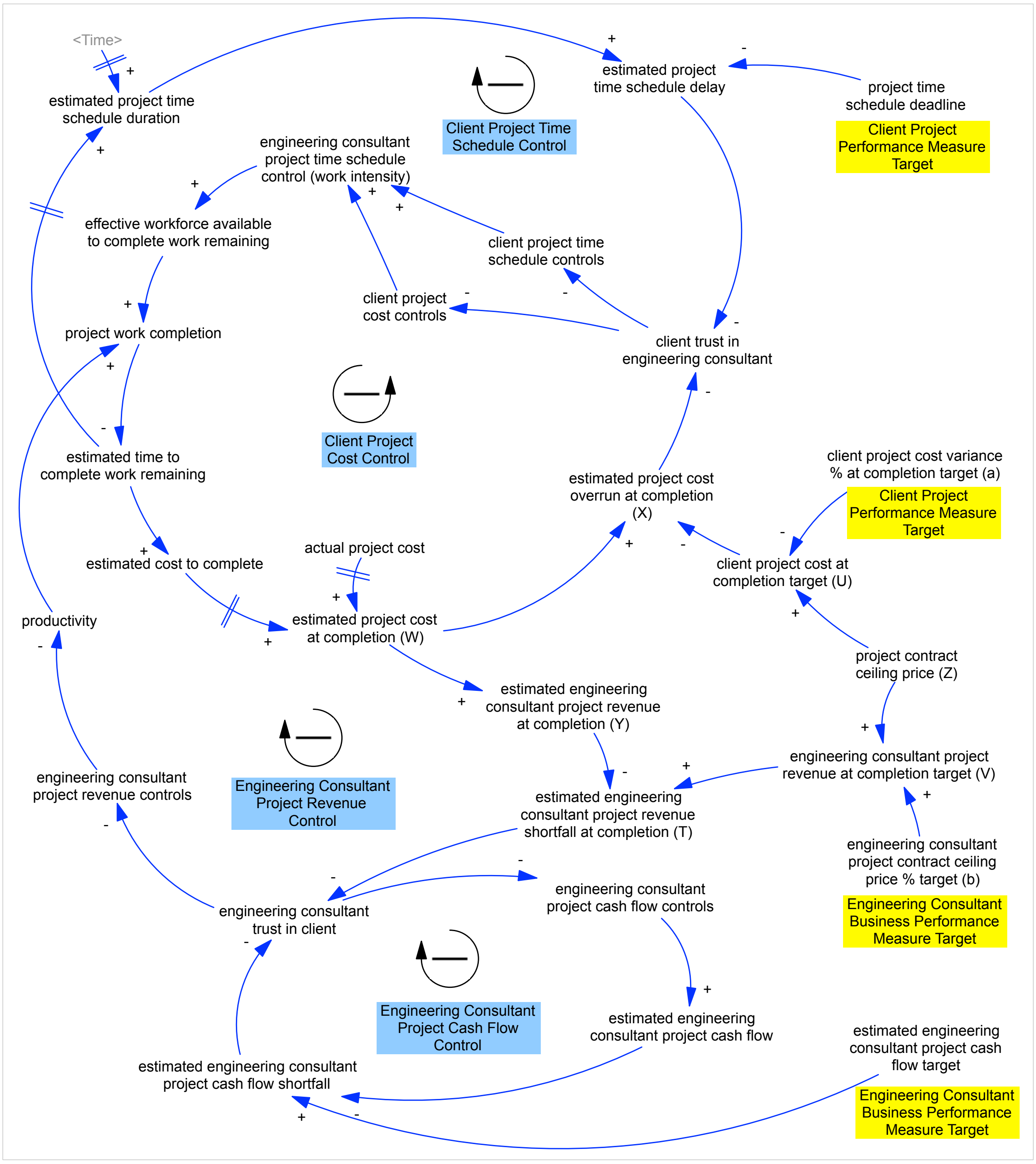


Figure 4.28: Integrated client and engineering consultant performance controlling feedbacks

Sources: Adapted from this research study (Figures 4.6, 4.12, 4.17 and 4.27), Anbari (2003), Ford et al. (2007), Manu et al. (2015), and Rodrigues and Williams (1998).

The reviewed existing literature, as discussed in Chapter 3 and highlighted in Sections 4.5 to 4.8, showed that: current project dynamics models are limited to project performance control actions of mainly the engineering consultant or construction contractor; control actions taken by the client to protect project performance are sparingly covered; current project performance controls are mainly aimed at achieving project time schedule target, yet there are many other key measures of project performance, as discussed in Section 3.3.1; and control actions taken by the engineering consultant and construction contractor to protect their individual business performance targets during project execution are sparingly covered.

Thus, the system dynamics conceptual formulated in this study and shown in Figure 4.28, that integrates various project controls [namely engineering consultant project performance control (time schedule), client project performance controls (time schedule and cost), and engineering consultant project business performance controls (revenue and cash flow)] of two key project participants (the client and the engineering consultant), with their different and competing performance measures and targets during project execution, contributes towards the filling of the above-mentioned gaps in existing literature on project controls and application of system dynamics to both project performance and business performance.

4.9.2. Competing Client and Engineering Consultant Performance Controls

A closer analysis at how the 'Client Project Cost Control' and the 'Engineering Consultant Project Revenue Control' negative feedback loops are interlinked, in Figure 4.28, reveals that the two loops act against (compete with) each other, reinforcing each other's performance gap, as shown in Figure 4.29. The resultant overall loop is a positive/ reinforcing loop, shown in red in Figure 4.29, representing the competing performance controls between the two key project participants (the client and the engineering consultant) during project execution. The two competing species are the client and the engineering consultant.

Every negative feedback loop must aim at eliminating/closing the performance gap between some performance target and the current/forecasted performance state (Sterman, 2000). In the 'Client Project Cost Control' negative feedback loop in Figure 4.29: the target is the 'client project cost at completion target (U)', which is influenced by the 'project contract ceiling price (Z)' and the 'client project cost variance % at completion target (a)'; the forecasted state is the 'estimated project cost at completion (W)'; and the gap to be eliminated (balanced out) is the 'estimated project cost overrun at completion (X)'.

In the 'Engineering Consultant Project Revenue Control' negative feedback loop: the target is the 'engineering consultant project revenue at completion target (V)', which is influenced by Z' and the 'engineering consultant project contract ceiling price % target' (b); the forecasted state is the 'estimated engineering consultant project revenue at completion (Y)'; and the gap to be eliminated (balanced out) is the 'estimated engineering consultant project revenue shortfall at completion (T)'.

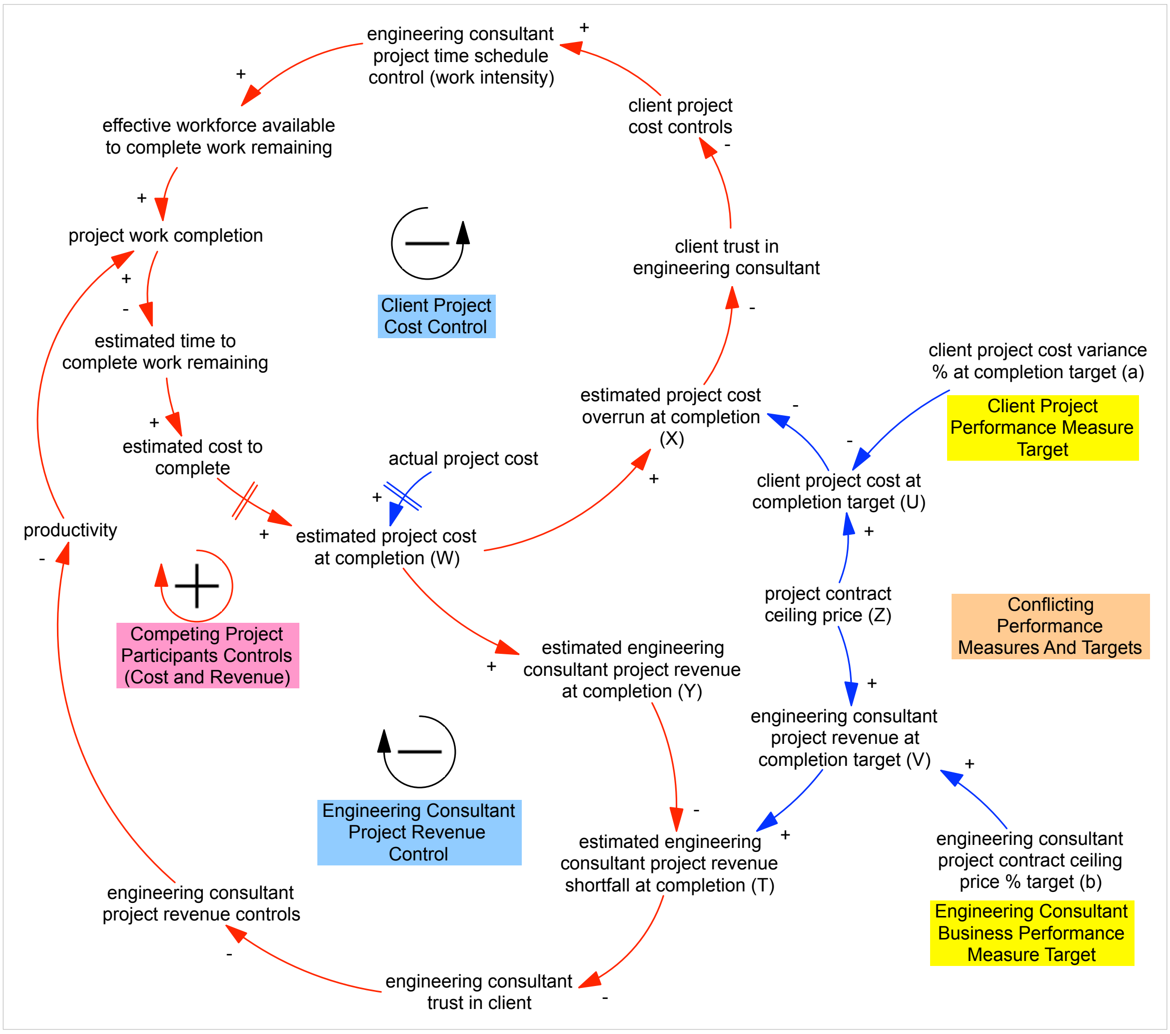


Figure 4.29: Competing client project cost and engineering consultant project revenue controls

Sources: Adapted from this research study (Figures 4.12 and 4.17), Anbari (2003), Ford et al. (2007), Manu et al. (2015), Rodrigues and Williams (1998), and Turner (2004).

Table 4.11 summarises a comparison of the two negative/balancing feedback loops shown in Figure 4.29. Project cost is the sum of all the costs incurred by the client throughout the project life cycle (Project Management Institute, 2017). Thus, the project cost for executing a typical engineering project is the sum of all the costs incurred by the client during project execution, and it includes the costs for project management services, engineering consultant services, and construction contractor works (including labour, material, equipment, and sub-contractors), among others. However, in this research study: only time-based contracts with a ceiling price (Turner, 2004) between the client and the engineering consultant were considered; and only the time-based costs for the engineering consultant services were considered for the project cost. Hence, the estimated project revenue to be realised by the engineering consultant at project completion was assumed to be equal to the estimated project cost to be incurred by the client at completion of the same project, i.e., Y = W, as shown in Table 4.11. The equations for the performance gaps to be closed by the negative feedback loops are in line with Sterman (2000), as discussed earlier in this sub-section.

Table 4.11: Client project cost control vs engineering consultant project revenue control

Feature	Client project cost control loop	Engineering consultant project revenue control loop
Common input	project contract ceiling price (Z)	
Differing inputs (individual project participant performance target)	client project cost variance % at completion target (a)	engineering consultant project contract ceiling price % target (b)
Effective negative feedback control loop performance target	client project cost at completion target (U); *U = (100 – a)Z*	engineering consultant project revenue at completion target (V); *V = bZ*
Negative feedback control loop actual/forecasted performance	estimated project cost at completion (W)	estimated engineering consultant project revenue at completion (Y); *Y=W*
Performance gap to be closed by the negative feedback control loop	estimated project cost overrun at completion (X); *X = W – U* *X = W – (100 – a)Z*	estimated engineering consultant project revenue shortfall at completion (T); *T = V – Y* *T = V – W* (since *Y = W)* *T = bZ – W*
Control action taken by the project participant	client project cost controls	engineering consultant project revenue controls
Unintended effect (positive/reinforcing loop)	Closing the gap (*X*) means decreasing *W* so that W = *(100 – a)Z* However, decreasing *W* increases *T (*a win-lose solution in favour of the client*)*, prompting engineering consultant project revenue controls.	Closing the gap (*T*) means increasing *W* so that W = *bZ* However, increasing *W* increases *X (*a win-lose solution in favour of the engineering consultant*)*, prompting client project cost controls.

On the one hand, the client takes appropriate project cost controls aimed at decreasing the project performance gap, *estimated project cost overrun at completion (X)*, by effectively first decreasing the *estimated project cost at completion (W)*. However, in the process, the *estimated engineering consultant project revenue shortfall at completion (T)* is increased by an amount equal to the increase in *W* (and *X*), assuming that *a*, *b* and *Z* are constant. That is, $W - \Delta W$ simultaneously leads to: $X - \Delta W$; and $T + \Delta W$. This is essentially a ‘win-lose’ solution in favour of the client. However, it prompts an unintended opposing reaction in the form of engineering consultant project revenue controls.

On the other hand, the engineering consultant takes appropriate project revenue controls aimed at decreasing his/her business performance gap, *T*, by effectively first increasing *W*. However, in the process, *X* is increased by an amount equal to the increase in *W* (and *T*), assuming that *a*, *b* and *Z* are constant. That is, $W + \Delta W$ simultaneously leads to: $T - \Delta W$ and $X + \Delta W$. This is essentially a 'win-lose' solution in favour of the engineering consultant. However, it prompts an unintended opposing reaction in the form of client project cost controls.

Hence, the two sets of project participant controls (client project cost controls and engineering consultant project revenue controls) are in conflict, and they reinforce each other's performance gap. Though the project controls of each project participant are often intendedly rational (Sterman, 2000), their mutually-exclusive and 'win-lose' solution orientation, coupled with the reactive project controls of the other project participant that are also mutually-exclusive and 'win-lose' solution orientated, effectively mean the use of competition (aimed at 'win-lose' end-results) as a conflict-handling style.

Indeed, Lyneis and Ford (2007), Mohammed et al. (2009), and Sutterfield et al. (2007) highlighted that the use of competition as a conflict-handling style is quite common among project participants during project execution, as each participant seeks to satisfy his/her own performance targets. Competition, as a conflict-handling style, is whereby one party seeks victory (win-lose) by exerting power, force, superior skill, aggression or domination at the expense of the other (Barki and Hartwick, 2001; Marques et al., 2015; Rahim, 2002; Schermerhorn et al., 2012).

4.9.3. Overall Project Participants Competition System Dynamics Conceptual Model

Project execution involves the rework cycle, according to Lyneis and Ford (2007), and Ford et al. (2007). Ford et al. (2007) investigated the impact of three engineering consultant / construction contractor project time schedule controls (overtime, work intensity, and adding more people) on project time schedule and cost. They found that the use of work intensity produced the largest amount of rework (Ford et al., 2007). Hence, including the (presumably engineering consultant) project time schedule control (work intensity) negative feedback loop of Ford et al. (2007) in Figure 4.29 yields the system dynamics causal loop diagram shown in Figure 4.30.

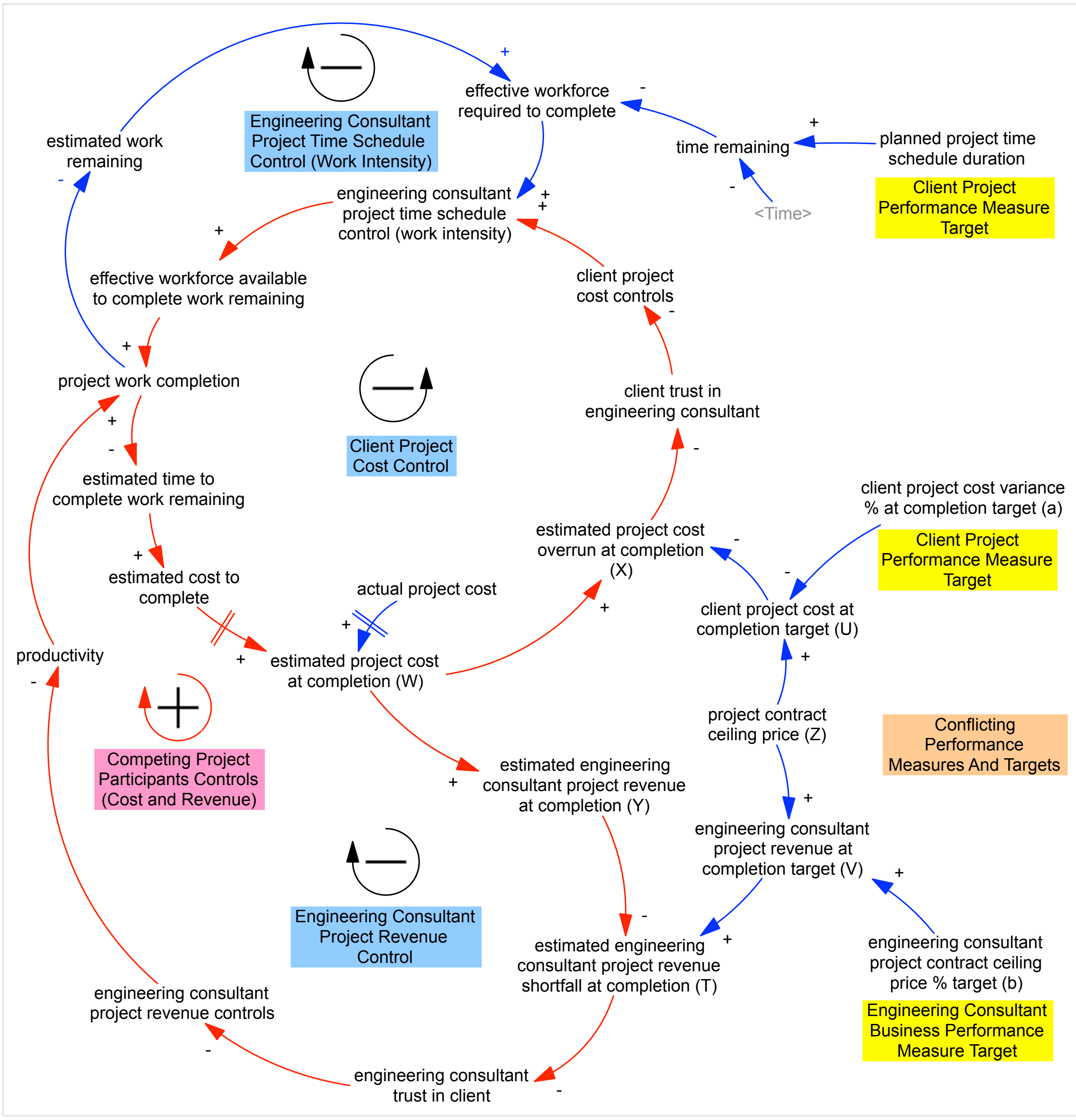


Figure 4.30: Competing client project cost control and engineering consultant project revenue control, and engineering consultant project schedule control

Source: Adapted from this research study (Figures 4.12 and 4.17), Anbari (2003), Ford et al. (2007), Manu et al. (2015), and Rodrigues and Williams (1998).

Integrating all the unintended effects of client project cost controls (Figure 4.12) and the unintended effect of engineering consultant project time schedule control (work intensity) (Ford et al., 2007) with Figure 4.30, yields the overall project participants (client and engineering consultant) competition system dynamics conceptual model shown in Figure 4.31. Noteworthy in Figure 4.31 is that 'client project cost controls' refers to the four client project cost controls (project progress reports, project progress meetings, project progress inspections, and delaying approval and payment of the engineering consultant's invoices) shown in Figure 4.12. Similarly, 'engineering consultant project revenue controls' refers to the two engineering consultant project revenue controls (project scope variation motivations and effort adjustment) shown in Figure 4.17.

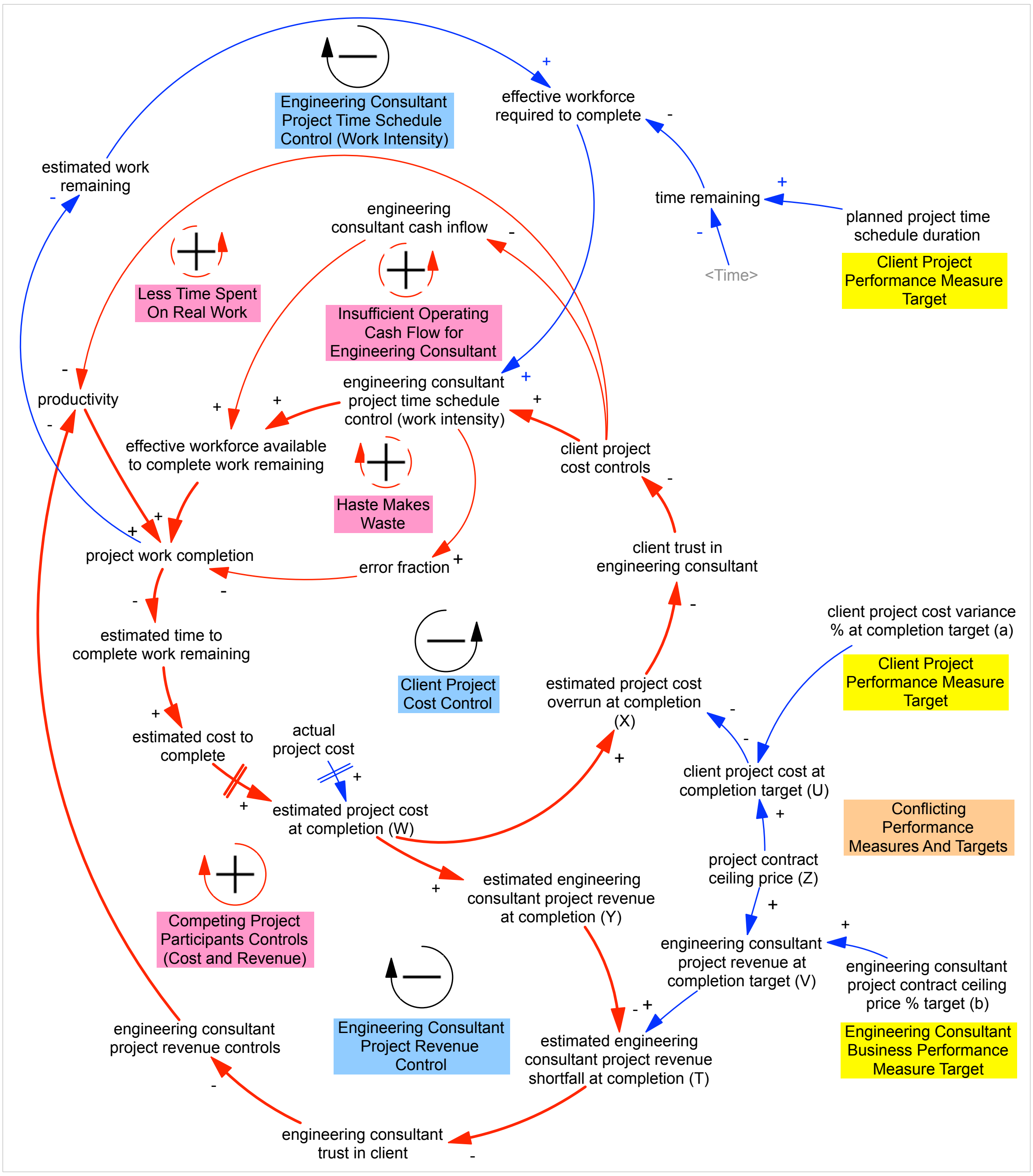


Figure 4.31: Overall project participants competition system dynamics conceptual model

Source: Adapted from this research study (Figures 4.12 and 4.17), Anbari (2003), Ford et al. (2007), Manu et al. (2015), and Rodrigues and Williams (1998).

The unintended effects (positive feedback loops) in Figure 4.31 can be grouped into three categories, as described next.

Unintended effect of engineering consultant time schedule control (work intensity):

- *Haste Makes Waste:* increases the project performance gap ('estimated project time schedule delay') that the engineering consultant project time schedule control (work intensity) intends to close/eliminate, as highlighted by Ford et al. (2007), and Lyneis and Ford (2007).

Unintended effects of the client project cost control:

- *Haste Makes Waste:* increases the project performance gap ('estimated project cost overrun at completion') that the client project cost controls intend to close/eliminate.
- *Less Time Spent on Real Work:* also increases the project performance gap ('estimated project cost overrun at completion').
- *Insufficient Operating Cash Flow for Engineering Consultant:* also increases the project performance gap ('estimated project cost overrun at completion').
- *Engineering Consultant Project Revenue Controls:* client project cost controls increase the engineering consultant project business performance gap ('estimated engineering consultant project revenue shortfall at completion'), prompting the engineering consultant to intensify the project revenue controls. This increases the project performance gap ('estimated project cost overrun at completion').

Unintended effects of the engineering consultant project revenue controls:

- *Client Project Cost Controls:* engineering consultant project revenue controls increase the project performance gap ('estimated project cost overrun at completion'), prompting the client to intensify project cost controls. This increases the engineering consultant project business performance gap ('estimated engineering consultant project revenue shortfall at completion') the engineering consultant project revenue controls intend to close/eliminate.

The key counterintuitive dynamic hypotheses presented in Figure 4.31 are:

- *the client project cost controls, which are aimed at reducing/eliminating the 'project cost overrun' by reducing the 'estimated project cost at completion' (a 'win-lose' control in favour of the client), tend to generate some unintended and counteractive consequences (unintended effects) that increase the 'estimated project cost at completion' and the 'project cost overrun';*
- *the engineering consultant project revenue controls, which are aimed at reducing/eliminating the 'project revenue shortfall' by increasing the 'estimated project cost at completion' (a 'win-lose' control in favour of the engineering consultant), tend to generate some unintended and counteractive consequence (unintended effect) that decreases the 'estimated project cost at completion' and increases the 'project revenue shortfall'; and*

- *the client project cost controls and the engineering consultant project revenue controls tend to oppose (compete with) each other, generating some unintended and counteractive consequences (unintended effects) that negatively influence both the project performance (increasing 'project time schedule delay' and 'project cost overrun') and the engineering consultant's project business performance (increasing 'project time schedule delay' and 'project revenue shortfall'). This is essentially a 'lose-lose' long-term result for the two key project participants.* It is the overall counterintuitive dynamic hypothesis presented in Figure 4.31.

As discussed in Chapter 3, the reviewed literature showed that: current project dynamics models are limited to project performance control actions of mainly the engineering consultant or construction contractor; and control actions taken by the client to protect project performance, as well as control actions taken by the engineering consultant and construction contractor to protect their individual business performance targets during project execution are sparingly covered. Also, no appropriate system dynamics project model could be identified, in the reviewed literature, that considers competition among project participants, with their different and competing performance measures and targets during project execution. Indeed, some scholars also called for research towards modelling (using system dynamics) of the competition among the different project participants (Lyneis and Ford, 2007).

Thus, the system dynamics conceptual shown in Figure 4.31 (formulated in this research study from a combination of existing literature, key findings from an embedded multiple-case study, and systems thinking) that captures the competing project controls (client project cost controls, and engineering consultant project revenue controls) of two key project participants (the client and the engineering consultant), with their different and competing performance measures and targets during project execution, contributes towards the filling of the abovementioned gaps in existing literature on project controls and application of system dynamics to both project performance and business performance. The abovementioned associated key counterintuitive dynamic hypotheses also provide new insights into the dynamic complexity of project controls and how the competition develops.

A provisional answer for research question number 1 posed in Section 1.6 is, thus, as follows:

<u>Research Question:</u>

1. *How can competition between two key project participants (client and engineering consultant) during project execution be conceptually modelled using systems thinking?*

Provisional Answer:

The competition between two key project participants (the client and the engineering consultant) during project execution, in the particular case of time-based contracts with a ceiling price, may be conceptually modelled using systems thinking (causal loop diagram) as shown in Figure 4.31. The competition arises from the use of conflicting performance measures and targets by the two participants, resulting in client project cost controls and engineering consultant project revenue controls that oppose (compete with) each other. The client project cost controls aim at reducing/eliminating the 'project cost overrun' by reducing the 'estimated project cost at completion' (a 'win-lose' control in favour of the client); whilst the engineering consultant project revenue controls aim at reducing/eliminating the 'project revenue shortfall' by increasing the 'estimated project cost at completion' (a 'win-lose' control in favour of the engineering consultant).

Though the project controls of each project participant are often intendedly rational, their mutually-exclusive and 'win-lose' solution orientation, coupled with the reactive project controls of the other project participant that are also mutually-exclusive and 'win-lose' solution orientated, effectively mean the use of competition (aimed at 'win-lose' end-results) as a conflict-handling style. Unintended effects of both the client project cost controls and the engineering consultant project revenue controls aggravate the competition.

4.10. Conclusion

This chapter focussed on the problem identification and definition, and system conceptualisation stages of the system dynamics modelling process recommended in the reviewed existing literature (Martinez-Moyano and Richardson, 2013; Sterman, 2000). System dynamics best-practices, such as those with regards to general graphical representation/visualization, variables naming convention, and structuring of negative and positive feedback loops, as recommended by such scholars as Ford et al. (2007), Lyneis and Ford (2007), Rahmandad and Sterman (2012), and Sterman (2000) were followed, as far as possible, in the formulation of all the system dynamics conceptual models presented in this chapter.

A system dynamics conceptual model for each of the four sets of project controls (client project time schedule controls, client project cost controls, engineering consultant project revenue controls, and engineering consultant project cash flow controls) and their associated unintended effects was formulated from a combination of: existing literature; key findings from an embedded multiple-case study that captured relevant mental models of client and engineering consultant project managers; and making use of causal loop diagrams (system dynamics' systems thinking tool). This helped to strengthen the validity of the formulated dynamic hypotheses and conceptual model, as recommended by Barlas (1996), Luna-Reyes and Andersen (2003), Martinez-Moyano and Richardson (2013), and Sterman (2000). The overall dynamic hypothesis represented by each of the four conceptual models was counterintuitive. For instance, that of the client project cost controls and associated unintended effects was that: *the client project cost controls, which are aimed at reducing/eliminating the 'project cost overrun' by reducing the 'estimated project cost at completion', tend to generate some unintended and counteractive consequences (unintended effects) that increase the 'estimated project cost at completion' and the 'project cost overrun'.*

Integrating the system dynamics conceptual models of client project cost controls (and their unintended effects) and engineering consultant project revenue controls (and their unintended effects), incorporating engineering consultant project time schedule control (work intensity) and its unintended effect as adapted from existing literature, yielded a system dynamics conceptual model of competition between two key project participants (client and engineering consultant) during project execution.

The conceptual model suggested that, in the particular case of time-based contracts with a ceiling price, the competition arises from the use of conflicting performance measures and targets by the two participants, resulting in client project cost controls and engineering consultant project revenue controls that oppose/conflict each other. The client project cost controls aim at reducing/eliminating the 'project cost overrun' by reducing the 'estimated project cost at completion' (a 'win-lose' control in favour of the client); whilst the engineering consultant project revenue controls aim at reducing/eliminating the 'project revenue shortfall' by increasing the 'estimated project cost at completion' (a 'win-lose' control in favour of the engineering consultant).

Though the project controls of each project participant are often intendedly rational, their mutually-exclusive and 'win-lose' solution orientation, coupled with the reactive project controls of the other project participant that are also mutually-exclusive and 'win-lose' solution orientated, effectively mean the use of competition (aimed at 'win-lose' end-results) as a conflict-handling style. Unintended effects of both the client project cost controls and the engineering consultant project revenue controls aggravate the competition.

These are essentially new insights into the dynamic complexity of project controls and how the competition develops, considering that no appropriate system dynamics project model could be identified, in the reviewed literature, that considered competition among project participants, with their different and competing performance targets during project execution. The conceptual model also provided a provisional answer to research question number 1, posed in Section 1.6, i.e., how the competition may be conceptually modelled using systems thinking. The overall counterintuitive dynamic hypothesis represented in the formulated system dynamics conceptual model of the project participants competition was that: *the client project cost controls and the engineering consultant project revenue controls tend to oppose (compete with) each other, generating some unintended and counteractive consequences (unintended effects) that negatively influence both the project performance (increasing 'project time schedule delay' and 'project cost overrun') and the engineering consultant's project business performance (increasing 'project time schedule delay' and 'project revenue shortfall'). This is essentially a 'lose-lose' long-term result for the two key project participants.* This dynamic hypothesis is further tested in Chapter 6.

In the next chapter, an appropriate system dynamics simulation model of the competition between the two key project participants is formulated.

5. Project Participants Competition System Dynamics Simulation Model (Quantitative Modelling)

5.1. Introduction

This chapter focusses on the simulation model formulation stage of the system dynamics modelling process recommended in the reviewed existing literature (Martinez-Moyano and Richardson, 2013; Sterman, 2000). It begins by highlighting the key assumptions made, and then proceeds to present an overview of the simulation model formulation process followed. It then highlights the boundary and the key subsystems of the system dynamics simulation model of the competition between the two key project participants (the client and the engineering consultant) during project execution. Then, the system dynamics simulation model is formulated and presented, subsystem by subsystem. Accordingly, the following research question, posed in Section 1.6, is addressed in this chapter:

2. *How can the competition between the two key project participants (client and engineering consultant) during project execution be quantitatively modelled (simulation model) using system dynamics?*

5.2. Model Assumptions

Key assumptions made in the formulation of the system dynamics simulation model presented in this chapter include:

- the model focussed only on project execution. All other project life cycle stages were excluded;
- only two key project participants (the client and engineering consultant) were considered. All other project participants and stakeholders were excluded;
- the only performance controls considered are: engineering consultant project time schedule control (only work intensity); engineering consultant project revenue controls; and client project cost controls. Any other performance controls were excluded; and
- only time-based contracts with a ceiling price (Turner, 2004) between the client and the engineering consultant were considered, with only the time-based costs for engineering consultant services considered for project cost.

5.3. Simulation Model Formulation Overview

5.3.1 Simulation Model Formulation and Best Practices

In this chapter, the system dynamics conceptual model of competition between two key project participants (the client and the engineering consultant), formulated in the preceding chapter and presented in Figure 4.31 (Section 4.9.3), is converted to an appropriate system dynamics simulation model using Vensim DSS software (Ventana Systems, 2018) by: developing appropriate model graphical representations (stocks and flows, and feedback loops); specifying mathematical equations for the relationships among the different model variables and constants (parameters), ensuring dimensional consistency in all equations; and specifying initial conditions, where applicable, as recommended by Martinez-Moyano and Richardson (2013) and Sterman (2000).

The system dynamics conceptual model presented in Figure 4.31 has three groups of project controls, namely: engineering consultant project time schedule control; client project cost control; and engineering consultant project revenue control. In this chapter, these three groups of controls (negative feedback loops) and their associated unintended effects (positive feedback loops) are converted to appropriate system dynamics simulation model subsystems in Sections 5.6, 5.7 and 5.8, respectively.

System dynamics best-practices, similar to those followed in the preceding chapter, such as those with regards to general graphical representation/visualization, variables naming convention, and structuring of negative and positive feedback loops, as recommended by such scholars as Ford et al. (2007), Lyneis and Ford (2007), Rahmandad and Sterman (2012), and Sterman (2000) were followed, as far as possible, in the formulation of the system dynamics simulation model presented in this chapter. In addition, best-practices guidelines for reporting system dynamics simulation models recommended to enhance reproducibility of the research results by Rahmandad and Sterman (2012) were also adopted in this chapter.

The system dynamics simulation model presented in this chapter was formulated using Vensim DSS for Macintosh Version 6.4E software (Ventana Systems, 2018) installed on an Apple MacBook Pro 13-inch 2014 laptop with an Intel Core i5 CPU at 2.6 GHz, with a 64-bit macOS High Sierra Version 10.13.6 operating system and 8 GB of RAM.

5.3.2 Use of Subscripts to Cater for Multiple Projects

The system dynamics simulation model formulated in this chapter was calibrated with and simulated using a total of 18 unique projects belonging to two types of raw water infrastructure projects (asset management planning and support-related, made up of 10 projects; and asset renewal-related, made up of 8 projects), as discussed in the next chapter. Only one system dynamics simulation model was formulated for all the 18 projects, instead of formulating multiple system dynamics simulation models (one for each project). This was made possible through the use of the ‘Subscripts’ module in Vensim DSS software. A ‘subscript’ makes it possible for one variable, parameter or equation to represent multiple different instances, such as projects (Ventana Systems, 2018). The subscript used in the system dynamics simulation model formulated in this chapter was named ‘project’. Each project was assigned a code: P0 to P9 for the 10 asset management planning and support-related projects; and P10 to P17 for the 8 asset renewal-related projects.

The ‘project’ subscript was set and used for all project-specific variables and parameters (and then used in the associated equations). Once the ‘project’ subscript was set for a project-specific variable or parameter, Vensim software then automatically appended the subscript in square brackets to the variable or parameter name; for instance, *initial project scope[project].* The project code was then used to refer to the variable or parameter name of a particular project; for instance, *initial project scope[P10].*

Regular variable and parameter names were used for non-project-specific variables and parameters; for instance, *TIME STEP* and *Project Payoff Weight.*

5.3.3 Use of Microsoft Excel for Exogenous Variables and Constants

The values of all the model parameters (both project-specific and non-project-specific) and time-series data gathered in this research study were captured in a Microsoft Excel file named ‘Project Participants Competition Model Parameters.xlsx’, under a sheet named ‘Input’. Functions in Vensim software were used to read the parameters and data series directly from the Microsoft Excel spreadsheet into the system dynamics simulation model. The functions used included *GET XLS SUBSCRIPT('file','tab',firstcell,'lastcell', 'prefix'),* GET XLS CONSTANTS ('file','tab','cell'), and *GET XLS DATA('file','tab','time row or col','cell')* (Ventana Systems, 2018).

As an example, the equation *initial project scope[project] = GET XLS CONSTANTS ('Project Participants Competition Model Parameters.xlsx', 'Input', 'C4')* was used to read the values of the parameter *initial project scope* for all the projects, starting with the value of the first project (P0) located in cell ‘C4’ (and going across the row for values of the other projects) of a sheet named *‘Input’* in the Microsoft Excel file named ‘*Project Participants Competition Model Parameters.xlsx''* located in the same folder as the system dynamics simulation model.

5.4. System Dynamics Simulation Model Boundary

A model boundary chart (that indicates which key variables are endogenous, exogenous, or excluded) assists in clearly defining the scope of a simulation model (Sterman, 2000). Table 5.1 shows the model boundary chart for the system dynamics simulation model formulated in this research study.

Table 5.1: Project participants competition simulation model boundary chart

Endogenous	Exogenous	Excluded
Client project cost control actions	client project cost variance % at completion target	Client project time schedule controls
Unintended effects of client project cost control actions	Client project cost control actions policies	
	Client project cost control actions adjustment delays	
Engineering consultant project revenue control actions	engineering consultant project contract ceiling price % target	Engineering consultant project cash flow controls
Unintended effects of engineering consultant project revenue control actions	engineering consultant project revenue control actions policies	
	engineering consultant project revenue control actions adjustment delays	
engineering consultant project time schedule control (only work intensity)		Other engineering consultant project time schedule controls (such as overtime; adding more people)
	initial project contract ceiling price	Other project stakeholders (other than client and engineering consultant) control actions and unintended effects thereof
	additional project contract price (data series)	
	initially planned project time schedule duration	
	additional project time schedule duration (data series)	
	initial project scope	
	additional project scope (data series)	
	Actual Project Time Schedule Duration	
	Actual Project Cost	
	actual engineering consultant project revenue (data series)	
	actual engineering consultant project cash inflow (data series)	
	base error fraction	
	normal productivity	
	average workforce unit cost	

The client project time schedule controls, and the engineering consultant project cash flow controls were excluded from system dynamics simulation model of competition between the client and the engineering consultant, formulated in this chapter, as they did not form part of the associated system dynamics conceptual model presented in Figure 4.31.

Table 5.2 shows the subsystems for the system dynamics simulation model formulated in this research study.

Table 5.2: Project participants competition simulation model subsystems

Subsystem	Purpose	Applicable section of this thesis
Project Work Flow and Remaining Work Estimation	Captures the project rework cycle, including the original work to do, undiscovered rework, rework to do, work done correctly, the total work done and percentage of work completed. It also includes estimation of remaining work.	5.5
Engineering consultant project time schedule control (work intensity) and its unintended effect	Captures one corrective control action (work intensity) as a negative feedback loop, and its unintended effect (haste makes waste) as a positive feedback loop, both adapted from existing literature, taken by engineering consultant project managers when a project is, or is forecasted to be, behind time schedule during project execution.	5.6
Client project cost controls and their unintended effects	Captures three corrective control actions (demand for more progress reports, demand for more progress meetings, and invoice approval and payment delay) as negative feedback loops, and their associated four unintended effects (haste makes waste, less time spent on real work, insufficient operating cash flow for the engineering consultant, and engineering consultant project revenue controls) as positive feedback loops, taken by client project managers when a project is, or is forecasted to be, above cost budget during project execution.	5.7
Engineering consultant project revenue controls and their unintended effects	Captures two corrective control actions (effort adjustment and project scope motivations) as negative feedback loops, and their associated unintended effect (client project cost controls) as a positive feedback loop, taken by engineering consultant project managers when they experience or forecast a project revenue shortfall during project execution.	5.8
Model Calibration	Captures the payoff functions used during the model calibration process.	6.4.2 and 6.5.2
Policy Optimisation	Captures the payoff function used during the policy optimisation process.	6.8.1

The next four sections present more details about each of the first four subsystems (noted in Table 5.2) of the system dynamics simulation model, respectively. The last two subsystems (model calibration and policy optimisation) focus on the testing and validation of the first four subsystems; as such, they are covered in the next chapter (Sections 6.4, 6.5 and 6.8). For all the detailed system dynamics simulation model equations, refer to Appendix E.

5.5. Project Work Flow and Remaining Work Estimation

5.5.1 Project Work Flow (Rework Cycle)

Model Structure Visualisation (Stock and Flow Diagram)

Figure 5.1 shows a graphical representation, stock and flow diagram (SFD), of the project work flow (rework cycle), which captures the 'error fraction' and part of the 'project work completion' shown in the system dynamics conceptual model presented in Figure 4.31, as adapted from Ford et al. (2007). In Figure 5.1 (and all the subsequent graphical representations in this chapter): rectangles represent levels (stocks), and valves represent flow rates in line with system dynamics standards for SFDs (Sterman, 2000); model parameters are presented in green italic font; auxiliary variables are presented in black lower-case font; and shadow variables (for stocks, rates, auxiliaries or parameters) are in grey font.

Some of the key improvements made, in this research study, to the project rework cycle SFD of Ford et al. (2007) include: the inclusion of the 'Work Released With Errors' stock and its associated 'incorrectly approve' flow, as shown in Figure 5.1; and the use of subscripts to cater for multiple projects, as discussed in Section 5.3.2.

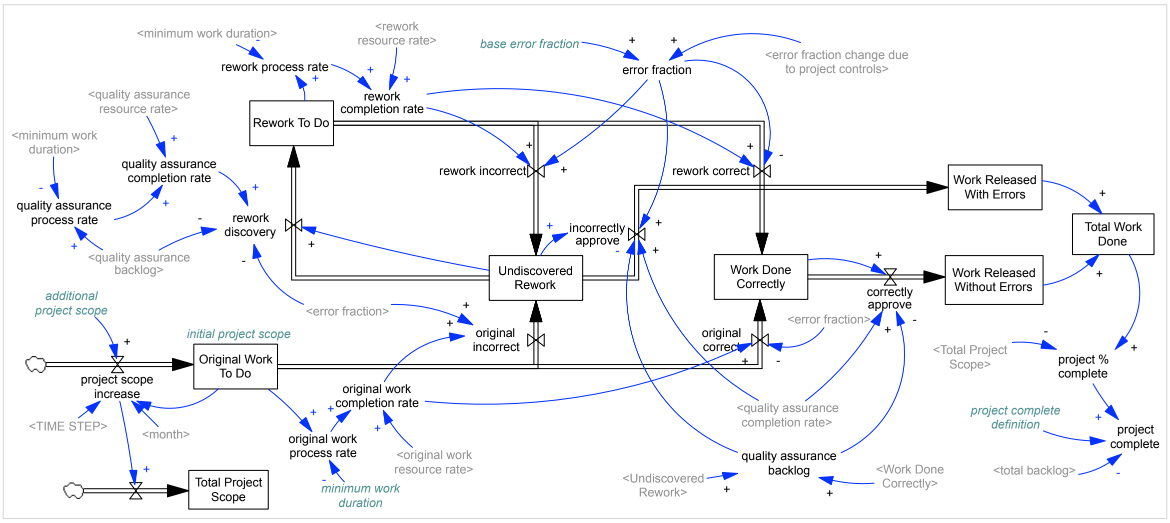


Figure 5.1: Graphical representation of the project work flow (rework cycle)

Source: Adapted from Ford et al. (2007)

Model Equations

According to Sterman (2000), in system dynamics, every stock integrates the net inflow rate (i.e., the difference between its inflow rates and its outflow rates), starting from a specified initial level; and equation $A(t) = A(0) + \int_0^t B(s)ds$ is the same as the more simplified equation *A = INTEG(B, A(0))* where A is the stock level, A(0) is the initial stock level, and B is the net inflow rate. Vensim software uses the more simplified equation for stocks, and the rest of this chapter also uses the same.

The values of all the model parameters (both project-specific and non-project-specific) and time-series data gathered in this research study were specified in a Microsoft Excel file named 'Project Participants Competition Model Parameters.xlsx', under a sheet named 'Input', as discussed in Section 5.3.3.

Table 5.3 shows some of the key equations related to the project work flow (rework cycle).

Table 5.3: Key model equations for the project work flow (rework cycle)

Formulations and comments	Units
Original Work To Do[project] = INTEG((project scope increase[project]-original correct[project]-original incorrect[project]), initial project scope[project]); *initial project scope[project] = GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C4')* The stock of *Original Work To Do* tasks increases as additional project scope is added and declines as project tasks are originally completed (both correctly and incorrectly). The value of the *initial project scope* is read from cell *'C4'* (for the first project, and across the row for the subsequent projects) of a sheet named *'Input'* in the Microsoft Excel spreadsheet named '*Project Participants Competition Model Parameters.xlsx''* located in the same folder as the system dynamics simulation model, as described in Section 5.3.3.	Tasks Tasks
original work process rate[project] = Original Work To Do[project]/minimum work duration The *original work process rate* is the average rate at which the *Original Work To Do* is completed (assuming unlimited project workforce is available). It is the *Original Work To Do* spread over the minimum time required to originally complete a project task if everything else required is available.	Tasks/Month
original work completion rate[project] = MIN(original work resource rate[project], original work process rate[project]) The *original work completion rate* is the effective rate at which the stock of *Original Work To Do* tasks declines. It is the rate at which project tasks are originally completed (both correctly and incorrectly), and is equal to the minimum of the *original work resource rate* and the *original work process rate.*	Tasks/Month
*original incorrect[project] = original work completion rate[project]*error fraction[project]* The *original incorrect* is the rate at which project tasks are originally completed incorrectly (i.e. with errors) and moved to the stock of *Undiscovered Rework* tasks.	Tasks/Month
original correct[project] = original work completion rate[project](1-error fraction[project])* The *original correct* is the rate at which project tasks are originally completed correctly (i.e. without any errors) and moved to the stock of *Work Done Correctly* tasks. The sum of the *original incorrect* and *original correct* rates is equal to the *original work completion rate.*	Tasks/Month

Formulations and comments	Units
Undiscovered Rework[project] = INTEG((original incorrect[project]+rework incorrect[project]-incorrectly approve[project]-rework discovery[project]), 0) The stock of *Undiscovered Rework* tasks increases as project tasks are originally completed incorrectly (i.e. with errors) and when project tasks are reworked incorrectly (i.e. with errors). It declines as project tasks requiring rework are discovered and moved to the stock of *Rework To Do* tasks, and when project tasks requiring rework are erroneously/incorrectly approved and moved to the stock of *Work Released With Errors* tasks. At the beginning of the project, the stock of *Undiscovered Rework* tasks is empty.	Tasks
Work Done Correctly[project] = INTEG((original correct[project]+rework correct[project]-correctly approve[project]), 0) The stock of *Work Done Correctly* tasks increases as project tasks are originally completed correctly (i.e. without any errors) and when project tasks are reworked correctly (i.e. without errors). It declines as project tasks completed correctly are approved and moved to the stock of *Work Released Without Errors* tasks. At the beginning of the project, the stock of *Work Done Correctly* tasks is empty.	Tasks

5.5.2 Remaining Project Work Estimation

Model Structure Visualisation (Stock and Flow Diagram)

Figure 5.2 shows a graphical representation (stock and flow diagram) for remaining project work estimation, which captures part of the ‘Engineering Consultant Project Time Schedule Control (Work Intensity)’ negative feedback loop (from ‘project work completion’ to ‘effective workforce required to complete’ the estimated work remaining) shown in the system dynamics conceptual model presented in Figure 4.31. The causal relationships from ‘Estimated Work Remaining) to ‘effective workforce required to complete’ were adopted from Ford et al. (2007).

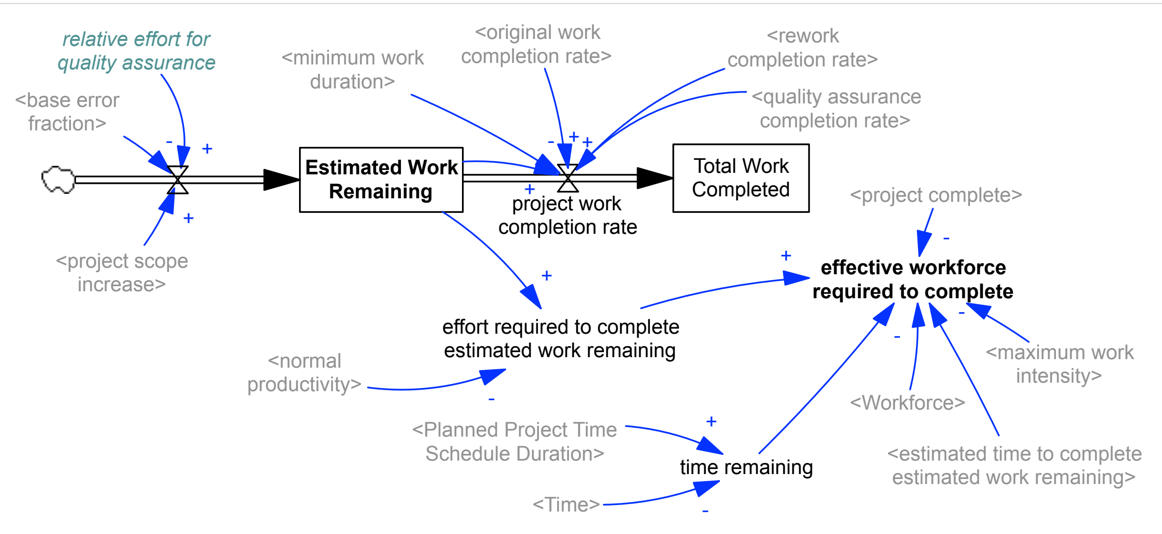


Figure 5.2: Graphical representation of remaining project work estimation

Source: Adapted from: Ford et al. (2007)

Model Equations

Table 5.4 shows some of the key equations related to the remaining project work estimation subsystem.

Table 5.4: Key model equations for remaining project work estimation

Formulations and comments	Units
Estimated Work Remaining[project] = INTEG(((project scope increase[project](1+relative effort for quality assurance[project])/(1-base error fraction[project]))-project work completion rate[project]), (initial project scope[project]*(1+relative effort for quality assurance[project])/(1-base error fraction[project]))* The stock of *Estimated Work Remaining* tasks contains the tasks that still needs to be completed, taking into consideration quality assurance as well. It increases as additional project scope is added and declines as project tasks are completed.	Tasks
project work completion rate[project] = MIN((original work completion rate[project]+rework completion rate[project]+quality assurance completion rate[project]), (Estimated Work Remaining[project]/minimum work duration)) The *project work completion rate* is the minimum between: the sum of the *original work completion rate, rework completion rate* and *quality assurance completion rate*; and average rate at which the *Estimated Work Remaining stock* is depleted (assuming unlimited project workforce is available).	Tasks/Month
Total Work Completed[project] = INTEG(project work completion rate[project], 0) The *Total Work Completed* stock accumulates the *project work completion rate.*	Tasks
effort required to complete estimated work remaining[project] = Estimated Work Remaining[project]/normal productivity[project] The *effort required to complete estimated work remaining* is determined based on the normal productivity of the project workforce.	person*Month
*effective workforce required to complete[project] = MIN(XIDZ(effort required to complete estimated work remaining[project], time remaining[project], ZIDZ(effort required to complete estimated work remaining[project], estimated time to complete estimated work remaining[project])), (Workforce[project]*maximum work intensity[project]))*(1-project complete[project])* The effective project workforce required to complete the estimated work remaining on the project is dependent on the time remaining or estimated time to complete and is limited by the maximum pressure (work intensity) that can be applied to the project workforce.	person

5.6. Engineering Consultant Project Time Schedule Control and its Unintended Effect

5.6.1 Control (Negative Feedback Loop)

Model Structure Visualisation (Stock and Flow Diagram, and Causal Loops)

As discussed in Section 5.6, Figure 5.1 and 5.2 are graphical representations of part of the 'Engineering Consultant Project Time Schedule Control (Work Intensity)' negative feedback loop (from 'project work completion' to 'effective workforce required to complete' the estimated work remaining) shown in the system dynamics conceptual model presented in Figure 4.31. Figure 5.3 is a graphical representation of the remaining part of the said negative feedback loop, which captures the 'engineering consultant project time schedule control (work intensity)' and 'effective workforce available to complete work remaining' shown in Figure 4.31, as adapted from Ford et al. (2007). In Figure 5.3, key changes made (in this study) to the model of Ford et al. (2007) were the inclusion of the 'total change in work intensity due to client project cost controls', 'change in workforce due to cash flow deficit', 'total change in productivity due to client project cost controls', and 'total change in productivity due to engineering consultant project revenue controls' variables.

In system dynamics causal loop diagrams, such as that shown in Figure 5.3, arrows and their polarity (+/-) indicate causal relationships (positive or negative influences) between the two variables they link together; and short circular arrows (almost a circle) with polarity (+/-) at their centres show the direction (clockwise/anticlockwise) and polarity (positive/negative) of the causal loop (Sterman, 2000).

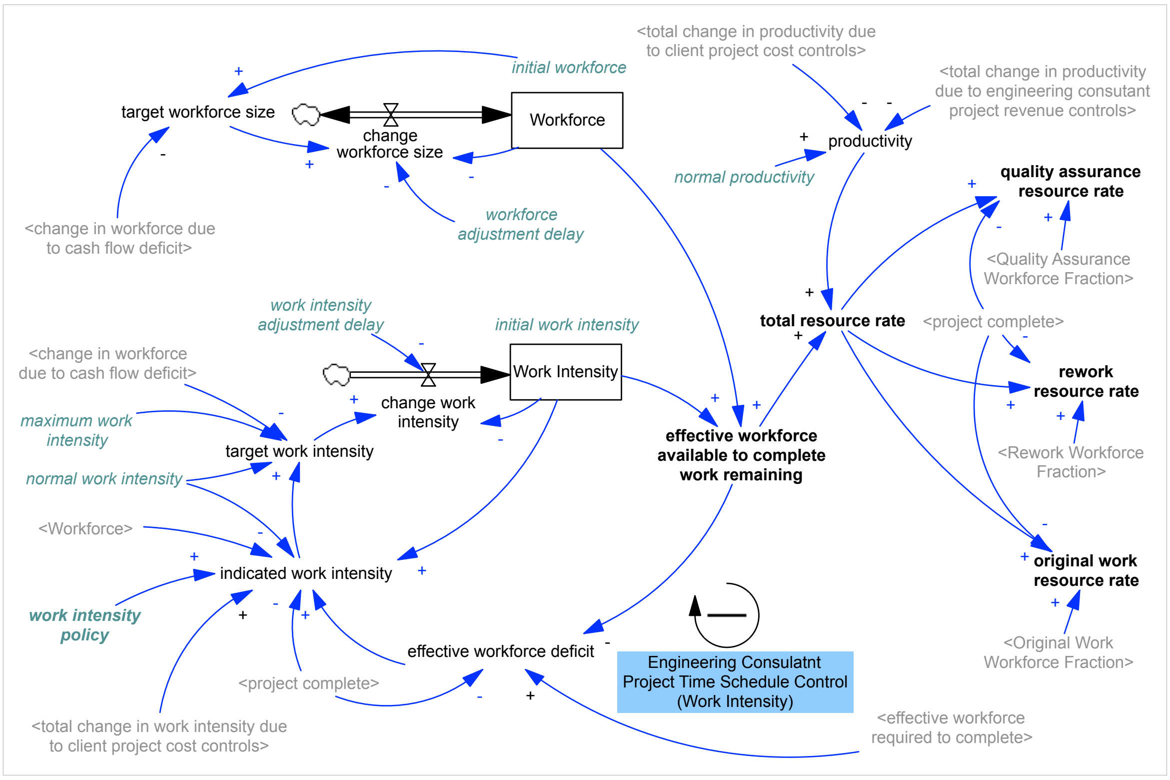


Figure 5.3: Graphical representation of engineering consultant project time schedule control (work intensity) negative feedback loop

Source: Adapted from Ford et al. (2007).

Model Equations

Table 5.5 shows some of the key equations related to the engineering consultant project time schedule control (work intensity) negative feedback loop.

Table 5.5: Key model equations for the engineering consultant project time schedule control (work intensity) negative feedback loop

Formulations and comments	Units
Workforce[project] = INTEG(change workforce size[project], initial workforce[project]); *change workforce size[project] = (target workforce size[project]-Workforce[project])/workforce adjustment delay;* *initial workforce[project] = GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C7')* The stock of project *Workforce* accumulates the *change workforce size* rate. The value of the *initial workforce* size is read from cell *'C7'* (for the first project, and across the row for the subsequent projects) of a sheet named *'Input'* in the Microsoft Excel spreadsheet named '*Project Participants Competition Model Parameters.xlsx''* located in the same folder as the system dynamics simulation model, as described in Section 5.3.3.	persons 1/Month persons
Work Intensity[project] = INTEG(change work intensity[project], initial work intensity[project]); *change work intensity[project] = (target work intensity[project]-Work Intensity[project])/work intensity adjustment delay;* *initial work intensity[project] = GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C60')* The stock of *Work Intensity* (pressure applied on the project workforce to work faster) accumulates the *change work intensity* rate. The value of the *initial work intensity* is read from cell *'C60'* (for the first project, and across the row for the subsequent projects) of a sheet named *'Input'* in the Microsoft Excel spreadsheet named '*Project Participants Competition Model Parameters.xlsx''* located in the same folder as the system dynamics simulation model, as described in Section 5.3.3.	Dimensionless 1/Month Dimensionless
*effective workforce available to complete work remaining[project] = Workforce[project]*Work Intensity[project]* The higher the *effective workforce available to complete work remaining* the higher the total resource rate at which original work, rework and quality assurance tasks are completed, and the lower the effective project workforce deficit.	persons
effective workforce deficit[project] = MAX(0, (effective workforce required to complete[project]-effective workforce available to complete work remaining[project]))(1-project complete[project])* The *effective workforce deficit* influences the amount of work intensity (pressure applied on the project workforce to work faster).	persons
productivity*[project] = MAX(0, (normal productivity[project]-total change in productivity due to client project cost controls[project]-total change in productivity due to engineering consultant project revenue controls[project]))* The average project workforce productivity is decreased from normal average productivity by the negative impacts of client project cost controls and engineering consultant project revenue controls.	Tasks/Month/ person

Formulations and comments	Units
*total resource rate[project] = effective workforce available to complete work remaining[project]*productivity[project]* The *total resource rate* is overall rate at which original work, rework and quality assurance tasks are completed, based on the effective project workforce available and the average project workforce productivity.	Tasks/Month
*original work resource rate[project] = Original Work Workforce Fraction[project]*total resource rate[project]*(1-project complete[project]);* *rework resource rate[project] = Rework Workforce Fraction[project]*total resource rate[project]*(1-project complete[project]);* *quality assurance resource rate[project] = Quality Assurance Workforce Fraction[project]*total resource rate[project]*(1-project complete[project]);* The *total resource rate* is split into three to give the rates at which original work, rework and quality assurance tasks are completed (based on the effective project workforce available), depending on the sizes of the original work, rework and quality assurance backlogs.	Tasks/Month Tasks/Month Tasks/Month

5.6.2 Unintended Effect (Positive Feedback Loop)

Model Structure Visualisation (Causal Loop Diagram)

Figure 5.4 shows a graphical representation of the unintended effect ('haste makes waste' positive feedback loop) of the engineering consultant project time schedule control (work intensity), as adapted from Ford et al. (2007) (the only changes made in this research study were variable naming, and the use of subscripts to cater for multiple projects, as discussed in Section 5.3.2).

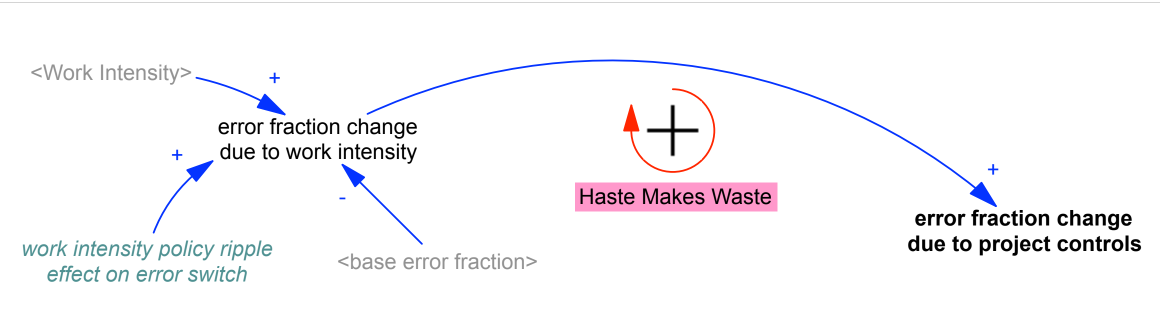


Figure 5.4: Graphical representation of the unintended effect of engineering consultant project time schedule control (work intensity)

Source: Adapted from Ford et al. (2007).

Model Equations

Table 5.6 shows the key equations related to the unintended effect (haste makes waste) of engineering consultant project time schedule control (work intensity).

Table 5.6: Key model equations for the unintended effect of engineering consultant project time schedule control (work intensity)

Formulations and comments	Units
error fraction change due to work intensity*[project] = (1-base error fraction[project])*(ZIDZ((Work Intensity[project]-1), Work Intensity[project]))* work intensity policy ripple effect on error switch;*	Dimensionless
error fraction change due to project controls[project] = error fraction change due to work intensity[project]	Dimensionless
The use of too much work intensity (applying too much pressure on the project workforce to work faster) increases the amount of errors in project deliverables.	

5.7. Client Project Cost Controls and their Unintended Effects

5.7.1 Project Performance

Model Structure Visualisation (Stock and Flow Diagrams)

Figures 5.5 and 5.6 show stock and flow diagrams for the two project performance measures (project time duration and cost, respectively) used in this research study. They cover the ‘planned project time schedule duration’ (Figure 5.5), and the ‘client project cost variance % at completion target’ and ‘client project cost at completion target (U)’ (Figure 5.6) shown in the system dynamics conceptual model presented in Figure 4.31. They also include the actual project time duration and cost, as well as the project time schedule and cost performance indices, respectively.

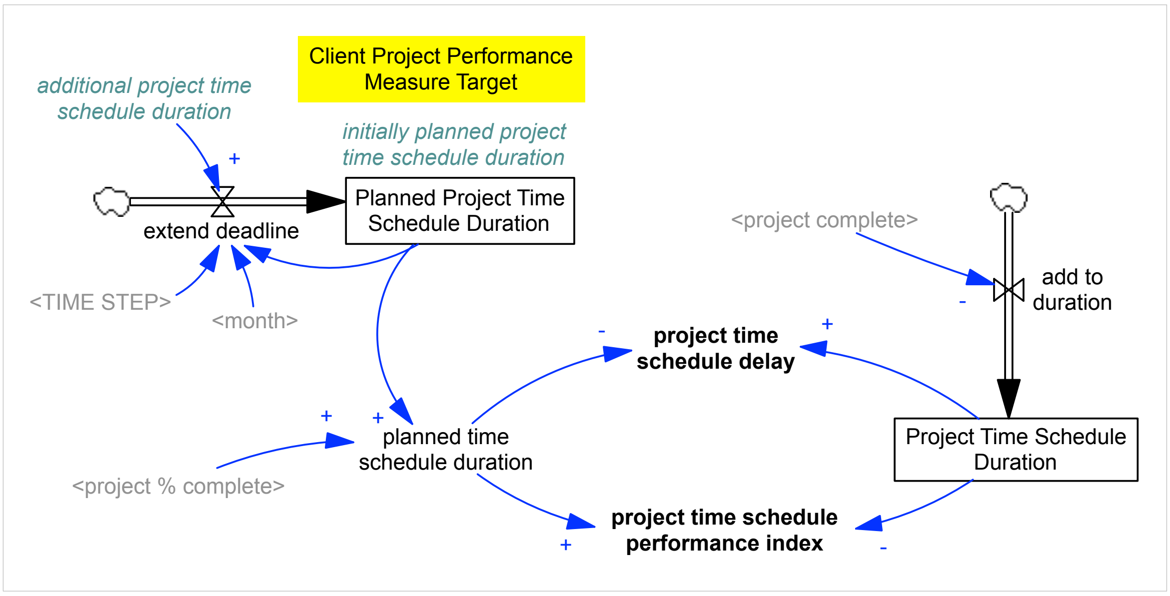


Figure 5.5: Graphical representation of project performance measure (project time duration)

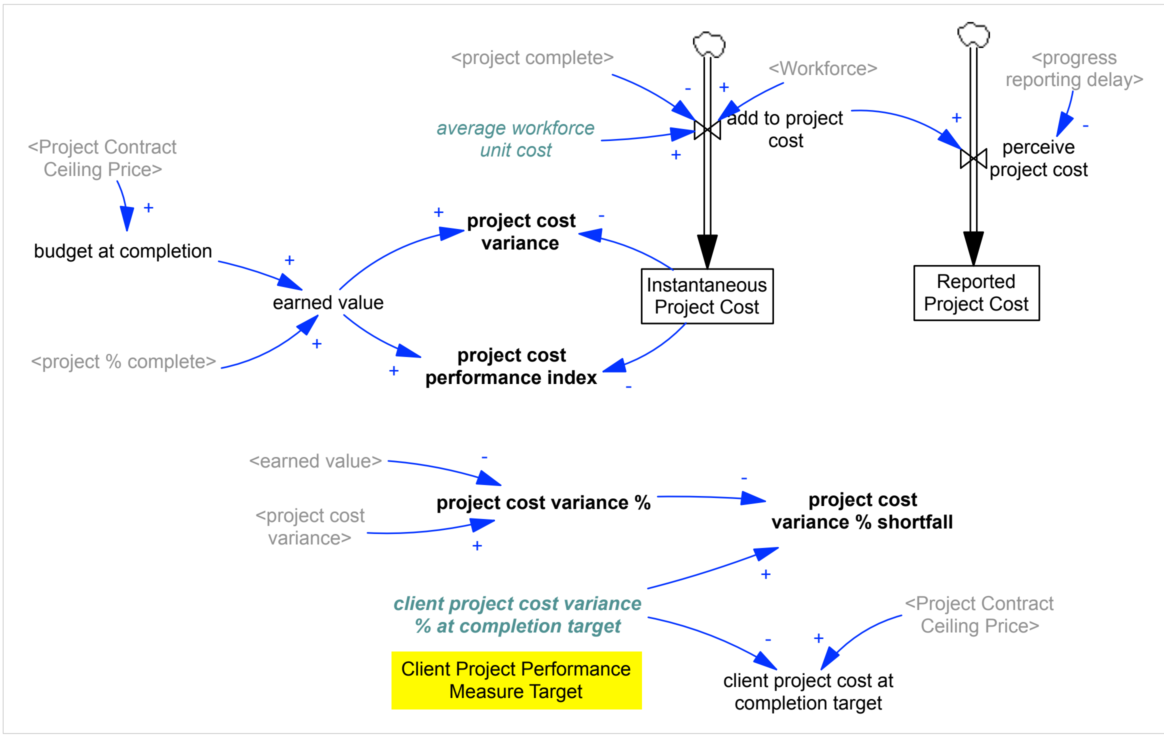


Figure 5.6: Graphical representation of project performance measure (project cost)

Model Equations

Table 5.7 shows some of the key equations related to the two key project performance measures used in this research study, namely project time schedule duration and project cost.

Table 5.7: Key model equations for the project performance measures

Formulations and comments	Units
Planned Project Time Schedule Duration[project] = INTEG(extend deadline[project], initially planned project time schedule duration[project]); *initially planned project time schedule duration[project] = GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C5')* The stock of *Planned Project Time Schedule Duration* increases as project deadline extensions are approved. The value of the *initially planned project time schedule duration* (one of the key client project performance targets) is read from cell *'C5'* (for the first project, and across the row for the subsequent projects) of a sheet named *'Input'* in the Microsoft Excel spreadsheet named '*Project Participants Competition Model Parameters.xlsx"* located in the same folder as the system dynamics simulation model, as described in Section 5.3.3.	Month Month
Project Time Schedule Duration[project] = INTEG(add to duration[project], 0); *add to duration[project] = 1-project complete[project]* The stock of *Project Time Schedule Duration* accumulates the actual project time duration, until the project is completed.	Month Dimensionless

Formulations and comments	Units
Instantaneous Project Cost[project] = INTEG(add to project cost[project], 0); *add to project cost[project] = (average workforce unit cost[project]* Workforce[project])*(1-project complete[project])* The stock of *Instantaneous Project Cost* accumulates the actual instantaneous project cost, until the project is completed. It differs from the *Reported Project Cost* due to measurement and reporting delays.	R R
client project cost at completion target[project] = Project Contract Ceiling Price[project](1-"client project cost variance % at completion target"[project]);* *client project cost variance % at completion target[project] = GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C9')* The value of the *client project cost variance % at completion target* (one of the key client project performance targets) is read from cell *'C9'* (for the first project, and across the row for the subsequent projects) of a sheet named *'Input'* in the Microsoft Excel spreadsheet named '*Project Participants Competition Model Parameters.xlsx''* located in the same folder as the system dynamics simulation model, as described in Section 5.3.3. It influences the *client project cost at completion target.*	R Dimensionless

5.7.2 Controls (Negative Feedback Loops)

This subsection presents the graphical representations (stock and flow diagrams, and causal loops) and associated key model equations for the 'Client Project Cost Control' negative feedback loop shown in the system dynamics conceptual model presented in Figure 4.31. As indicated in Section 4.9.3, 'client project cost controls' in Figure 4.31 refers to the four client project cost controls (project progress reports, project progress meetings, project progress inspections, and delaying approval and payment of the engineering consultant's invoices) shown in Figure 4.12.

Model Structure Visualisation (Stock and Flow Diagrams, and Causal Loops)

Figures 5.7 to 5.9 show the graphical representations for three client project cost controls (demand for more progress reports, demand for more progress meetings, and invoice approval and payment delay, respectively), as negative feedback loops, in line with Figures 4.12 and 4.31. Progress inspections demand was excluded from the simulation model as only a few (total of 4) client inspections were conducted on only 2 projects from which the data for the second stage of the study was gathered.

Noteworthy in Figures 5.7 to 5.9 (and other figures in the rest of this chapter) is that some key variables (defined, including their causal influences, in separate views of the simulation model in the Vensim DSS software) were included as stand-alone shadow variables only for the purposes of indicating how the associated loop is constructed. For instance, the '<Work Intensity>' and '<effective workforce available

to complete work remaining>' shadow variables are included in Figure 5.7 simply to show how the 'Client Project Cost Control (Progress Reports)' negative feedback loop is completed, but they are defined in a separate view as shown in Figure 5.3.

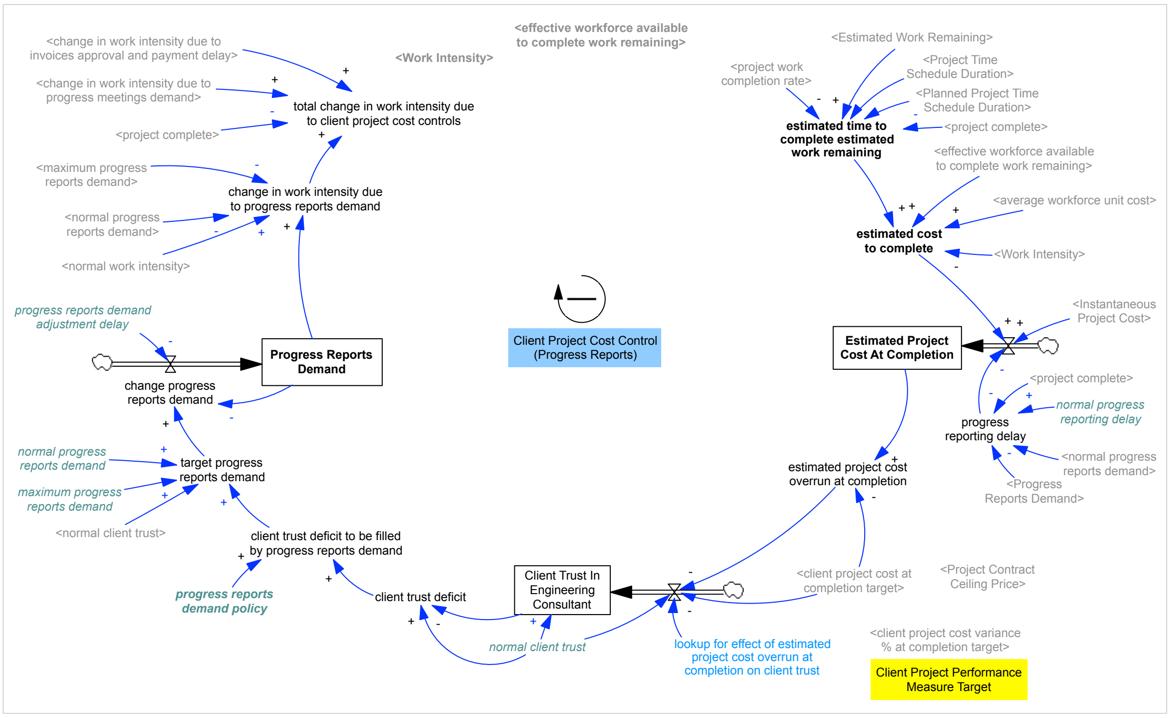


Figure 5.7: Graphical representation of client project cost control (progress reports demand)

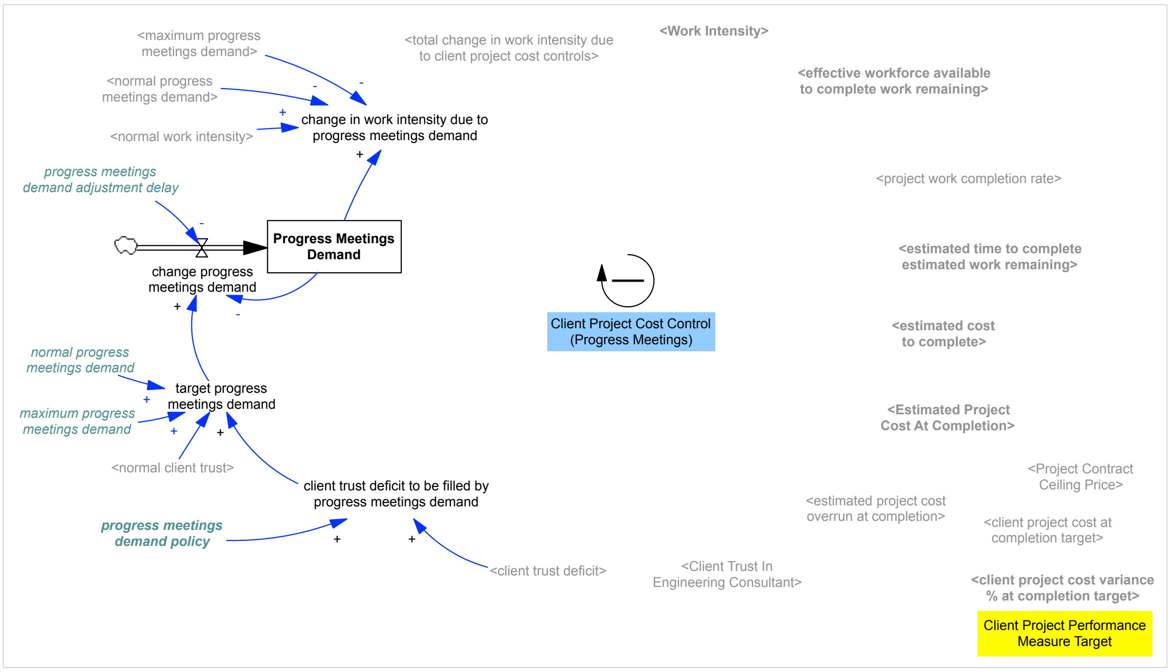


Figure 5.8: Graphical representation of client project cost control (progress meetings demand)

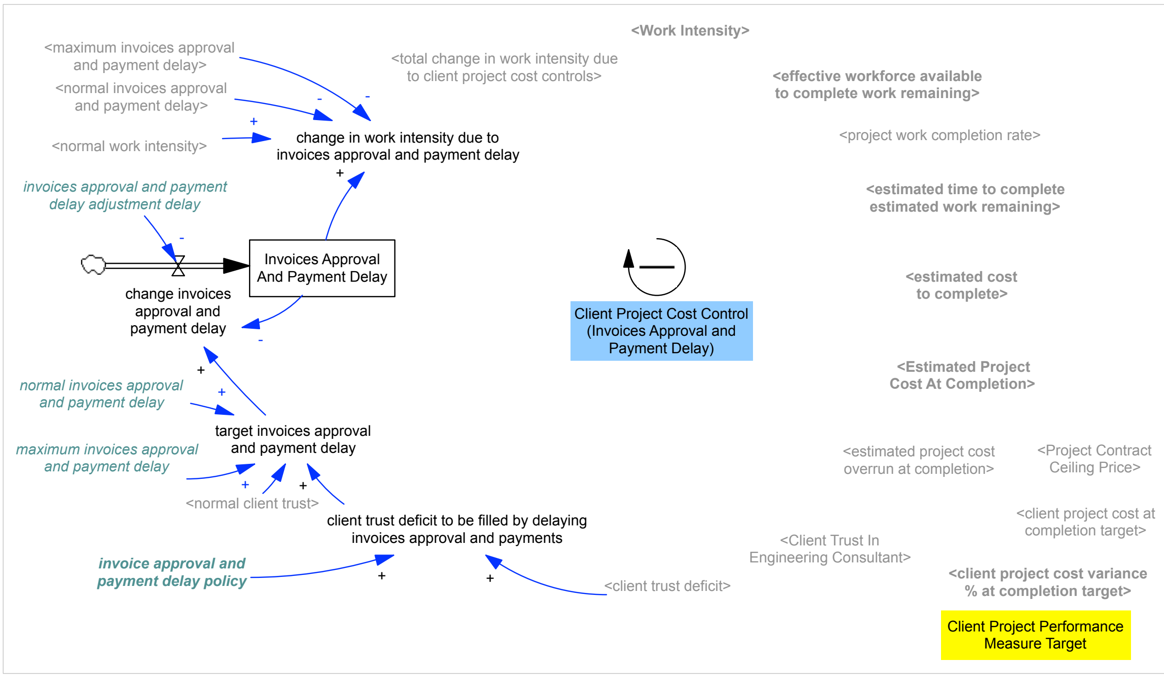


Figure 5.9: Graphical representation of client project cost control (invoice approval and payment delay)

Model Equations

Table 5.8 shows some of the key model equations related to the client project cost control negative feedback loops shown in Figures 5.7 to 5.9.

Table 5.8: Key model equations for client project cost control loops

Formulations and comments	Units
*estimated cost to complete[project] = (estimated time to complete estimated work remaining[project]*effective workforce available to complete work remaining[project]*average workforce unit cost[project])/Work Intensity[project]* The *estimated cost to complete* the project is determined based on the *estimated time to complete estimated work remaining and the available project workforce size*, in the particular case of time-based contracts.	R
Estimated Project Cost At Completion[project] = DELAY INFORMATION ((estimated cost to complete[project]+Instantaneous Project Cost[project]), progress reporting delay[project], (budget at completion[project](1-client project cost variance % at completion target[project])))* The value of the *Estimated Project Cost At Completion* is determined by the sum of the *Instantaneous Project Cost* (actual project cost to-date) and the *estimated cost to complete*, and considering project *progress reporting delays.*	R
estimated project cost overrun at completion[project] = Estimated Project Cost At Completion[project]-client project cost at completion target[project] The *estimated project cost overrun at completion* is the performance gap [the difference between the system state (*Estimated Project Cost At Completion*) and the target / desired system state (*client project cost at completion target)*] that the 3 client project cost control negative feedback loops aim to close.	R

Formulations and comments	Units
*Client Trust In Engineering Consultant[project] = DELAY FIXED(normal client trust[project]*lookup for effect of estimated project cost overrun at completion on client trust[project](((client project cost at completion target[project]+ estimated project cost overrun at completion[project])/client project cost at completion target[project])), 0, normal client trust[project])* The *Client Trust In Engineering Consultant* diminishes as the *estimated project cost overrun at completion* increases. The lookup table was estimated from the non-project-specific qualitative data gathered in the first stage of the research study, in line with Sterman (2000), and used for all the projects in this study.	Dimensionless
Progress Reports Demand[project] = INTEG(change progress reports demand[project], normal progress reports demand[project]); *change progress reports demand[project] = (target progress reports demand[project]-Progress Reports Demand[project])/progress reports demand adjustment delay[project]* *normal progress reports demand[project] = GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C63')* The stock of *Progress Reports Demand* holds information about the number of progress reports to be produced per month. It increases or decreases in line with the *target progress reports demand* which is positively influenced by the client trust deficit. The value of the *normal progress reports demand* is read from cell *'C63'* (for the first project, and across the row for the subsequent projects) of a sheet named *'Input'* in the Microsoft Excel spreadsheet named '*Project Participants Competition Model Parameters.xlsx''* located in the same folder as the system dynamics simulation model, as described in Section 5.3.3. Similar model equation formulations were made for related variables and parameters for the other two client project cost control (demand for progress meetings, and invoice approval and payment delay) negative feedback loops.	reports/Month reports/(Month* Month) reports/Month

5.7.3 Unintended Effects (Positive Feedback Loops)

This subsection presents the graphical representations (stock and flow diagrams, and causal loops) and associated key model equations for the unintended effects of the 'Client Project Cost Control' negative feedback loop shown in the system dynamics conceptual model presented in Figure 4.31 and detailed in Figure 4.12.

Model Structure Visualisation (Stock and Flow Diagrams, and Causal Loops)

Figures 5.10 and 5.11 show graphical representations for two unintended effects ('less time spent on real work', and 'insufficient operating cash flow for the engineering consultant', respectively) of the client project cost controls, as positive feedback loops, in line with Figures 4.12 and 4.31. As discussed in Section 5.7.2, the stand-alone shadow variables in the two figures were included only for the purposes of indicating how the associated loop is constructed, and they are defined (including their causal influences) in separate views of the simulation model in the Vensim DSS software.

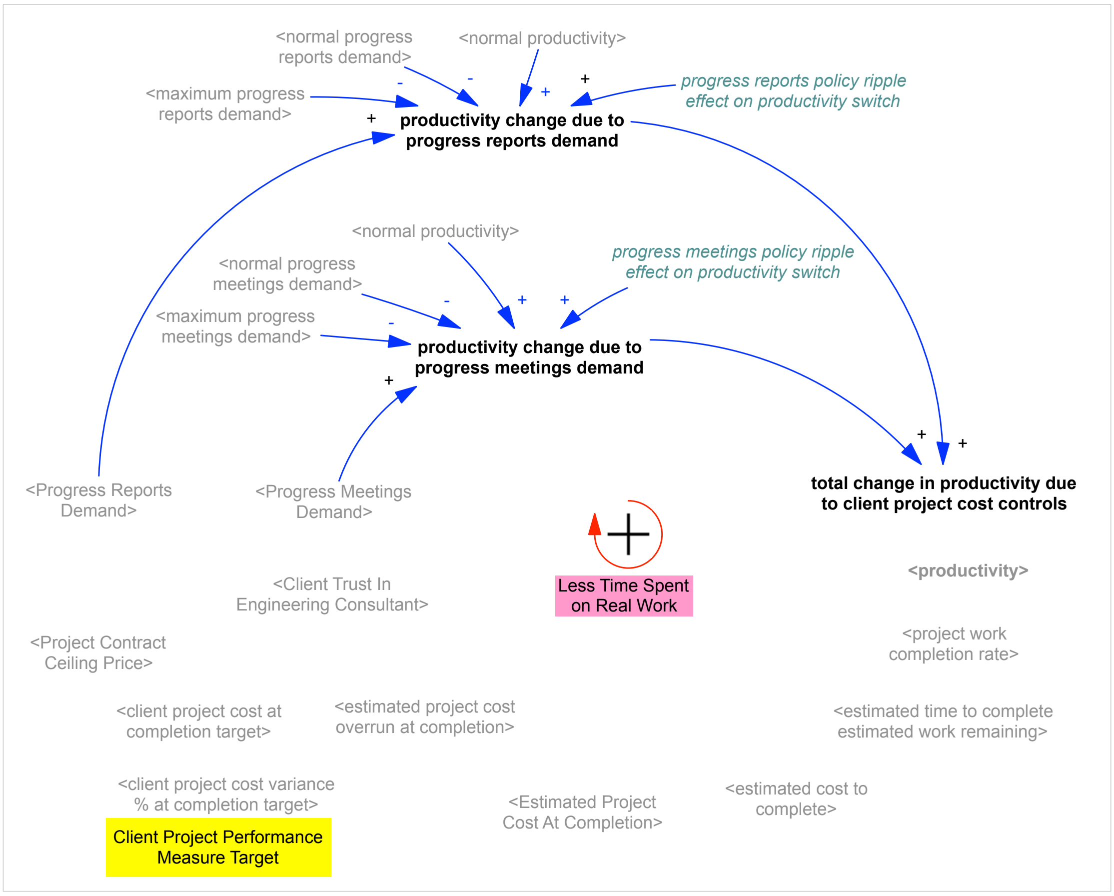


Figure 5.10: Graphical representation of unintended effects of client project cost control (less time spent on real work)

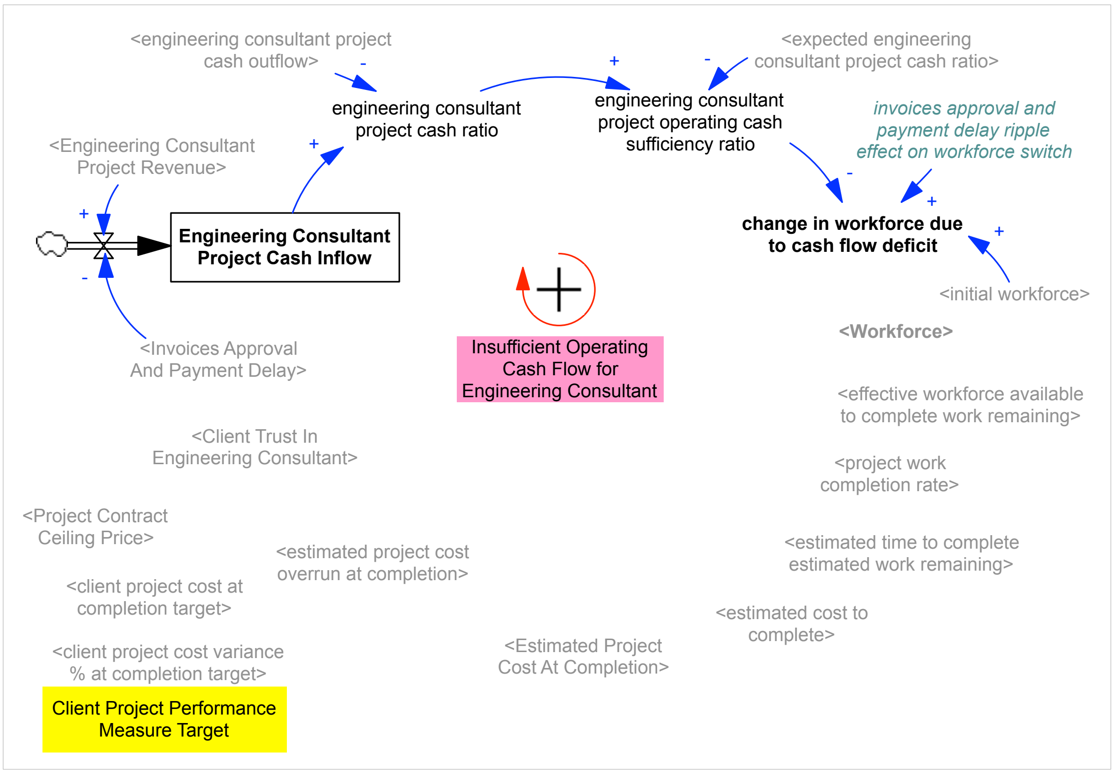


Figure 5.11: Graphical representation of unintended effects of client project cost control (insufficient operating cash flow for the engineering consultant)

The third unintended effect ('haste makes waste') of the client project cost controls, shown in Figures 4.12 and 4.31, is the same as that discussed and presented in Section 5.6.2. The fourth unintended effect ('engineering consultant project revenue controls') is discussed and presented in Section 5.8.2. While engineering consultant project revenue controls are negative feedback loops when considered in isolation, they act as an unintended effect of the client project cost controls when the two are considered together, as discussed in Chapter 4.

Model Equations

Table 5.9 shows some of the key equations related to the unintended effects (positive feedback loops) of the client project cost controls.

Table 5.9: Key model equations for unintended effects of client project cost controls

Formulations and comments	Units
productivity change due to progress reports demand[project] = (normal productivity[project]((Progress Reports Demand[project]-normal progress reports demand[project])/maximum progress reports demand[project]))*progress reports policy ripple effect on productivity switch* The productivity of the project workforce diminishes when they have to produce too many progress reports.	Tasks/(Month* person)
productivity change due to progress meetings demand[project] = (normal productivity[project]((Progress Meetings Demand[project]-normal progress meetings demand[project])/maximum progress meetings demand[project]))* progress meetings policy ripple effect on productivity switch* The productivity of the project workforce diminishes when they have to attend too many progress meetings.	Tasks/(Month* person)
total change in productivity due to client project cost controls[project] = productivity change due to progress reports demand[project]+productivity change due to progress meetings demand[project] The two effects are additive (not multiplicative) as one can occur in isolation of the other.	Tasks/(Month* person)

5.8. Engineering Consultant Project Revenue Controls and their Unintended Effects

5.8.1 Engineering Consultant's Business Performance

In this research study, two key measures (project time schedule duration and project revenue) were used for the engineering consultant's project business performance. Project time schedule duration is a common measure for both project performance and business performance, as discussed in Section 3.3. Thus, the graphical representation and model equations for project time schedule duration as a measure of the engineering consultant's project business performance are the same as those presented in Section 5.7.1 for project performance.

Model Structure Visualisation (Stock and Flow Diagrams)

Figure 5.12 shows a graphical representation (stock and flow diagram) for the engineering consultant's project revenue. It covers the 'project contract price (Z)', 'engineering consultant project contract ceiling price % target (b)', and 'engineering consultant project revenue at completion target (V)' shown in the system dynamics conceptual model presented in Figure 4.31. It also includes the actual engineering consultant project revenue.

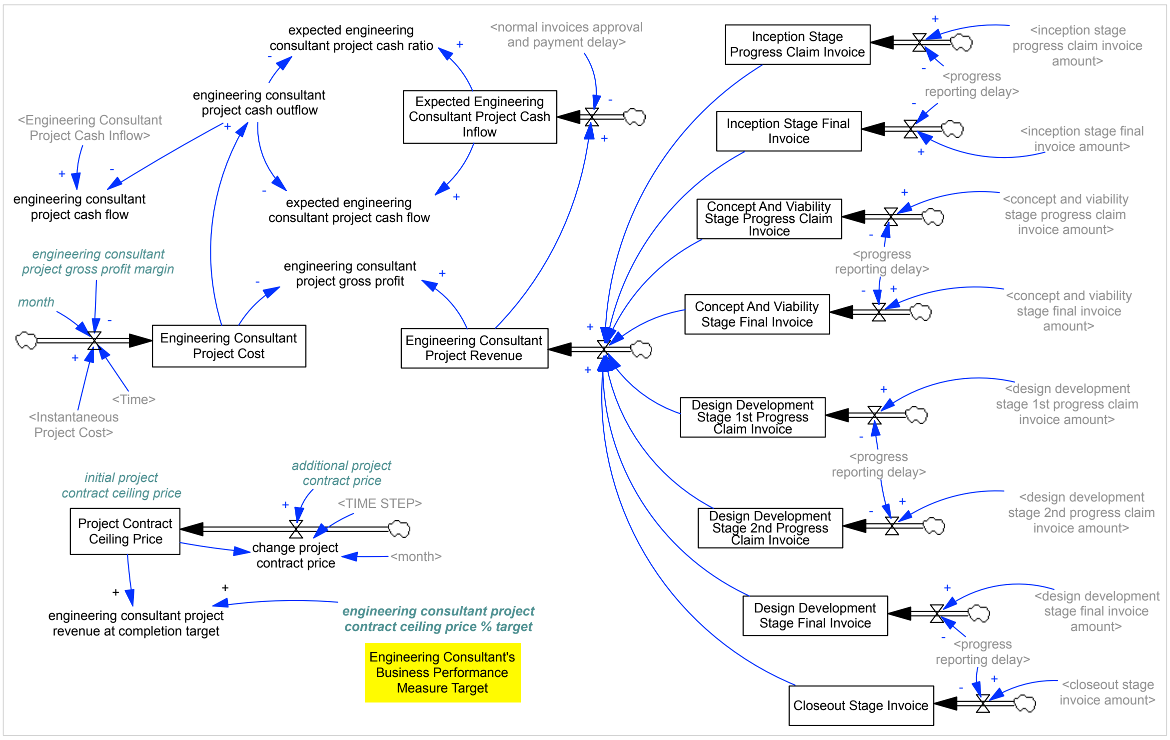


Figure 5.12: Graphical representation of engineering consultant's project business performance measure (project revenue)

Model Equations

Table 5.10 shows some of the key equations related to one of the key engineering consultant's project business performance measures (project revenue) used in this research study.

Table 5.10: Key model equations for the engineering consultant's project business performance measure (project revenue)

Formulations and comments	Units
Project Contract Ceiling Price[project] = INTEG(change project contract price[project], initial project contract ceiling price[project]);	R
change project contract price[project] = STEP((((Project Contract Ceiling Price[project]+additional project contract price[project])-Project Contract Ceiling Price[project])/TIME STEP), month)+STEP(-(((Project Contract Ceiling Price[project]+additional project contract price[project])-Project Contract Ceiling Price[project])/TIME STEP), month+TIME STEP)	R/Month
initial project contract ceiling price[project] = GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C6')	R
The stock of *Project Contract Ceiling Price* increases as additional project cost variations are approved. The value of the *initial project contract ceiling price* is read from cell *'C6'* (for the first project, and across the row for the subsequent projects) of a sheet named *'Input'* in the Microsoft Excel spreadsheet named '*Project Participants Competition Model Parameters.xlsx"* located in the same folder as the system dynamics simulation model, as described in Section 5.3.3.	
*engineering consultant project revenue at completion target[project] = engineering consultant project contract ceiling price % target [project]*Project Contract Ceiling Price[project];*	R
engineering consultant project contract ceiling price % target[project] = GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C10')	Dimensionless
The value of the *engineering consultant project contract ceiling price % target* (one of the key engineering consultant performance targets) is read from cell *'C10'* (for the first project, and across the row for the subsequent projects) of a sheet named *'Input'* in the Microsoft Excel spreadsheet named '*Project Participants Competition Model Parameters.xlsx"* located in the same folder as the system dynamics simulation model, as described in Section 5.3.3. It influences the *engineering consultant project revenue at completion target.*	
Engineering Consultant Project Revenue[project] = DELAY FIXED((Inception Stage Progress Claim Invoice[project]+Inception Stage Final Invoice[project]+ Concept And Viability Stage Progress Claim Invoice[project]+Concept And Viability Stage Final Invoice[project]+Design Development Stage 1st Progress Claim Invoice[project]+Design Development Stage 2nd Progress Claim Invoice [project]+Design Development Stage Final Invoice[project]+Closeout Stage Invoice[project]), 0, 0)	R
The stock of *Engineering Consultant Project Revenue* accumulates the different project invoices submitted to the client from project inception to project close-out.	

5.8.2 Controls (Negative Feedback Loops)

This subsection presents the graphical representations (stock and flow diagrams, and causal loops) and associated key model equations for the 'Engineering Consultant Project Revenue Control' negative feedback loop shown in the system dynamics conceptual model presented in Figure 4.31. As indicated in Section 4.9.3, 'engineering consultant project revenue controls' in Figure 4.31 refers to the two engineering consultant project revenue controls (project scope variation motivations and effort adjustment) shown in Figure 4.17.

Model Structure Visualisation (Stock and Flow Diagrams, and Causal Loops)

Figures 5.13 and 5.14 show the graphical representations for the two engineering consultant project revenue control (effort adjustment and project scope variation motivations, respectively) negative feedback loops, in line with Figures 4.17 and 4.31. As discussed in Section 5.7.2, the stand-alone shadow variables in the two figures were included only for the purposes of indicating how the associated loop is constructed, and they are defined (including their causal influences) in separate views of the simulation model in the Vensim DSS software.

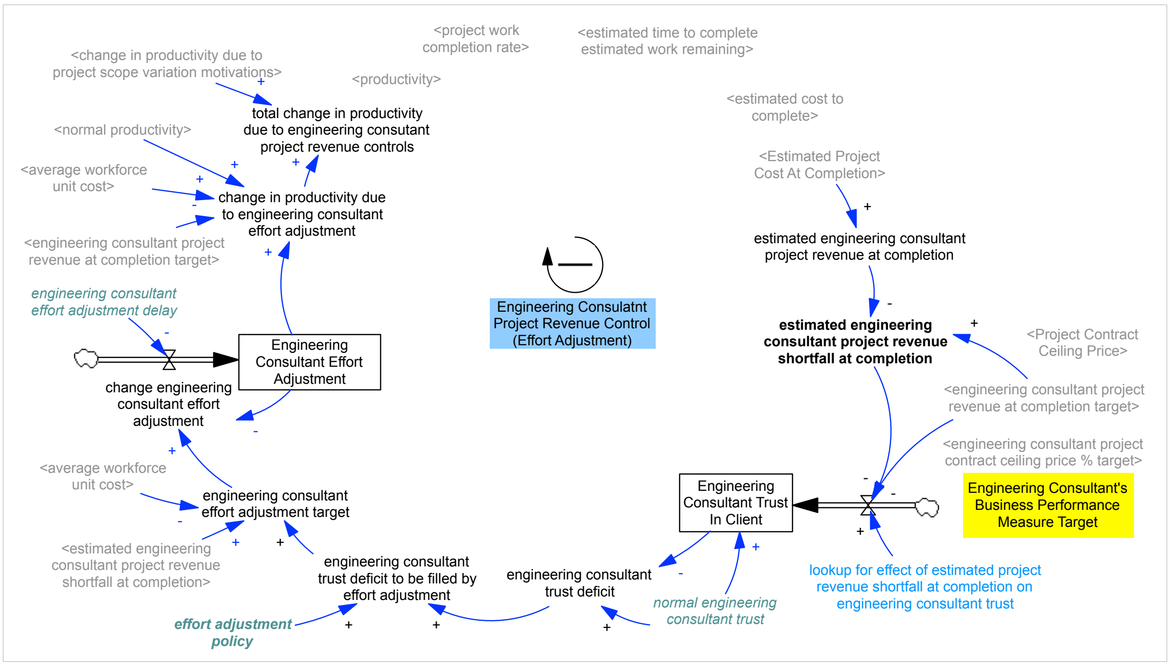


Figure 5.13: Graphical representation of engineering consultant project revenue control (effort adjustment)

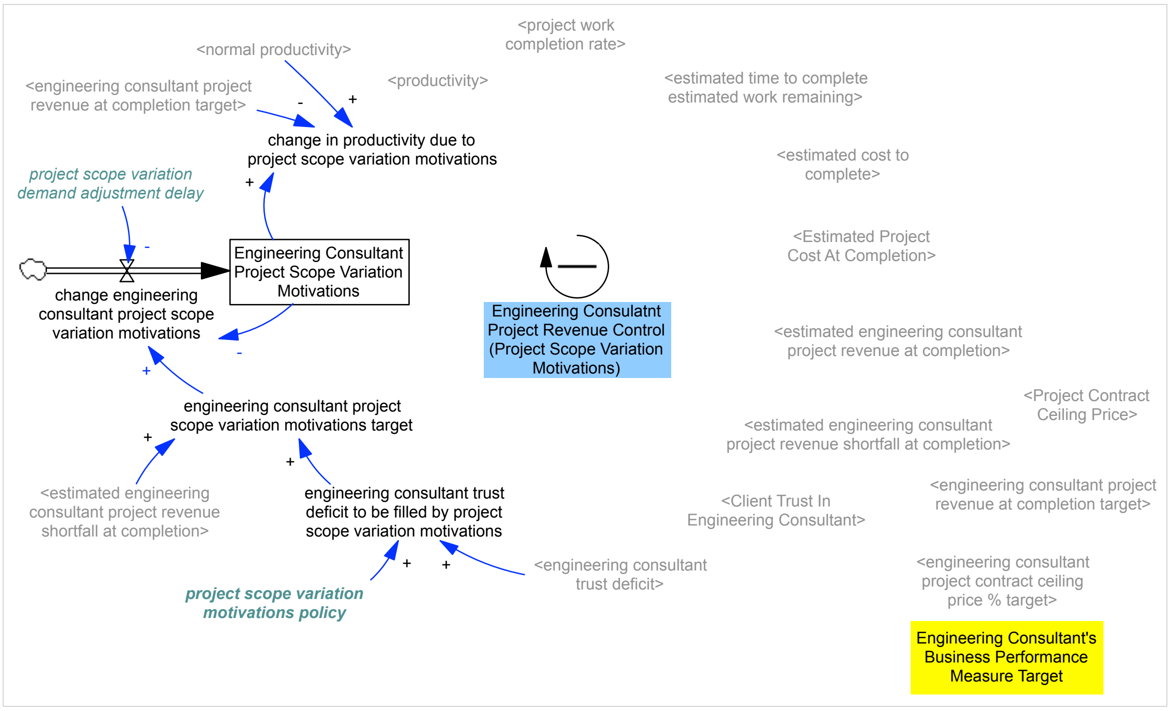


Figure 5.14: Graphical representation of engineering consultant project revenue control (project scope variation motivations)

Model Equations

Table 5.11 shows some of the key equations related to the engineering consultant project revenue control negative feedback loops.

Table 5.11: Key model equations for engineering consultant project revenue controls

Formulations and comments	Units
estimated engineering consultant project revenue at completion[project] = Estimated Project Cost At Completion[project] The project cost for executing a typical engineering project is the sum of all the costs incurred by the client during project execution (Project Management Institute, 2017), and it includes the costs for project management services, engineering consultant services, and construction contractor works (including labour, material, equipment, and sub-contractors), among others. However, in this research study only the time-based cost for the engineering consultant services were considered for the project cost. Hence, the estimated project revenue to be realised by the engineering consultant at project completion was assumed to be equal to the estimated project cost to be incurred by the client at completion of the same project.	R
estimated engineering consultant project revenue shortfall at completion [project] = engineering consultant project revenue at completion target[project] - estimated engineering consultant project revenue at completion[project] The *estimated engineering consultant project revenue shortfall at completion* is the performance gap [difference between system state (*estimated engineering consultant project revenue at completion*) and the target/desired system state	R

Formulations and comments	Units
(*engineering consultant project revenue at completion target)*] that the two *engineering consultant project revenue* negative feedback loops aim to close.	
*Engineering Consultant Trust In Client[project] = DELAY FIXED(normal engineering consultant trust[project]*lookup for effect of estimated project revenue shortfall at completion on engineering consultant trust[project](((engineering consultant project revenue at completion target[project]-estimated engineering consultant project revenue shortfall at completion[project])/engineering consultant project revenue at completion target[project])), 0, normal engineering consultant trust[project])* The *Engineering Consultant Trust In Client* diminishes as the *estimated engineering consultant project revenue shortfall at completion* increases. The lookup table was estimated from the non-project-specific qualitative data gathered in the first stage of the research study, in line with Sterman (2000), and used for all the projects considered in this study.	Dimensionless
Engineering Consultant Effort Adjustment[project] = INTEG(change engineering consultant effort adjustment[project], 0); *change engineering consultant effort adjustment[project] = (engineering consultant effort adjustment target[project]-Engineering Consultant Effort Adjustment[project])/engineering consultant effort adjustment delay* *engineering consultant effort adjustment delay = GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C40')* The stock of *Engineering Consultant Effort Adjustment* holds information about the amount of effort to be adjusted. It increases or decreases in line with the *engineering consultant effort adjustment target* which is positively influenced by the engineering consultant trust deficit. The value of the *engineering consultant effort adjustment delay* is read from cell *'C40'* (for the first project, and across the row for the subsequent projects) of a sheet named *'Input'* in the Microsoft Excel file named '*Project Participants Competition Model Parameters.xlsx''* located in the same folder as the system dynamics simulation model, as described in Section 5.3.3. Similar model equation formulations were made for related variables and parameters for the other engineering consultant project revenue control (project scope variation motivations) negative feedback loop.	Month*person Month*person/ Month Month

5.8.3 Unintended Effects (Positive Feedback Loops)

The unintended effect ('client project cost controls') of the engineering consultant project revenue controls, shown in the system dynamics conceptual models presented in Figures 4.17 and 4.31, is as discussed and presented in Section 5.7.2. While client project cost controls are negative feedback loops when considered in isolation, they act as an unintended effect of the engineering consultant project revenue controls when the two are considered together, as discussed in Chapter 4.

5.9. Discussion

In the preceding Sections 5.5 to 5.8, the system dynamics conceptual model of the competition between two key project participants (the client and the engineering consultant) during project execution, in the particular case of time-based contracts with a ceiling price, formulated in the preceding chapter (Figure 4.31 in Section 4.9.3) was converted to an appropriate system dynamics simulation model using Vensim DSS software by: developing appropriate model graphical representations (stock and flow diagrams, and feedback loops); specifying mathematical equations for the relationships among the different model variables and constants (parameters), ensuring dimensional consistency in all equations; and specifying initial conditions, where applicable, as recommended by Martinez-Moyano and Richardson (2013) and Sterman (2000).

The formulated system dynamics simulation model is made up of six subsystems, namely: *project work flow and remaining work estimation, engineering consultant project time schedule control (work intensity) and its unintended effect, client project cost controls and their unintended effects, engineering consultant project revenue controls and their unintended effects, model calibration,* and *policy optimisation.* The first four subsystems are the core ones as they capture the competition between the two key project participants. For each of them, appropriate graphical representations (stock and flow diagrams, and causal loop diagrams), model equations, and initial conditions, where applicable, were formulated and presented.

In the reviewed literature (Chapter 3), no appropriate system dynamics project model could be identified that considers competition among project participants; yet, some previous researchers (Lyneis and Ford, 2007; Mohammed et al., 2009; Sutterfield et al., 2007) highlighted that such competition is a common challenge during project execution. Lyneis and Ford (2007) further called for research towards modelling and improvement of the competition among the different project participants. Thus, the system dynamics simulation model of the competition between the two key project participants (the client and the engineering consultant) during project execution formulated in this chapter is a key step towards the filling of the above-mentioned gap in existing project management and system dynamics literature. Steps towards improvement of the competition are discussed in the next chapter (Section 6.8) when the last subsystem (*policy optimisation*) of the formulated system dynamics simulation model is covered.

A provisional answer for the research question number 2, posed in Section 1.6, is as follows:

Research Question:

2. *How can the competition between the two key project participants (client and engineering consultant) during project execution be quantitatively modelled (simulation model) using system dynamics?*

Provisional Answer:

The competition between two the key project participants (the client and the engineering consultant) during project execution, in the particular case of time-based contracts with a ceiling price, may be quantitatively modelled using system dynamics by converting the conceptual model formulated in Chapter 4 (Figure 4.31) into an appropriate system dynamics simulation model made up of six subsystems, namely: project work flow and remaining work estimation, engineering consultant project time schedule control (work intensity) and its unintended effect, client project cost controls and their unintended effects, engineering consultant project revenue controls and their unintended effects, model calibration, and policy optimisation.

The first four subsystems are the core ones as they capture the competition between two the key project participants. For each of them, appropriate graphical representations (stock and flow diagrams, and causal loop diagrams), model equations, and initial conditions, where applicable, were formulated and presented in Sections 5.5 to 5.8. The last two subsystems (model calibration and policy optimisation) focus on the testing and validation of the first four subsystems, and are discussed in the next chapter.

5.10. Conclusion

The preceding chapter formulated a system dynamics conceptual model of the competition between two key project participants (client and engineering consultant) during project execution (refer to Figure 4.31 in Section 4.9.3). The conceptual model consisted of three groups of project controls (negative feedback loops), namely engineering consultant project time schedule control (work intensity), client project cost controls, and engineering consultant project revenue controls, as well as their associated unintended effects (positive feedback loops).

This chapter focussed on the 'simulation model formulation' (Sterman, 2000) stage, also referred to as the 'model formulation' stage by Martinez-Moyano and Richardson (2013), of the system dynamics modelling process. Thus, the system dynamics conceptual model of the competition formulated in the preceding chapter (refer to Figure 4.31 in Section 4.9.3) was converted to an appropriate system dynamics simulation model using Vensim DSS software by: developing appropriate model graphical representations (stock and flow diagrams, and feedback loops);

specifying mathematical equations for the relationships among the different model variables and constants (parameters), ensuring dimensional consistency in all equations; and specifying initial conditions, where applicable, as recommended by Martinez-Moyano and Richardson (2013) and Sterman (2000).

The formulated system dynamics simulation model is made up of six subsystems, namely: *project work flow and remaining work estimation, engineering consultant project time schedule control (work intensity) and its unintended effect, client project cost controls and their unintended effects, engineering consultant project revenue controls and their unintended effects, model calibration,* and *policy optimisation.* The first four subsystems captured the competition between two the key project participants (the client and the engineering consultant) during project execution, in the particular case of time-based contracts with a ceiling price. For each of them, appropriate graphical representations (stock and flow diagrams, and causal loop diagrams), model equations, and initial conditions, where applicable, were formulated and presented. This provided a provisional answer to research question number 2 posed in Section 1.6, i.e., how the competition may be quantitatively modelled (simulation model) using system dynamics.

System dynamics best-practices with regards to general graphical representation/ visualization, variables naming convention, and structuring of negative and positive feedback loops, as recommended by such scholars as Ford et al. (2007), Lyneis and Ford (2007), Rahmandad and Sterman (2012), and Sterman (2000) were followed, as far as possible, in the formulation of the system dynamics simulation model. In addition, best-practices guidelines for reporting system dynamics simulation models recommended, to enhance reproducibility of the research results, by Rahmandad and Sterman (2012) were also adopted in this chapter.

The last two subsystems (*model calibration* and *policy optimisation*) of the formulated system dynamics simulation model focus on the testing and validation of the first four subsystems. As such, they are covered in the next chapter (refer to Sections 6.4, 6.5 and 6.8), which validates and tests the formulated system dynamics simulation model of the competition between the two key project participants.

6. Project Participants Competition System Dynamics Simulation Model Validation

6.1. Introduction

This chapter focusses on the model testing and evaluation, as well as policy analysis and design stages of the system dynamics modelling process recommended in the reviewed existing literature (Martinez-Moyano and Richardson, 2013; Sterman, 2000). It begins with a review of best practices in system dynamics model validation and testing, and then indicates how the project participants competition model formulated in this research study is validated and tested. Next, data gathered for two sets of unique raw water infrastructure projects (asset management planning and support-related, and asset-renewal related) are used to calibrate the system dynamics simulation model formulated in the preceding chapter. Subsequently, simulation experiments are conducted on the calibrated simulation models to analyse the impact of the competition on both the project performance and the business performance of the engineering consultant. In both cases, the analyses are conducted separately for each set of projects, with subsequent comparison and discussion of the results.

In the end, policy optimisation experiments are conducted aimed at improving the competition so as to enhance both the project performance and the business performance of the engineering consultant, yielding ‘win-win’ long-term results. The policy optimisations are also conducted separately for each set of raw water infrastructure projects, with subsequent comparison and discussion of the results.

The following research questions posed in Section 1.6 are, accordingly, addressed in this chapter:

3. *How does the competition between the two key project participants (client and engineering consultant) influence project performance?* (Section 6.6).
4. *How does the competition between the two key project participants (client and engineering consultant) influence the business performance of the engineering consultant?* (Section 6.7).
5. *How can the competition be improved so as to enhance both the project performance and the business performance of the engineering consultant during project execution, yielding ‘win-win’ long-term results for the two key project participants?* (Section 6.8).

6.2. System Dynamics Model Validation and Testing Best Practices

6.2.1 Model Definition and Classification

According to Sterman (2000), models (be it formal or mental): are simplified (and thus, limited) representations of real-world systems; are different from the reality they represent, but some are useful; and the usefulness of a model lies in its ability to simplify the system that it represents and to address a specific problem with the system, thereby assisting to enhance the performance of the system. As such, models cannot be viewed as being either true or false, as they rather lie on a continuum of usefulness (Barlas and Carpenter, 1990). The *usefulness* of a model, for the purpose of this research study, can be considered from the perspectives of the two broad categories of a society:

- *the business fraternity, politicians and general public* – who consider a model to be useful when it: illuminates and explains the causes of pertinent problems; and assists in designing new policies and intervention strategies that help to change problematic behaviour, thereby enhancing the future performance of their systems; and
- *scientists* – who consider a model to be useful when it: gives insight into the internal structure of a real-world system; makes correct behaviour pattern/event predictions; and excites future research questions that help to expand scientific knowledge (Forrester and Senge, 1980).

Every model must be built for a *specific purpose*, as a model must be formulated for a specific system problem (Barlas, 1996; Forrester and Senge, 1980; Sterman, 2000). Put differently, one needs to model a specific system problem, not the whole system (Sterman, 2000). Thus, the usefulness of a model needs to be assessed with respect to the model's specific purpose (Barlas, 1996).

Every decision is based on some model, be it formal or mental (Sterman, 2002). Thus, the quality of a decision may be viewed as being proportional to the usefulness of the model used in making that decision. Simulation models, in particular, promote double-loop learning as they enable system actors to expand their mental models to include some feedbacks and/or organisations previously excluded, thereby enhancing the accuracy of their mental models, and ultimately improving the quality of the resulting decisions (Kim, MacDonald and Andersen, 2013; Sterman, 2000). As such, models can be useful risk management tools.

There are many ways of classifying models, such as: mental or formal (Sterman 2000); static or dynamic; deterministic or stochastic; hardware or software; and the like. Barlas (1996) differentiates between "correlational" (purely data-driven, "black-box") and "causal-descriptive" (theory-like, "white-box") models. In correlational (black-box) models: the individual causal relationships within the internal model structure are hidden; only the overall model output behaviour is of interest; and the model is considered valid when its overall model output behaviour is similar to that of the real world (Barlas, 1996).

In causal-descriptive models: the individual causal relationships within the internal model structure are clearly articulated and help explain how the model output behaviour is generated, effectively suggesting how the behaviour may be changed so as to enhance the performance of the system; and the validity of the internal model structure is of paramount importance. All system dynamics models, as assemblies of causal relationships among model variables (model internal structure) that support time-evolutionary output (model output behaviour) (Lane, 2015), are effectively causal-descriptive (white-box) models (Barlas, 1996).

The next sub-section discusses the meanings of the terms ‘validity’ and ‘validation’ when applied to models in general and for the purpose of this research study, and system dynamics models in particular.

6.2.2 Model Validity and Validation

The internal structure of a system dynamics model needs to adequately represent aspects of the system which are relevant to the problematic behaviour to be addressed; this helps to ensure not only that the model output matches the observed system behaviour, but also that the model generates the “right output behaviour for the right reasons” (Barlas, 1996), a key model validation phrase similarly highlighted and emphasised by many other researchers and scholars, such as Forrester and Senge (1980), Lane (2015), Oliva (2003) and Sterman (2000).

Traditionally, ‘validity’ is used to mean ‘absolute/objective truth’, and ‘validation’ to mean ‘supported by absolute/objective truth’ (Forrester and Senge, 1980; Sterman, 2000). It is not possible to validate any model using such definitions of validity and validation, considering that models are just representations of reality, not the reality itself (Forrester and Senge, 1980; Sterman, 2000). It is not possible to prove the “absolute correctness with which a model represents reality” (Forrester and Senge, 1980).

‘Validity’ of a model is rather considered to be meaning having ‘confidence’ in the model (Barlas, 1996; Forrester and Senge, 1980; Lane, 2015). The validity of a white-box model (like a system dynamics model) primarily refers to having confidence in its internal structure: “right output behaviour for the right reasons” (Barlas, 1996). ‘Model validation’ for a white-box model is, thus, defined as the process of building confidence in: the appropriateness of the model’s internal structure in representing aspects of the system which are relevant to the problematic behaviour to be addressed; the accuracy of the model output in matching the observed system behaviour; and, the usefulness of the model in policy analysis and designing of new intervention strategies that help to address the problematic system behaviour, thereby enhancing system performance (Barlas, 1996; Forrester and Senge, 1980; Lane, 2015). Thus, validation of a white-box model (like a system dynamics model) is much more involving than that of a black-box model.

Logically, the steps of building confidence in a model are about developing confidence: *firstly*, that the model's internal structure adequately represents aspects of the system which are relevant to the problematic behaviour to be addressed; *next*, that the model output behaviour matches the observed system behaviour for the right reasons; and *then*, that the model is useful in policy analysis and designing of new polices and intervention strategies that help to address the problematic system behaviour, thereby enhancing the system's performance; the confidence being assessed relative to the model's specific purpose, and each step being conducted only after gathering adequate confidence in the preceding step (Barlas, 1996; Forrester and Senge, 1980; Lane, 2015; Sterman, 2000).

Practically, however, building confidence in a model is an *iterative* and gradual process that spans across all the stages of the modelling process (Barlas, 1996; Forrester and Senge, 1980; Lane, 2015; Oliva, 2003; Sterman, 2000); for instance, from 'problem identification and definition', through 'system conceptualisation', 'model formulation', 'model testing and evaluation', 'model use, implementation and dissemination', to 'design of learning strategy/infrastructure', as the system dynamics modelling process stages recommended by Martinez-Moyano and Richardson (2013), with many back and forth iterations among the stages.

In the final analysis, the ultimate objective of building confidence in a system dynamics model (model validation) is centred around establishing confidence in the model's internal structure; confidence in the model's reproduction of observed real-world system behaviour and in the usefulness of the model in policy analysis and designing of new policies and intervention strategies is also required, but this is meaningful only if sufficient confidence in the model's internal structure has already been established (Barlas, 1996; Forrester and Senge, 1980; Lane, 2015; Oliva, 2003; Sterman, 2000).

There must be *shared confidence* in the model: confidence building needs to be not only for the model builder, but also for the model critics and (potential) end users (Barlas, 1996; Forrester and Senge, 1980; Lane, 2015; Oliva, 2003; Sterman, 2000).

Confidence in a system dynamics model is gradually accumulated/built throughout the entire modelling process by means of:

- clearly articulating the problematic system behaviour to be addressed and the specific purpose of the model (Sterman, 2000);
- formulating the system dynamics model from a combination of: existing literature; empirical study that captures the relevant formal and mental models of the contemporary system actors; and system dynamics' systems thinking tools (causal loop diagrams and/or stock and flow diagrams), in line with the recommendations of Barlas (1996), Luna-Reyes and Andersen (2003), Martinez-Moyano and Richardson (2013), and Sterman (2000);
- making use of all types of data (numerical, written and mental) in the formulation of the model, as recommended by Forrester (1980), Luna-Reyes and Andersen (2003) and Sterman (2000);
- making use of data from multiple-cases in formulating and testing the model, in line with Forrester and Senge (1980), Parvan (2012), Parvan et al. (2015), Sterman (2000), and Yin (2014);
- conducting multiple model tests (structure, structure-oriented behaviour, behaviour pattern/event, and policy implications tests), whilst ensuring alignment with the model's specific purpose (model boundary), and also involving the model critics and (potential) end-users (Barlas, 1996; Forrester and Senge, 1980; Lane, 2015; Oliva, 2003; Sterman, 2000); and
- model documentation in line with system dynamics best-practices, as recommended by Rahmandad and Sterman (2012), Martinez-Moyano (2012) and Sterman (2000).

The next sub-section discusses testing of system dynamics models in more detail.

6.2.3 Model Testing

Model testing is one of the imperative ways of building confidence in a model; as such, it is an essential part of the broader model validation process (Barlas, 1996; Forrester and Senge, 1980; Lane, 2015; Sterman, 2000), as indicated in the preceding sub-section. A system dynamics model needs to be tested against a wide range of empirical evidence, seeking refutation, and in the process building confidence in the model's usefulness as the model withstands the tests (Forrester and Senge, 1980).

Testing a model helps to discover flaws in the model's internal structure; when the identified flaws are rectified, confidence that the model is appropriate for its intended purpose is strengthened (Barlas, 1996; Forrester and Senge, 1980; Lane, 2015; Sterman, 2000). This helps to increase the usefulness and use of the model in policy analysis and designing of new polices and intervention strategies that help to address the problematic system behaviour, thereby enhancing the system's performance (i.e., helping management to make better decisions) (Sterman, 2000). Model testing needs to be conducted relative to the model's specific purpose (Barlas, 1996; Forrester and Senge, 1980; Lane, 2015; Sterman, 2000). Furthermore, to ensure shared confidence, the (potential) model end-users and critics need to be involved in the model testing (Barlas, 1996; Forrester and Senge, 1980; Lane, 2015; Sterman, 2000). In the case of a scientific research study, full model documentation to ensure replication needs to be produced and made available for public scrutiny, as recommended by Rahmandad and Sterman (2012). In this research study, appropriate model documentation has been produced, as is especially evident in Chapters 4 to 6 of this thesis report.

Logically, as discussed in the preceding sub-section, the steps of building confidence in a model are about developing confidence: *firstly*, that the model's internal structure adequately represents aspects of the system which are relevant to the problematic behaviour to be addressed; *next*, that the model output behaviour matches the observed system behaviour for the right reasons; and *then*, that the model is useful in policy analysis and designing of new polices and intervention strategies that help to change the problematic system behaviour, thereby enhancing the system's performance (Barlas, 1996; Forrester and Senge, 1980; Lane, 2015; Sterman, 2000). Model testing needs to follow a similar logical order. As such there are three broad categories of model testing, that logically focus on: model structure; model behaviour; and model's policy implications (Sterman, 2000).

Practically, however, model testing is an *iterative* and gradual process that spans across all the stages of the modelling process (Barlas, 1996; Forrester and Senge, 1980; Lane, 2015; Oliva, 2003; Sterman, 2000). In the final analysis, though, all system dynamics model tests are centred around establishing confidence in the model's internal structure (model structure tests); model behaviour and policy implications tests help in discovering flaws in the model's internal structure, and are successful only if sufficient confidence in the model's internal structure has already been established (Barlas, 1996; Forrester and Senge, 1980; Lane, 2015; Sterman, 2000).

The more tests are conducted on a model the greater the number of flaws in the model's internal structure are (potentially) uncovered and rectified, and the more confidence in the model is built; as such, multiple tests (not just one) must be conducted on a model, as recommended by Barlas (1996), Forrester and Senge (1980), Lane (2015), and Sterman (2000).

Table 6.1 shows the key system dynamics model tests recommended in the reviewed relevant existing literature.

Table 6.1: Key system dynamics model confidence-building tests

Test category	Test sub-category	Test name	Test description	Recommended / Used by
Model structure test: Ensuring that the model's internal structure adequately represents aspects of the system which are relevant to the problematic behaviour to be addressed and to the model purpose.	*Direct structure test:* - assessing model structure validity by direct comparison with empirical and/or theoretical knowledge about the real-world system structure; - no examination of relationships between structure and behaviour; - no simulation involved.	Model boundary adequacy	Assessing the appropriateness of the model boundary versus the model's specific purpose, ensuring no important feedbacks are omitted and no endogenous variables are mistakenly treated as exogenous.	Forrester and Senge (1980); Sterman (2000)
		Structure verification/ assessment	Comparing the form of model equations with the form of their corresponding real-world relationships.	Barlas (1996); Forrester and Senge (1980); Sterman (2000)
		Dimensional consistency test	- Specifying the correct measurement units for each variable; - Checking both sides of the equation for dimensional consistency, without the use of arbitrary scaling factors that have no meaning in the real world.	Barlas (1996); Forrester and Senge (1980); Martinez-Moyano and Richardson (2013); Sterman (2000)
		Parameter verification/ assessment	- Ensuring every model parameter has a real-world meaning, conceptually and numerically; and - Estimating parameter values statistically from numerical data or judgmentally from expert opinion interviews, archival material or direct experience.	Barlas (1996); Forrester and Senge (1980); Oliva (2003); Parvan (2012); Parvan et al. (2015); Sterman (2000)
		Direct extreme-conditions (Reality checks)	- Checking the validity of the output of each model equation under extreme input conditions. - It involves assigning extreme values (e.g. minus infinity, zero and plus infinity) to	Barlas (1996); Forrester and Senge (1980); Sterman (2000)

Test category	Test sub-category	Test name	Test description	Recommended / Used by
			the equation's input variables and comparing the output variable value with what is expected in the real-world system under the same extreme conditions.	
	Structure-oriented behaviour test: - indirectly assessing the validity/ robustness of the model internal structure by applying certain behaviour tests on the model-generated behaviour patterns. - involves dynamic simulation.	Indirect extreme-conditions (Reality checks)	It involves assigning extreme values (e.g. zero and very large values) to some selected parameters and comparing the model output (generated behaviour) with what is expected in the real-world system under the same extreme conditions.	Barlas (1996); Forrester and Senge (1980); Sterman (2000)
		Behaviour anomaly	Identification of anomalous features of the model's output behaviour which acutely conflict with observed real-world system behaviour; often an indication of obvious flaws in the model assumptions.	Forrester and Senge (1980); Sterman (2000)
		Family member	Ensuring the model structure (general theory) represents the structure of the entire class to which the system belongs. Individual class members' (e.g. projects) behaviours to differ based on different parameters and policies that vary from member to member.	Forrester and Senge (1980); Sterman (2000)
		Behaviour reproduction test plus parameter re-estimation (model calibration)	Re-estimation of values for the model parameters so as to minimise errors between the model simulation outputs and their associated real-world data.	Forrester and Senge (1980); Martinez-Moyano and Richardson (2013); Oliva (2003); Parvan (2012); Parvan et al. (2015); Sterman (2000)

Test category	Test sub-category	Test name	Test description	Recommended / Used by
		Behaviour sensitivity test	Running model behaviour sensitivity analysis and identifying those parameters for which the model is highly sensitive, and verifying if the real-world system exhibits similar high sensitivity to the corresponding parameters.	Barlas (1996); Forrester and Senge (1980); Parvan (2012); Parvan et al. (2015); Sterman (2000)
		Phase-relationship	Comparison of phase relationships between two variables – simulated versus what is expected in the real-world system.	Barlas (1996); Forrester and Senge (1980)
Model behaviour pattern test: Assessing how accurately the model can reproduce the key behaviour patterns (such as periods, frequencies, trends, phase lags and amplitudes) exhibited by the real-world system.	*Transient, highly non-stationary behaviour:* not possible to conduct any statistical tests.	Behaviour pattern reproduction test: graphical / visual comparisons	Comparison of graphical / visual measures of behaviour-pattern characteristics, such as amplitude of a peak, periods, slope or phase relationships.	Barlas (1996); Forrester and Senge (1980); Sterman (2000)
		Behaviour pattern prediction test: graphical / visual comparisons	Same as above	Forrester and Senge (1980); Parvan (2012); Parvan et al. (2015)
Policy Implications tests: Analysis and comparison of policy changes in the model and in the corresponding real-world system.	*Future prediction capability*	Changed-behaviour prediction	Assessing if the model correctly predicts how system behaviour will change in future when a governing policy is changed.	Forrester and Senge (1980)
	Impact of uncertainty in model parameter values	Policy sensitivity	Assessing extent to which policy recommendations are influenced by changes in parameter values.	Forrester and Senge (1980); Parvan (2012); Sterman (2000)

The next section indicates the key model validation measures taken and the model tests conducted on the system dynamics model formulated in this research study.

6.3. System Dynamics Model Validation and Testing Conducted in this Research Study

6.3.1 Model Validation

As indicated in Section 6.2.2, model validation entails building confidence in: the appropriateness of the model's internal structure in representing aspects of the system which are relevant to the problematic behaviour to be addressed; the accuracy of the model output in matching the observed system behaviour; and, the usefulness of the model in policy analysis and designing of new intervention strategies that help to address the problematic system behaviour, thereby enhancing system performance (Barlas, 1996; Forrester and Senge, 1980; Lane, 2015). Table 6.2 shows the key measures taken to build confidence in the system dynamics model formulated in this research study.

Table 6.2: Measures taken to build confidence in the model (model validation) formulated in this research study

Confidence building measure	Measure description	Recommended by	Applicable chapter/ section
System problem and model purpose (model boundary)	▪ Clearly articulated the problematic system behaviour and the specific purpose of the model; ▪ Outlined the model boundary by way of charts / sub-system diagrams.	Barlas (1996); Forrester and Senge (1980); Martinez-Moyano and Richardson (2013); Sterman (2000)	Chapter 1 (Sections 1.3 and 1.5); Chapter 4 (Sections 4.2 and 4.4); and Chapter 5 (Sections 5.2 and 5.4).
Multiple sources of evidence	▪ Formulated the system dynamics conceptual model from a combination of: existing literature; key findings from an empirical embedded multiple-case study that captured the relevant formal and mental models of the interviewed contemporary client and engineering consultant project managers; and system dynamics' systems thinking tool (causal loop diagram). ▪ Converted the system dynamics conceptual model formulated in the previous stage to a system dynamics simulation model, making use of system dynamics' systems thinking tools (stock and flow diagram, and causal loop diagram).	Barlas (1996); Luna-Reyes and Andersen (2003); Martinez-Moyano and Richardson (2013); Sterman (2000); Yin (2014)	Chapters 1 to 6

Confidence building measure	Measure description	Recommended by	Applicable chapter/ section
All data types (numerical, written, mental)	▪ Use of all data types (numerical, written, mental) in the formulation and testing of the system dynamics model.	Forrester (1980); Luna-Reyes and Andersen (2003); Martinez-Moyano and Richardson (2013); Sterman (2000)	Chapters 1 to 6
Multiple-cases (projects)	▪ Used multiple-cases (18 projects) in testing the model: used real-world project-specific data gathered for two sets of unique raw water infrastructure projects (asset management planning and support-related, made up of 10 projects; and asset renewal-related, made up of 8 projects) to calibrate the model, and to conduct subsequent simulation and optimisation experiments (including associated impact analyses).	Forrester and Senge (1980); Parvan (2012), Parvan et al. (2015); Sterman (2000); Yin (2014)	Chapters 2, 5 and 6
Model testing	▪ Multiple model tests (as indicated in Section 6.3.2) conducted iteratively throughout the system dynamics modelling process; ▪ Made the model available for public scrutiny through related publications (conference papers and journal articles) and the eventual publication of this thesis report.	Barlas (1996); Forrester and Senge (1980); Lane (2015); Martinez-Moyano and Richardson (2013); Oliva (2003); Parvan (2012); Parvan et al. (2015); Sterman (2000)	Chapter 6 (Section 6.3.2); List of Related Publications
Model documentation	▪ Well-documented system dynamics modelling process followed. ▪ Well-documented system dynamics conceptual and simulation models.	Martinez-Moyano (2012); Rahmandad and Sterman (2012); Sterman (2000)	Chapters 1 to 7

The next sub-section indicates the core model tests conducted on the system dynamics model formulated in the current research study.

6.3.2 Model Testing

Core System Dynamics Model Confidence-Building Tests Conducted

Table 6.3 shows the core confidence-building tests conducted on the system dynamics model of the competition between the client and the engineering consultant formulated in the current research study.

Table 6.3: Core system dynamics model confidence-building tests conducted

Test category	Test sub-category	Test name	How the test was done with Vensim software	Chapter/ Section
Model structure test	Direct structure test:	Model boundary adequacy	Causal loop diagrams, and stock and flow diagrams. Also, used model boundary charts (not part of Vensim).	Chapters 4 and 5
		Structure verification/ assessment	Causal loop diagrams, stock and flow diagrams, and Equations Editor.	Chapters 5 and 6
		Dimensional consistency test	Equations Editor and Units Check	Chapters 5 and 6
		Parameter verification/ assessment	Causal loop diagrams, stock and flow diagrams, and Equations Editor.	Chapters 4, 5 and 6
		Direct extreme-conditions (Reality checks)	Reality Checks	Chapter 6 (Section 6.3.2)
	Structure-oriented behaviour test	Indirect extreme-conditions (Reality checks)	Reality Checks	Chapter 6 (Section 6.3.2)
		Behaviour anomaly	Simulation Analysis Tools (Graph, Table and Statistics)	Chapter 6
		Family member	Subscripts [the system dynamics simulation model is based on Subscripts, except for a few common parameters (indicated in Sections 6.4.2 and 6.5.2).	Chapters 5 and 6
		Behaviour reproduction test plus parameter estimation (model calibration)	Optimize (optimisation module which makes use of the Powell conjugate search algorithm). Simulation Analysis Tools	Chapter 6 (Sections 6.4 and 6.5)
		Behaviour sensitivity test	Monte Carlo (sensitivity analysis module)	Chapter 6 (Sections 6.6.2, 6.6.4, 6.7.2, 6.7.4)
Model behaviour pattern test:	Transient, highly non-stationary behaviour	Behaviour pattern reproduction test: Graphical / visual comparisons	Optimize (optimisation module). Simulation Analysis Tools	Chapter 6 (Sections 6.4 and 6.5)
Policy implications tests		Policy optimisation and impact analysis	Optimize (optimisation module).	Chapter 6 (Section 6.8)

Details of the Computer and Software Used for Model Testing

The system dynamics model tests were conducted using Vensim DSS for Macintosh Version 6.4E software (Ventana Systems, 2018) installed on an Apple MacBook Pro 13-inch 2014 laptop with an Intel Core i5 CPU at 2.6 GHz with a 64-bit macOS High Sierra Version 10.13.6 operating system and 8 GB of RAM. Additional analysis, tables and graphs were produced using Microsoft Excel for Mac Version 16.16.3.

Direct and Indirect Extreme-Conditions (Reality checks)

Reality check tests were conducted on the system dynamics simulation model formulated in the current research study using the 'Reality Checks' module in Vensim DSS software. Reality check equations work by creating certain behavioural conditions and then checking to see if the model's internal structure generates the appropriate behavioural consequence/response as observed in reality; thus, they are statements about behaviour: "if this happens, then that must happen" (Ventana Systems, 2018).

The behavioural condition ("if this happens") is called a "test input"; whilst the combination of a behavioural condition and its associated behavioural consequence ("if this happens, then that must happen") is called a "constraint" (Ventana Systems, 2018). Test input equations are formulated using the normal model parameters and variables; while constraint equations are formulated using test inputs (only for the behavioural condition portion) and/or the normal model parameters and variables. When a constraint is violated it indicates that there is a problem with the model's internal structure (Ventana Systems, 2018).

Figures 6.1 to 6.3 show graphical representations of the reality checks (18 in total) that were conducted for the project work flow and engineering consultant project time schedule control (work intensity), client project cost controls, and engineering consultant project revenue controls, respectively, developed as part of the system dynamics simulation model presented in this thesis. In the three figures: the first 'column' contains normal model parameters and variables (as shadow variables) used in the test input equations; the second 'column' contains the test inputs (with names starting with 'TI' for test input); and the third 'column' contains the reality check constraints (with names starting with 'RC' for reality check constraint).

The three figures are interpreted as follows, using the first constraint (topmost in the third 'column') of Figure 6.1 as an example: If there is no project workforce, then there must be no project work completion. That is, if the variable 'Workforce' is forced to be equal to zero (in the test input 'TI Workforce to zero'), then the variable 'project work completion rate' must drop to zero.

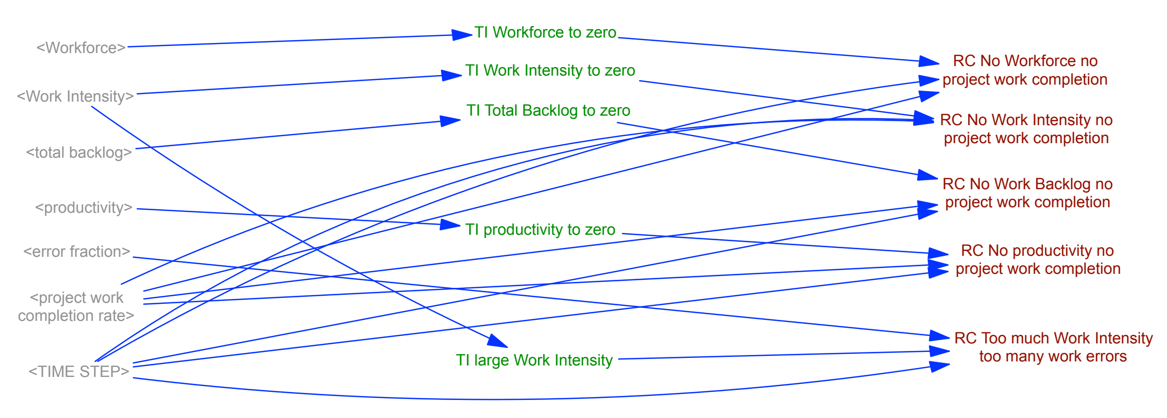


Figure 6.1: Graphical representation of the project work flow and engineering consultant project time schedule control (work intensity) reality checks

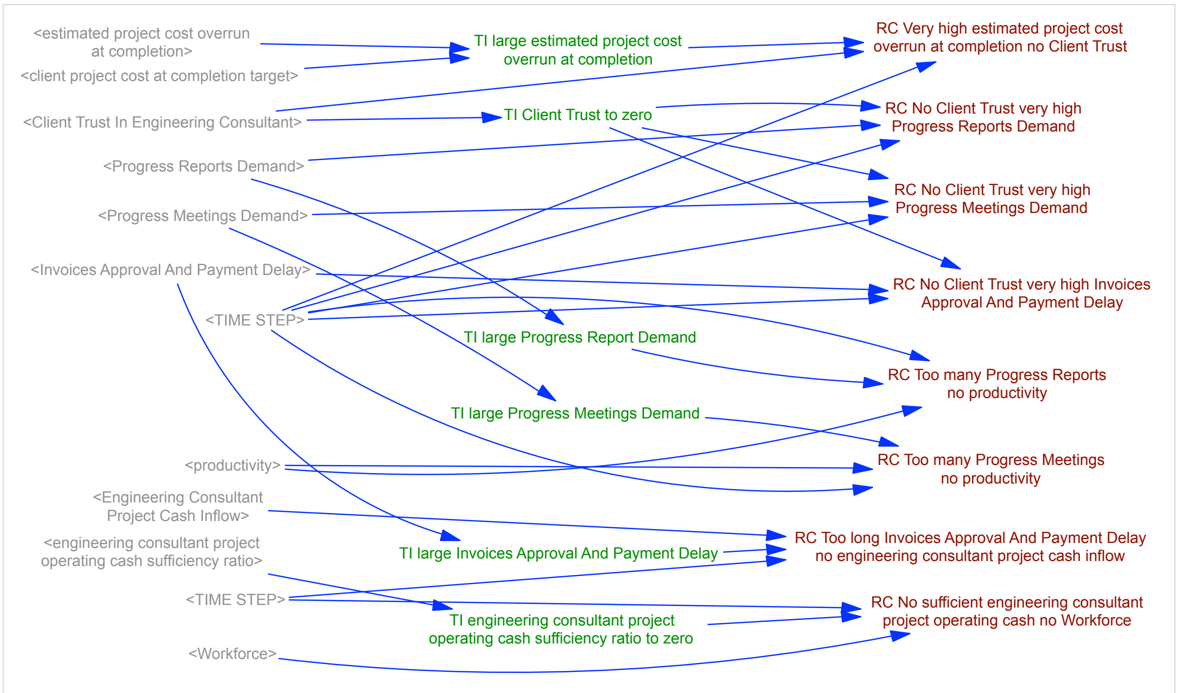


Figure 6.2: Graphical representation of the client project cost controls reality checks

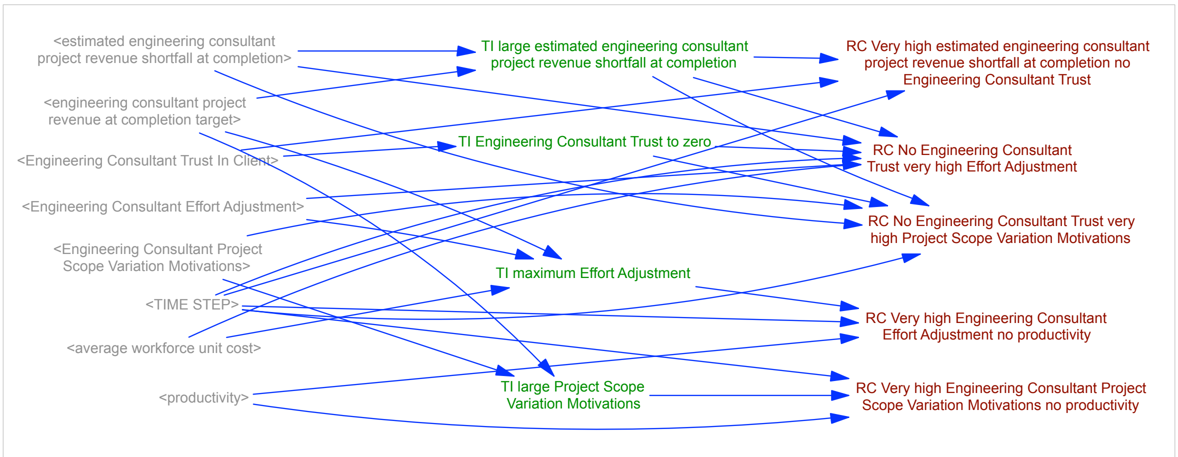


Figure 6.3: Graphical representation of the engineering consultant project revenue controls reality checks

Appendix E shows the equations for the reality checks shown in Figures 6.1 to 6.3, while Appendix F shows the constraint checking report indicating that none of the 18 constraints were violated (closeness score is 100.0% on 18 measurements).

Model Calibration

Model calibration, which is part of the wider system dynamics model testing and validation, entails estimation of values for the model parameters (model constants, which form part of model structure) so as to minimise the error between the simulated behaviour (simulation model outputs) and the corresponding observed behaviour (gathered real-world data) (Oliva, 2003; Parvan et al., 2015; Rahmandad and Sterman, 2012). When a calibrated model generates behaviour that matches the behaviour observed in the real world, it means the model cannot be rejected because of the real-world data, and thus, confidence in the model is enhanced (Oliva, 2003). However, model calibration needs to not only focus on best fit to historical data (observed behaviour), but also needs to ensure that the calibrated model also captures the observed system structural characteristics (Oliva, 2003). Hence, model calibration needs to be iterative, evaluating the calibrated parameters against the observed system structural characteristics, making necessary adjustments to parameter optimisation ranges, and recalibrating the model, as necessary (Oliva, 2003; Parvan et al., 2015).

Real-world data gathered for two sets of unique raw water infrastructure projects (10 asset management planning and support-related projects, and 8 asset renewal-related projects) were used to conduct two separate model calibrations on the system dynamics simulation model formulated in Chapter 5. Section 6.4 discusses the first model calibration which was conducted using data gathered for the first set of projects, while Section 6.5 discusses the second model calibration which was conducted using data gathered for the second set of projects. The resultant two calibrated system dynamics simulation models were then used to separately conduct similar simulation and optimisation experiments, with subsequent comparison of results from the two sets, aimed at enhancing the validity of the resulting provisional answers for research questions number 3 to 5 (posed in Section 1.6), as discussed in Sections 6.6 to 6.8.

The calibration of the system dynamics simulation model using two sets of unique projects belonging to two types of raw water infrastructure projects, as conducted in this research study, offers a novel extension to the existing system dynamics simulation model testing and validation body of knowledge, considering that model calibration in the reviewed literature was limited to either only one project (Oliva, 2003) or multiple projects of the same project type (Parvan, 2012; Parvan et al., 2015). It is, thus expected to benefit future system dynamics research studies.

6.4. Model Calibration (Infrastructure Asset Management Planning and Support Projects)

Section 6.3.2 defined and discussed 'model calibration', highlighting that real-world data gathered for two sets of unique raw water infrastructure projects were used to conduct two separate model calibrations on the system dynamics simulation model formulated in Chapter 5. This section discusses the first model calibration that was conducted using real-world data gathered for the first set of unique raw water infrastructure projects (10 asset management planning and support-related projects) considered in this research study. It effectively covers the parameter estimation and behaviour reproduction tests, which are part of the structure-oriented behaviour test as discussed in Section 6.3. The second model calibration that was conducted using real-world data gathered for the second set of unique raw water infrastructure projects (8 asset renewal-related projects) is discussed in Section 6.5.

6.4.1 Gathered Project-Specific Data

Real-world project-specific data were gathered, through individual face-to-face semi-structured interviews with both client and engineering consultant project managers, and document analysis, for use in calibrating the formulated system dynamics simulation model, in line with Oliva (2003) and Parvan et al. (2015). The real-world projects used in this study were unique raw-water infrastructure related, and made use of time-based contracts, with a ceiling price (Turner, 2004), between the client and the engineering consultant. The gathered data were for 10 unique raw water infrastructure asset management planning and support-related projects from the same engineering consultant (firm), but from varying clients.

The key data gathered for each project included, among others: the initially planned time schedule duration; actual time schedule duration; initial contract ceiling price; actual cost; initially planned scope; variations (time schedule, contract ceiling price and scope); actual cost curve (based on invoices submitted to the client by the engineering consultant, which also indicated the engineering consultant's project revenue); and actual invoice payments curve (based on client invoice payments, which also indicated the engineering consultant's project cash inflow).

Tables 6.4 shows the descriptive statistics of the 10 raw water infrastructure asset management planning and support-related projects' key project performance (time schedule and cost) data used to calibrate the system dynamics simulation model in this research study. Table 6.5 shows the key data per project from which the descriptive statistics (shown in Table 6.4) were generated. Project cost is the sum of all costs incurred by the client throughout the project life cycle (Project Management Institute, 2017). Thus, the project cost for executing a typical engineering project is the sum of all costs incurred by the client during project execution, and it includes the costs for project management services, engineering consultant services, and construction contractor works (including labour, material, equipment, and sub-contractors), among others. However, in this research study: only time-based contracts with a ceiling price (Turner, 2004) between the client and the engineering consultant were considered; and only the time-based costs for the engineering consultant services were considered for the project cost. Hence, the project cost and project time schedule duration values in Tables 6.4 and 6.5 (and the rest of this chapter) are only for the engineering consultant services.

As shown in Table 6.4, the considered projects had: initially planned project time schedule durations of between 6 months and 26 months; and initial project contract ceiling prices of between approximately R3.8 million to approximately R42.9 million. On average, the project time schedule delay was approximately 28.4% (with the actuals varying between 10.7% and 50.8%), and the project cost overrun was approximately 9.6% (with the actuals varying between -7.8% and 20.4%).

Table 6.4: Descriptive statistics of the model calibration projects data (asset management planning and support related)

Parameter / Variable	Unit	n=10				
		Median	Mean	Standard deviation	Minimum	Maximum
initially planned project time schedule duration	Month	12.0	12.9	6.8	6.0	26.0
Actual Project Time Schedule Duration	Month	14.9	16.7	9.0	7.5	34.8
Project Time Schedule Delay	*Month*	*3.8*	*3.8*	*3.0*	*0.8*	*10.8*
Project Time Schedule Delay	*%*	*27.1*	*28.4*	*14.7*	*10.7*	*50.8*
initial project contract ceiling price	R	11,380,219	13,487,151	11,752,366	3,816,529	42,936,796
Actual Project Cost	R	13,567,765	14,551,523	11,235,990	3,518,735	40,250,620
Project Cost Overrun	*R*	1,602,650	1,064,372	1,779,465	(2,686,176)	3,171,845
Project Cost Overrun	*%*	*14.2*	*9.6*	*11.3*	*-7.8*	*20.4*

Table 6.5: Model calibration projects key data (asset management planning and support related projects)

Project Code	Parameter (unit / value)							
	Initially planned project time schedule duration (Month)	Actual Project Time Schedule Duration (Month)	*Project Time Schedule Delay* (Month)	*Project Time Schedule Delay (%)*	initial project contract ceiling price (R)	Actual Project Cost (R)	*Project Cost Overrun* (R)	*Project Cost Over-run (%)*
P0	12.0	16.0	*4.0*	*33.3*	13,473,446	16,150,000	*2,676,554*	*19.9*
P1	12.0	18.1	*6.1*	*50.8*	15,021,802	17,051,200	*2,029,398*	*13.5*
P2	24.0	34.8	*10.8*	*44.8*	42,936,796	40,250,620	*(2,686,176)*	*-6.3*
P3	9.0	10.0	*1.0*	*11.1*	5,751,597	5,901,250	*149,653*	*2.6*
P4	6.0	7.5	*1.5*	*25.0*	3,840,352	3,840,352	-	*0.0*
P5	9.0	13.0	*4.0*	*44.4*	5,992,154	7,217,300	*1,225,146*	*20.4*
P6	26.0	30.0	*4.0*	*15.4*	21,278,400	24,450,245	*3,171,845*	*14.9*
P7	7.0	7.8	*0.8*	*10.7*	3,816,529	3,518,735	*(297,794)*	*-7.8*
P8	12.0	15.5	*3.5*	*29.2*	12,170,387	14,565,325	*2,394,938*	*19.7*
P9	12.0	14.3	*2.3*	*18.8*	10,590,051	12,570,205	*1,980,154*	*18.7*

6.4.2 Calibration as an Optimisation Problem

Model Calibration as an Optimisation Problem

Oliva (2003) highlighted that the model calibration problem can be expressed as a single optimization problem that has an error function (objective function) containing all the available data and allowing for the adjustment of all the necessary model parameters. Thus, the calibration of a system dynamics simulation model can be expressed as a single optimization problem as shown in Equation 6.1:

$$\text{Minimise} \quad \text{Payoff} = \text{f}\left(o_{sim,t} - o_{act,t}\right),$$
$$\text{subject to} \quad \boldsymbol{o_{sim,t}} = \boldsymbol{c}(\boldsymbol{s_t}, \boldsymbol{p}, \boldsymbol{i_t}), \quad \boldsymbol{ll} \leq \boldsymbol{p} \leq \boldsymbol{ul} \qquad (6.1)$$

where:

Payoff = objective function, a function of error between simulated model output and actual real-world data;

$o_{sim,t}$ = simulated model output variables at time *t*;

$o_{act,t}$ = actual real-world data at time *t*;

c = constraints function of model state variables, model parameters and model inputs;

s_t = model state variables at time t;
p = model parameters to be calibrated;
i_t = model inputs at time t;
ll = lower limit of model parameters feasible range;
ul = upper limit of model parameters feasible range;

In Vensim software, the: payoff function definition is captured in the *.vpd* file; functions for the model output variables are defined through model equations; lower and upper limits of the model parameters feasible ranges are captured in the *.voc* file; and calibrated parameters are saved to a *.out* file (Ventana Systems, 2018).

Model Calibration Objective Functions (Payoffs)

Parvan et al. (2015) calibrated their system dynamics simulation model of inter-phase feedbacks in design-bid-build educational building construction projects by minimising a pre-defined payoff function formed by a linear combination of three sources of error between the model simulation outputs and their corresponding real-world project data, namely project time duration, project cost, and project cost curve (based on the invoicing schedule). This research study adapted the payoff function used by Parvan et al. (2015): to new real-world data gathered for two sets of unique raw water infrastructure projects (10 asset management planning and support-related projects, and 8 asset renewal-related projects); and extending it to include the engineering consultant project cash inflow (invoice payment) curve as a fourth source of error.

Thus, the system dynamics simulation model formulated in this research study was calibrated by minimising a payoff function formed by a linear combination of four sources of error between the model simulation outputs and their corresponding real-world project data, namely project time duration, project cost, project cost curve (assumed to be based on the project invoices submitted by the engineering consultant to the client), and project invoice payment curve (which is indicative of the engineering consultant project cash inflow curve). This new payoff function, as used in this research study, helps to produce more accurate calibrated model parameters and thus, better model reproduction of observed real-world behaviour for the right reasons, owing to the additional source of error. As such, it extends the existing project model calibration payoff functions, and is expected to benefit related future research.

Equation 6.2 shows the individual project payoff function (used for individual project optimisation), whilst Equation 6.3 shows the payoff function used for simultaneous optimisation of all the 10 projects.

$$\text{Project Payoff}_i = W_t\left(\frac{T_{sim,i}-T_{act,i}}{|T_{sim,i}|+|T_{act,i}|}\right)^2 + W_c\left(\frac{C_{sim,i}-C_{act,i}}{|C_{sim,i}|+|C_{act,i}|}\right)^2 + W_{cc}\frac{1}{Dur_{sim,i}}\int_0^{Dur_{sim,i}}\left(\frac{C_{sim,i}(t)-C_{act,i}(t)}{|C_{sim,i}(t)|+|C_{act,i}(t)|}\right)^2 dt + W_{ipc}\frac{1}{Dur_{sim,i}}\int_0^{Dur_{sim,i}}\left(\frac{IP_{sim,i}(t)-IP_{act,i}(t)}{|IP_{sim,i}(t)|+|IP_{act,i}(t)|}\right)^2 dt \quad (6.2)$$

where:

W_t = weight for the project time schedule duration component;
$T_{sim,i}$ = simulated project time schedule duration for project *i*;
$T_{act,i}$ = actual project time schedule duration for project *i*;
W_c = weight for the project cost component;
$C_{sim,i}$ = simulated project total cost for project *i*;
$C_{act,i}$ = actual project total cost for project *i*;
W_{cc} = weight for the project cost curve (invoicing curve) component;
$C_{sim,i}(t)$ = simulated project cost curve (invoicing curve) for project *i*;
$C_{act,i}(t)$ = actual project cost curve (invoicing curve) for project *i*;
$Dur_{sim,i}$ = simulation final time for project *i*;
W_{ipc} = weight for the project invoice payment curve component;
$IP_{sim,i}(t)$ = simulated project invoice payment curve for project *i*;
$IP_{act,i}(t)$ = actual project invoice payment curve for project *i*;

$$\text{All Projects Payoff} = \sum_{i=1}^{n}\text{Project Payoff}_i \quad (6.3)$$

where:

n = the number of the projects considered;

Figure 6.4 shows a graphical representation of the systems dynamics simulation model calibration payoffs used in this research study that was generated using Vensim DSS software. For the full list of associated equations fundamentally developed for this new research application, refer to Appendix E.

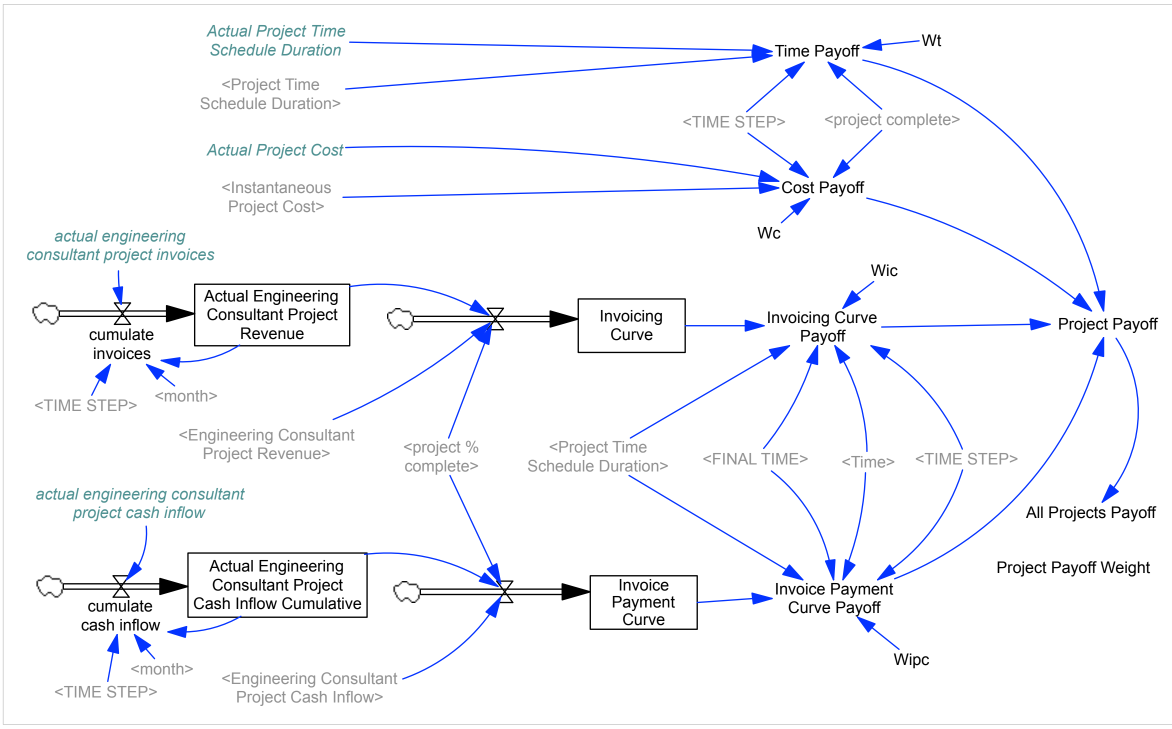


Figure 6.4: Graphical representation of the model calibration payoffs

Model Calibration Parameters

The parameters (model constants) which are used to calibrate the simulation model presented in the preceding chapter fall into two categories, namely: project-specific parameters (whose values were assumed to vary from project to project); and non-project-specific parameters (whose values were assumed to be common across all the projects), as shown in Table 6.6. In this research study, the data gathered for model calibration was from the same engineering consultant but with varying clients. Thus, all the client-related parameters were assumed to be project-specific. All the 5 engineering consultant-related parameters concerned with adjustment delays were assumed to be non-project-specific, considering that the interviewed engineering consultant project managers were managing multiple projects and they also relied on common support functions such as human resources and finance.

Table 6.6: Model calibration parameters

Parameter category	Parameter name	Related project participant	Units
Project-specific (assumed to vary from project to project)	progress reports demand policy	client	Dimensionless
	progress meetings demand policy		
	invoice approval and payment delay policy		
	progress reports demand adjustment delay		Month
	progress meetings demand adjustment delay		
	invoices approval and payment delay adjustment delay		
	effort adjustment policy	engineering consultant	Dimensionless
	project scope variation motivations policy		
	base error fraction		
	normal productivity		Tasks/(Month*person)
Non-project-specific (assumed to be common across all projects)	workforce adjustment delay	engineering consultant	Month
	work intensity adjustment delay		
	workforce fraction adjustment delay		
	engineering consultant effort adjustment delay		
	project scope variation demand adjustment delay		

The total number of parameters to be estimated was 105 (10 project-specific x 10 projects + 5 non-project-specific).

Model Calibration as an Optimisation Experiment

The system dynamics simulation model formulated in this research study was calibrated in a three-stage process, adapted from Parvan et al. (2015), as follows:

<u>*Stage 1:*</u> Vensim software's built-in optimisation module (which makes use of the Powell conjugate search algorithm) was used to simultaneously estimate all the 105 parameters (i.e. all the 10 project-specific parameters for each of the 10 projects, plus all the 5 non-project-specific parameters), providing approximate estimates for all the parameters. The optimisation was conducted simultaneously across all the 10 projects and the *All Projects Pay-off* (Equation 6.3) was used as the objective function for minimisation in the optimisation. The ability to simultaneously estimate such a large number of parameters, made possible through the use of Vensim software's 'Subscripts' (Section 5.3.2) and optimisation modules, as well as treating the model calibration process as an optimisation problem, is expected to benefit future research in two ways. Firstly, it allows the

inclusion of many relevant parameters in project models that help to deepen our understanding of project dynamic complexity, thereby enabling the development and institution of appropriate policies and structures that help enhance both project performance and the business performances of such key project participants as the engineering consultant and the construction contractor. Secondly, it allows the inclusion of many projects in a single research study, thereby enhancing the extent to which research findings can be generalised beyond their associated research study.

Stage 2: Firstly, a project by project optimisation was conducted on the model, only changing the project-specific parameters, with the 5 non-project-specific parameters fixed (unchanging) at their respective estimated values obtained from Stage 1. Thus, 10 separate calibrations with corresponding 10 *Project Pay-offs* (Equation 6.2) used as the objective functions for minimisation in the optimisation. The calibrations provided improved estimates for all the project-specific parameters.

Secondly, another optimisation was conducted on the model, this time simultaneously across all the 10 projects and only changing the 5 non-project-specific parameters, with the 100 project-specific parameters fixed (unchanging) at their respective estimated values obtained from the preceding step. The *All Projects Pay-off* (Equation 6.3) was used as the objective function for minimisation in the optimisation. The calibration provided improved estimates for all the non-project-specific parameters.

Stage 3: A final optimisation was conducted on the model, this time simultaneously across all the 10 projects and changing all the 105 parameters (both project-specific and non-project-specific), starting from the values obtain in the preceding step. The *All Projects Pay-off* (Equation 6.3) was used as the objective function for minimisation in the optimisation. The calibration provided more fine-tuned estimates for all the parameters.

Appendix G shows the simulation model calibration configuration details (for the final optimisation) text of the: payoff (objective function) definition *.vpd* file; and the optimisation control *.voc* file, which also indicates the parameter search space (lower and upper limits of the model parameters’ feasible ranges). Specifying the lower and upper limits of the feasible range for each and every model parameter to be automatically estimated using the Vensim software’s built-in optimisation module helps to obtain more accurate/feasible estimates for the parameters. It eliminates the risk of obtaining parameter estimates that are meaningless/infeasible in the real world but make the simulation model outputs match the real-world observed behaviour. The next sub-section presents the final results of the calibration process.

6.4.3 Calibration results

Calibrated Parameters

The final values of all the calibrated parameters for all the 10 asset management planning and support-related projects were saved in the calibration (optimisation) output *.out* file. Table 6.7 shows the final calibrated non-project-specific parameters (those whose values were assumed to be common across all the projects); whilst Table 6.8 shows the descriptive statistics of the final calibrated project-specific parameters (those whose values were assumed to vary from project to project). The values of the calibrated parameters shown in Tables 6.7 and 6.8 are the optimal values of the parameters which resulted in the minimisation of the *All Projects Pay-off* (refer to Equation 6.3) during the Stage 3 of the optimisation procedure discussed in the preceding sub-section.

Table 6.7: Calibrated non-project-specific parameters (asset management planning and support related projects)

Parameter name	Units	Calibrated value
workforce adjustment delay	Month	0.262
work intensity adjustment delay	Month	0.050
workforce fraction adjustment delay	Month	0.184
engineering consultant effort adjustment delay	Month	0.397
project scope variation demand adjustment delay	Month	0.905

Table 6.8: Descriptive statistics of the calibrated project-specific parameters (asset management planning and support related projects)

Parameter name	Units	N=10				
		Median	Mean	Standard deviation	Minimum	Maximum
progress reports demand policy	Dimensionless	0.271	0.205	0.162	0.000	0.418
progress meetings demand policy	Dimensionless	0.312	0.279	0.076	0.120	0.354
invoice approval and payment delay policy	Dimensionless	0.305	0.302	0.179	0.035	0.697
effort adjustment policy	Dimensionless	0.525	0.536	0.044	0.500	0.635
project scope variation motivations policy	Dimensionless	0.500	0.568	0.140	0.500	0.941
base error fraction	Dimensionless	0.250	0.233	0.079	0.131	0.400
normal productivity	Tasks / (Month x person)	9.418	10.981	5.878	4.690	21.700
progress reports demand adjustment delay	Month	0.125	0.701	1.196	0.050	3.888
progress meetings demand adjustment delay	Month	0.125	0.162	0.119	0.050	0.450
invoices approval and payment delay adjustment delay	Month	3.112	3.026	1.425	0.595	6.000

Calibration Errors (Behaviour Reproduction Tests Results)

The mean absolute percentage error (MAPE), which is one key type of a behaviour reproduction test measure according to Sterman (2000), was used as the calibration error descriptive statistic in this research study. The MAPE measure is a point-by-point fit (correspondence) error measure between the simulated model output and its corresponding observed real-world data (Sterman, 2000). The formula for calculating a simple dimensionless MAPE is as shown in Equation 6.4.

For each project, five different calibration errors (MAPE values) were determined, namely, calibration errors for: final project time schedule duration (T MAPE); final project cost (C MAPE); project cost curve (same as engineering consultant project revenue curve) (CC MAPE); project invoices payment curve (engineering consultant project cash inflow curve) (IPC MAPE); and the overall calibration error (O MAPE).

Equation 6.4, consistent with Sterman (2000) for the determination of a dimensionless MAPE, was used for determining each of the constituent calibration errors (dimensionless T MAPE, C MAPE, CC MAPE and IPC MAPE) for each project; whilst Equation 6.5, adapted from Parvan et al. (2015), was used for the overall calibration error (dimensionless O MAPE) for each project. The O MAPE is a weighted average of the four constituent calibration errors (T MAPE, C MAPE, CC MAPE and IPC MAPE). The weights (W_t, W_c, W_{cc} and W_{ipc}) used in the calculation of the O MAPE (Equation 6.5) were exactly the same as those used in the project payoff function (Equation 6.2). While Equations 6.4 and 6.5 yield dimensionless MAPE values (as used in this research study), multiplying the two equations by 100 would yield the percentage values.

$$MAPE_i = \frac{1}{n}\sum_{i=1}^{n}\frac{|X_{sim,i} - X_{act,i}|}{X_{act,i}} \tag{6.4}$$

where:

n = the number of data points considered (n=1 for T MAPE and C MAPE; and n=50 for CC MAPE and IPC MAPE).

$$\text{O MAPE} = W_t(T\ MAPE) + W_c(C\ MAPE) + W_{cc}(CC\ MAPE) + W_{ipc}(IPC\ MAPE) \tag{6.5}$$

where:

W_t = weight for the project time schedule duration component;

W_c = weight for the project cost component;

W_{cc} = weight for the project cost curve component;

W_{ipc} = weight for the project invoice payment curve component.

Table 6.9 shows the five calibration errors, dimensionless (not percentage) T MAPE, C MAPE, CC MAPE, IPC MAPE and O MAPE, for each project, sorted in descending order of the overall calibration error (dimensionless O MAPE); whilst Figure 6.5 is a graphical representation of the same. Project [P7] had the least overall calibration error (indicating the project with the best-fit between the simulated outputs and the observed real-world project data); whilst Project [P2] had the largest overall calibration error (accordingly it is the project with the worst-fit), as shown in Table 6.9 and Figure 6.5.

Table 6.9: Calibration errors (dimensionless MAPE values) per project (asset management planning and support related projects)

Project No.	Mean Absolute Percent Error (MAPE) [Dimensionless Values (Not %)]				
	T MAPE	C MAPE	CC MAPE	IPC MAPE	O MAPE
[P2]	0.058	0.131	0.362	0.322	0.177
[P6]	0.042	0.074	0.247	0.358	0.139
[P9]	0.090	0.072	0.095	0.069	0.081
[P3]	0.028	0.027	0.116	0.176	0.067
[P5]	0.017	0.038	0.085	0.151	0.058
[P8]	0.010	0.014	0.118	0.138	0.051
[P0]	0.008	0.015	0.051	0.112	0.035
[P1]	0.005	0.013	0.031	0.040	0.018
[P4]	0.000	0.004	0.026	0.045	0.013
[P7]	0.000	0.001	0.009	0.042	0.009

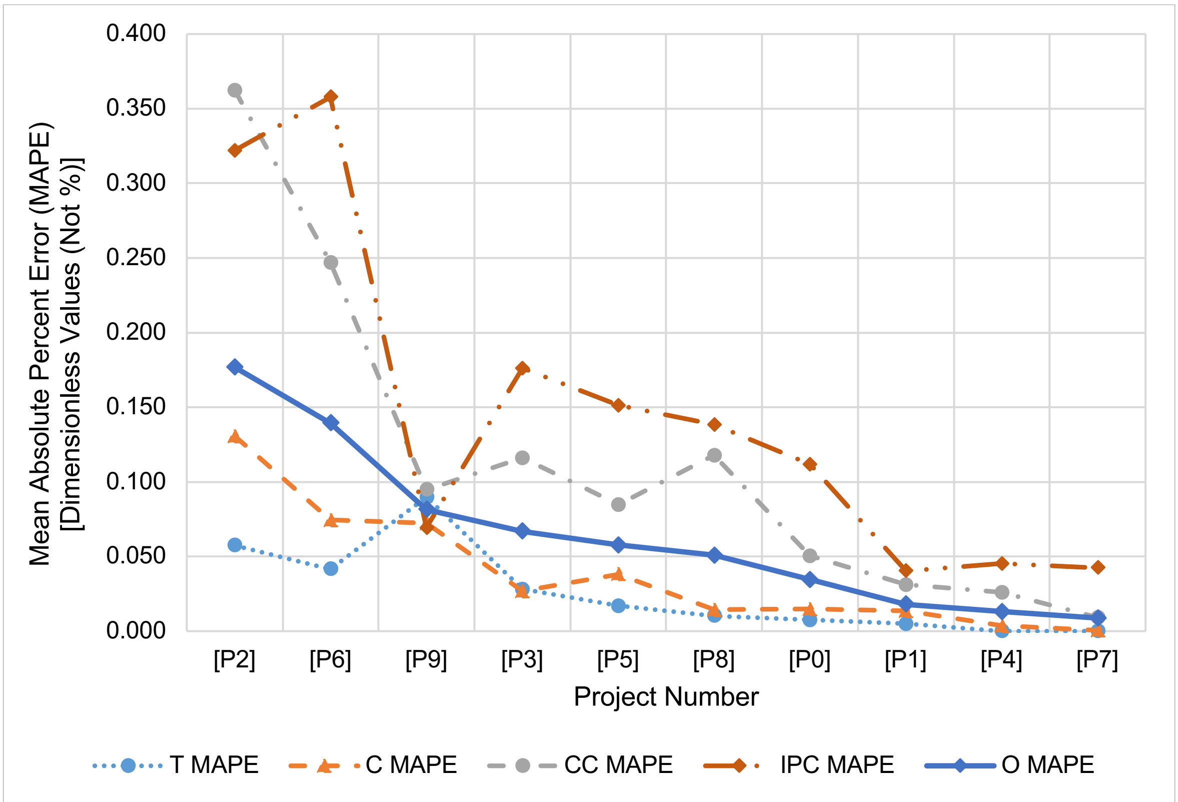
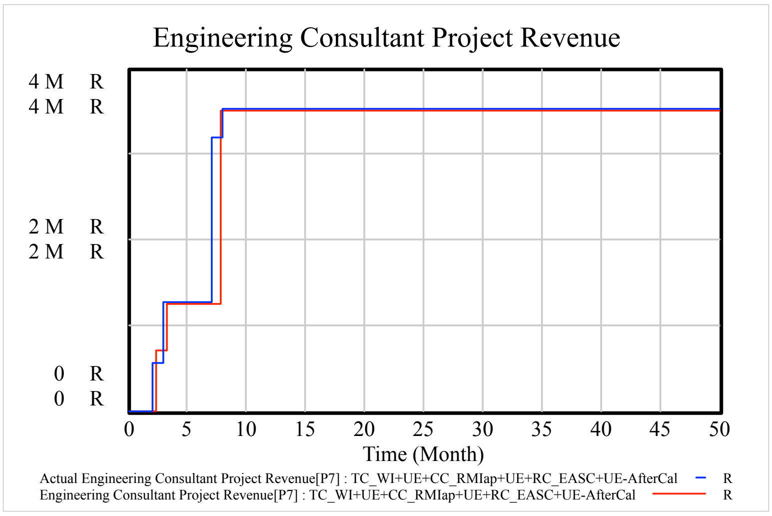


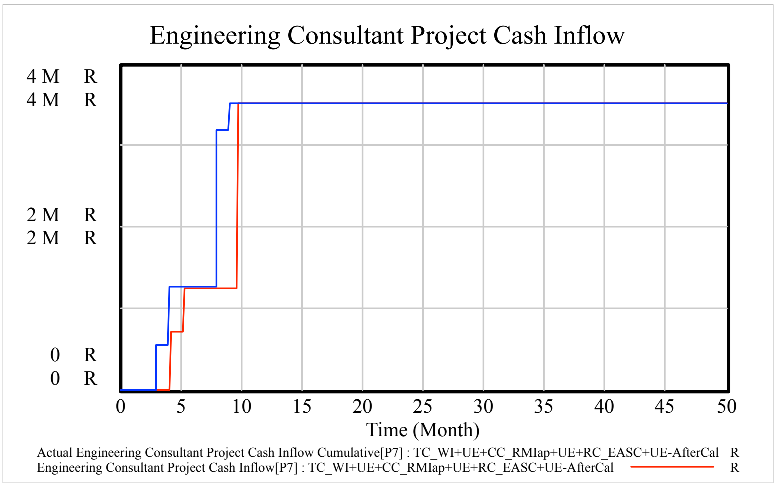
Figure 6.5: Calibration errors (dimensionless MAPE values) per project (asset management planning and support related projects)

Figures 6.6 and 6.7 show the simulated output versus the actual observed data for the best-fit project (Project [P7]) and the worst-fit project (Project [P2]) among the 10 calibrated asset management planning and support related projects.

Project cost curve (engineering consultant project revenue curve):



Project invoices payment curve (engineering consultant project cash inflow curve):

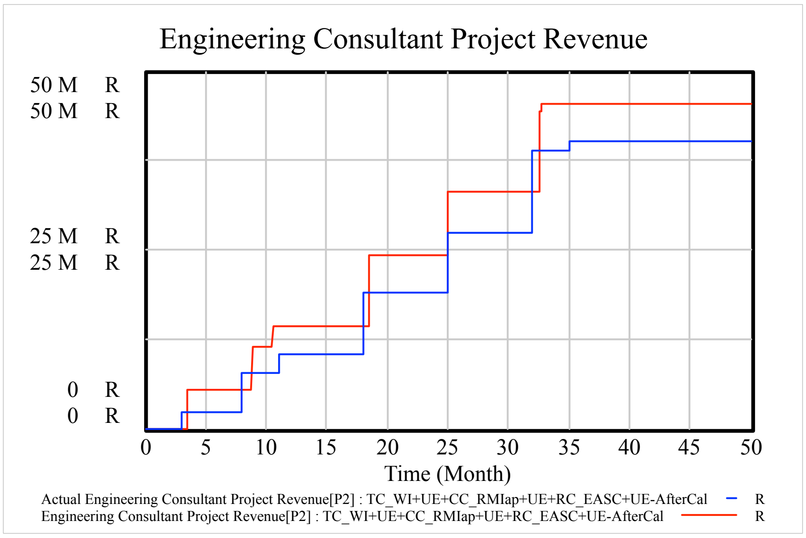


Project time schedule duration:
7.75 months (simulated and actual)

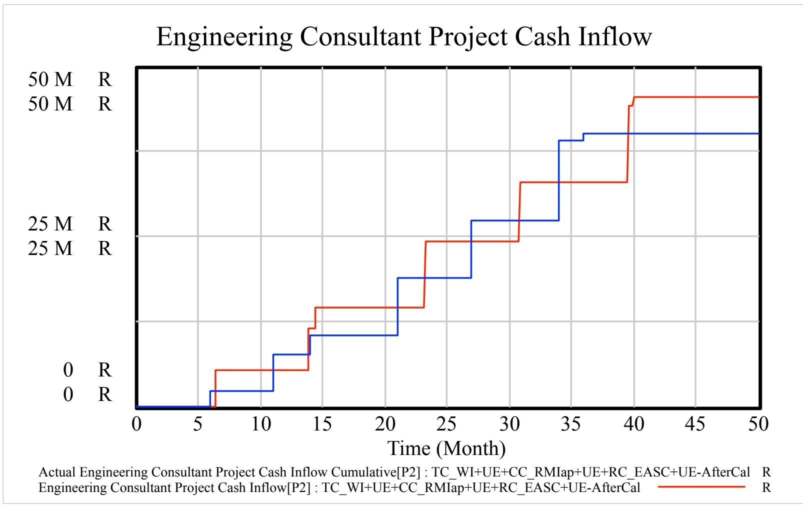
Project cost (engineering consultant project revenue):
R3.517 million (simulated); R3.519 million (actual)

Figure 6.6: Simulated output vs actual observed data (best-fit, Project [P7]) (asset management planning and support related projects)

Project cost curve (engineering consultant project revenue curve):



Project invoices payment curve (engineering consultant project cash inflow curve):



Project time schedule duration:
32.75 months (simulated);
34.75 months (actual)

Project cost (engineering consultant project revenue):
R45.510 million (simulated);
R40.250 million (actual)

Figure 6.7: Simulated output vs actual observed data (worst-fit, Project [P2]) (asset management planning and support related projects)

6.4.4 Discussion

Model calibration, as part of the wider system dynamics model testing and validation, entails estimation of values for the model parameters (model constants, which form part of model structure) so as to minimise the error between the simulated behaviour (simulation model outputs) and the corresponding observed behaviour (gathered real-world data) (Oliva, 2003; Parvan et al., 2015; Rahmandad and Sterman, 2012). In this research study, the system dynamics simulation model calibration problem was expressed as a single optimization problem that has an error function (objective function / payoff) containing all the relevant available data and allowing for the adjustment of certain model parameters, as recommended by Oliva (2003). Two project payoffs were defined and used (for minimisation during the optimisation process), namely: the *Project Pay-off* (used for individual project optimisation); and the *All Projects Pay-off* (sum of the individual *Project Pay-offs* used for simultaneous optimisation of all the 10 projects).

Parvan et al. (2015) calibrated their system dynamics simulation model of inter-phase feedbacks in design-bid-build educational building construction projects by minimising a pre-defined payoff function formed by a linear combination of three sources of error between the model simulation outputs and their corresponding real-world project data, namely project time duration, project cost, and project cost curve (based on the invoicing schedule). This research study adapted the payoff function used by Parvan et al. (2015): to new data gathered for two sets of unique raw water infrastructure projects (10 asset management planning and support-related, and 8 asset renewal-related); and extending it to include the engineering consultant project cash inflow (invoice payment) curve as a fourth source of error.

Thus, the *Project Pay-off* was formulated as a linear combination of four sources of error between key model simulation outputs and their associated real-world project data, namely project time duration, project cost, project cost curve (assumed to be based on the project invoices submitted by the engineering consultant to the client), and project invoice payment curve (which is indicative of the engineering consultant project cash inflow curve). This new payoff function, as used in this research study, helps to produce more accurate calibrated model parameters and thus, better model reproduction of observed real-world behaviour for the right reasons, owing to the additional source of error. Thus, it extends the existing project model calibration payoff functions, and is expected to benefit future research.

Real-world data gathered for the first set of unique raw water infrastructure projects (asset management planning and support-related, made up of 10 projects) were used in the model calibration discussed in this Section 6.4. Vensim software's built-in optimisation module (which makes use of the Powell conjugate search algorithm) was used to simultaneously estimate all the 105 parameters (10 project-specific x 10 projects + 5 non-project-specific) so as to minimise the error between the simulated behaviour (simulation model outputs) and the corresponding observed behaviour (gathered real-world data). The ability to simultaneously estimate such a large number of parameters, made possible through the use of Vensim software's 'Subscripts' (Section 5.3.2) and optimisation modules, as well as treating the model calibration process as an optimisation problem, is expected to benefit future research in two ways. Firstly, it allows the inclusion of many relevant parameters in project models that help to deepen our understanding of project dynamic complexity, thereby enabling the development and institution of appropriate policies and structures that help enhance both project performance and the business performances of such key project participants as the engineering consultant and the construction contractor. Secondly, it allows the inclusion of many projects in a single research study, thereby enhancing the extent to which research findings can be generalised beyond their associated research study.

The calibration error descriptive statistic used in this research study was the mean absolute percentage error (MAPE), which is one key type of a behaviour reproduction test measure according to Sterman (2000). The MAPE measure is a point-by-point fit (correspondence) error measure between the simulated model output and its corresponding observed real-world data (Sterman, 2000).

While the model calibration test results, as presented in Section 6.4.3, helped to build confidence in the system dynamics simulation model formulated in this research study, calibration is only a partial (model) test of the causal link between structure and behaviour as highlighted by Oliva (2003). Thus, generating observed behaviour does not necessarily make the model right; this is due to the possibility of many other rival hypotheses (structures that may be capable of generating the same observed real-world behaviour) as highlighted by Oliva (2003) and Sterman (2000). Hence, the need to conduct multiple model tests so as to assist in ruling out more possible alternative explanations, thereby building more confidence in the model and ensuring that the model generates ‘the right behaviour for the right reasons’ (Oliva, 2003; Sterman, 2000). The complete list of tests conducted on the system dynamics simulation model formulated in this study is as shown in Section 6.3.2.

None of the 10 raw water infrastructure asset management planning and support-related projects used in the model calibration provided a 100% match between the model simulated output and the real-world project data (dimensionless O MAPE values ranged from 0.009 to 0.177). Possible alternative explanations for the difference between the simulated model outputs and the observed behaviours may include, among others:

- simplifying assumptions made in the model, such as the use of average values for workforce salary, normal productivity and base error fraction;
- measurement errors in the gathered real-world project data; and
- other factors not included in the model, such as client delays in reviewing and/or approving deliverables, force majeure events (like strikes), delays by the engineering consultant in invoicing, and premature invoicing.

As discussed in Section 6.3.2, real-world data gathered for two sets of unique raw water infrastructure projects were used to conduct two separate model calibrations on the system dynamics simulation model formulated in Chapter 5. The first model calibration was conducted using data gathered for the first set of unique raw water infrastructure projects (10 asset management planning and support-related projects), as discussed in this Section 6.4. The next section discusses the second model calibration that was conducted using data gathered for the second set of unique raw water infrastructure projects (8 asset renewal-related projects). The resultant two calibrated system dynamics simulation models were then separately used to conduct some simulation and optimisation experiments, with subsequent comparison of results from the two sets, yielding more valid provisional answers for research questions number 3 to 5 (Section 1.6), as discussed in Sections 6.6 to 6.8.

The calibration of a system dynamics simulation model using two sets of unique projects belonging to two types of raw water infrastructure projects, as conducted in this research study, is a novel extension to the existing system dynamics simulation model testing and validation body of knowledge, considering that model calibration in the reviewed literature was limited to either only one project (Oliva, 2003) or multiple projects of the same project type (Parvan, 2012; Parvan et al., 2015). As such, it is expected to benefit future research studies by making it possible to conduct, in a single research study, separate simulation and optimisation experiments using data gathered for two or more sets of projects (belonging to two or more types of projects), with subsequent comparison of results from the different sets, thereby enhancing the validity of the research findings and the extent to which the findings can be generalised beyond their associated research study.

6.5. Model Calibration (Infrastructure Asset Renewal Projects)

Section 6.3.2 defined and discussed ‘model calibration’, highlighting that real-world data gathered for two sets of unique raw water infrastructure projects were used to conduct two separate model calibrations on the system dynamics simulation model formulated in Chapter 5. Section 6.4 discussed the first model calibration that was conducted using data gathered for the first set of unique raw water infrastructure projects (10 asset management planning and support-related projects) considered in this study. This section discusses the second model calibration that was conducted using data gathered for the second set of unique raw water infrastructure projects (8 asset renewal-related projects) considered in this research study. It effectively covers the parameter estimation and behaviour reproduction tests, which are part of the structure-oriented behaviour test as discussed in Section 6.3.

As discussed in Section 6.3.2, the two model calibrations were conducted so as to produce two calibrated system dynamics simulation models which would then be used to separately conduct similar simulation and optimisation experiments, with subsequent comparison of results from the two sets, yielding more valid provisional answers for research questions number 3 to 5 (posed in Section 1.6), as discussed later in Sections 6.6 to 6.8.

6.5.1 Gathered Project-Specific Data

Data were gathered for 8 further new/unique raw water infrastructure asset renewal-related projects from the same engineering consultant (firm), but from varying clients, similar to the first set of projects discussed in Section 6.4.1. Table 6.10 shows the descriptive statistics of the 8 projects' key project performance (time schedule and cost) data used to calibrate the system dynamics simulation model formulated and presented in Chapter 5. Table 6.11 shows the key data per project from which the descriptive statistics (shown in Table 6.10) were generated. Similar to the first set of projects discussed in Section 6.4.1, the project cost and project time schedule duration values in Tables 6.10 and 6.11 (and the rest of this chapter) are only for the engineering consultant services.

As shown in Table 6.10, the considered projects had: initially planned project time schedule durations of between 4 months and 10 months; and initial project contract ceiling prices of between approximately R2.5 million to approximately R7.6 million. On average, the project time schedule delay was approximately 29.3% (with the actuals varying between 10% and 62.5%); and the project cost overrun was approximately 10.9% (with the actuals varying between 0% and 22.2%).

Table 6.10: Descriptive statistics of the model calibration projects data (asset renewal-related)

Parameter / Variable	Unit	n=8				
		Median	Mean	Standard Deviation	Minimum	Maximum
initially planned project time schedule duration	Month	6.00	6.75	2.31	4.00	10.00
Actual Project Time Schedule Duration	Month	7.75	8.84	3.52	4.75	14.00
Project Time Schedule Delay	*Month*	*1.50*	*2.09*	*1.58*	*0.50*	*5.00*
Project Time Schedule Delay	*%*	*27.5%*	*29.3%*	*16.6%*	*10.0%*	*62.5%*
initial project contract ceiling price	R	3,819,198	4,555,696	2,063,855	2,535,273	7,591,531
Actual Project Cost	R	4,329,125	5,139,069	2,526,529	2,632,243	8,500,000
Project Cost Overrun	*R*	*509,927*	*583,374*	*514,058*	*-*	*1,479,694*
Project Cost Overrun	*%*	*12.0%*	*10.9%*	*7.6%*	*0.0%*	*22.2%*

Table 6.11: Model calibration projects key data (asset renewal-related)

Project Code	Parameter (unit / value)							
	Initially planned project time schedule duration (Month)	Actual Project Time Schedule Duration (Month)	*Project Time Schedule Delay (Month)*	*Project Time Schedule Delay (%)*	initial project contract ceiling price (R)	Actual Project Cost (R)	*Project Cost Overrun (R)*	*Project Cost Over-run (%)*
P10	10.00	14.00	4.0	40.0%	6,520,756	7,500,000	979,244	15.0%
P11	5.00	6.50	1.5	30.0%	2,857,062	2,857,062	-	0.0%
P12	4.00	4.75	0.8	18.8%	2,535,273	2,815,000	279,727	11.0%
P13	6.00	7.50	1.5	25.0%	4,326,716	4,850,100	523,384	12.1%
P14	10.00	11.50	1.5	15.0%	7,591,531	8,500,000	908,469	12.0%
P15	6.00	8.00	2.0	33.3%	3,311,679	3,808,150	496,471	15.0%
P16	8.00	13.00	5.0	62.5%	6,670,306	8,150,000	1,479,694	22.2%
P17	5.00	5.50	0.5	10.0%	2,632,243	2,632,243	-	0.0%

6.5.2 Calibration as an Optimisation Problem

The second model calibration that was conducted using data gathered for the second set of unique raw water infrastructure projects (8 asset renewal-related projects) was done exactly the same way as the first model calibration that was conducted using data gathered for the first set of unique raw water infrastructure projects (10 asset management planning and support-related projects) as discussed in Section 6.4. Thus, the same expression of the calibration problem as a single optimization problem, the model calibration optimisation objective functions/payoffs (Equations 6.2 and 6.3), the parameters (model constants) estimated (10 project-specific parameters per project and 5 non-project-specific parameters, as shown in Table 6.6), the three-stage model calibration process, and the simulation model calibration configuration details (Appendix G) used for the first model calibration (conducted using the asset management planning and support-related projects data) as discussed in Section 6.4.2, were all utilised in the second model calibration (conducted using the asset renewal-related projects data).

It was necessary to follow the same calibration process considering that: the two model calibrations were being conducted (though separately) on exactly the same system dynamics simulation model formulated in Chapter 5; and the resultant two calibrated system dynamics simulation models would then be used to separately conduct similar simulation and optimisation experiments, with subsequent comparison of results from the two sets, so as to yield more valid provisional answers for research questions number 3 to 5 (posed in Section 1.6), as discussed later in Sections 6.6 to 6.8. It is also a novel contribution towards the enhancement of the existing system dynamics simulation model testing and validation procedures.

The only difference between the two model calibrations was the total number of parameters estimated: 105 (10 project-specific x 10 asset management planning and support-related projects + 5 non-project-specific) for the first calibration, and 85 (10 project-specific x 8 asset renewal-related projects + 5 non-project-specific) for the second calibration, owing to the difference in the number of projects considered.

As discussed in Section 6.4.2, the parameters (model constants) estimated fell into two categories, namely: project-specific parameters (whose values were assumed to vary from project to project); and non-project-specific parameters (whose values were assumed to be common across all the projects), as shown in Table 6.6. The data gathered for the model calibrations were from the same engineering consultant but with varying clients. Thus, all the client-related parameters were assumed to be project-specific. All the 5 engineering consultant-related parameters concerned with adjustment delays were assumed to be non-project-specific, considering that the interviewed engineering consultant project managers were managing multiple projects and they also relied on common support functions such as human resources and finance.

The next sub-section presents the final results of the second model calibration.

6.5.3 Calibration results

Calibrated Parameters

The final values of all the calibrated parameters for all the 8 asset renewal-related projects were saved in the calibration (optimisation) output *.out* file. Table 6.12 shows the final calibrated non-project-specific parameters; while Table 6.13 shows the descriptive statistics of the final calibrated project-specific parameters. The values of the calibrated parameters shown in Tables 6.12 and 6.13 are the optimal values of the parameters which resulted in the minimisation of the *All Projects Pay-off* (Equation 6.3 in Section 6.4.2) during Stage 3 of the optimisation procedure discussed in Section 6.4.2.

Table 6.12: Calibrated non-project-specific parameters (asset renewal-related projects)

Parameter Name	Units	Calibrated Value
workforce adjustment delay	Month	0.250
work intensity adjustment delay	Month	0.125
workforce fraction adjustment delay	Month	0.122
engineering consultant effort adjustment delay	Month	0.125
project scope variation demand adjustment delay	Month	0.115

Table 6.13: Descriptive statistics of the calibrated project-specific parameters (asset renewal-related projects)

Parameter Name	Units	n=8				
		Median	Mean	Standard Deviation	Minimum	Maximum
progress reports demand policy	Dimensionless	0.333	0.358	0.209	0.078	0.810
progress meetings demand policy	Dimensionless	0.329	0.282	0.126	0.000	0.424
invoice approval and payment delay policy	Dimensionless	0.332	0.325	0.137	0.055	0.489
effort adjustment policy	Dimensionless	0.500	0.511	0.024	0.500	0.566
project scope variation motivations policy	Dimensionless	0.500	0.500	0.000	0.500	0.500
base error fraction	Dimensionless	0.202	0.212	0.055	0.144	0.317
normal productivity	Tasks / (Month x person)	19.309	21.624	9.515	12.376	42.000
progress reports demand adjustment delay	Month	0.170	0.505	0.700	0.050	1.847
progress meetings demand adjustment delay	Month	0.125	0.168	0.100	0.050	0.360
invoices approval and payment delay adjustment delay	Month	3.096	3.438	1.147	2.113	6.000

Calibration Errors (Behaviour Reproduction Tests Results)

As discussed in Section 6.4.3, the calibration error descriptive statistic used in this research study was the mean absolute percentage error (MAPE), and for each project five different calibration errors (MAPE values) were determined, namely the calibration errors for: final project time schedule duration (T MAPE); final project cost (C MAPE); project cost curve (same as engineering consultant project revenue curve) (CC MAPE); project invoices payment curve (engineering consultant project cash inflow curve) (IPC MAPE); and the overall calibration error (O MAPE). Also, Equation 6.4 was used for determining each of the constituent calibration errors (dimensionless T MAPE, C MAPE, CC MAPE and IPC MAPE) for each project; while Equation 6.5 was used for the overall calibration error (dimensionless O MAPE) for each project.

Table 6.14 shows the five calibration errors, dimensionless (not percentage) MAPE values, for each project, sorted in descending order of the overall calibration error (dimensionless O MAPE); while Figure 6.8 is a graphical representation of the same. Project [P17] had the least overall calibration error (indicating the project with the best-fit between the simulated outputs and the observed real-world project data);

whilst Project [P14] had the largest overall calibration error (and accordingly it is the project with the worst-fit).

Table 6.14: Calibration errors (dimensionless MAPE values) per project (asset renewal-related)

Project No.	Mean Absolute Percent Error (MAPE) [Dimensionless Values (Not %)]				
	T MAPE	C MAPE	CC MAPE	IPC MAPE	O MAPE
[P14]	0.024	0.021	0.072	0.066	0.038
[P10]	0.018	0.021	0.054	0.068	0.033
[P15]	0.000	0.007	0.047	0.090	0.025
[P13]	0.004	0.020	0.034	0.044	0.021
[P16]	0.002	0.003	0.033	0.053	0.016
[P11]	0.005	0.007	0.021	0.042	0.014
[P12]	0.007	0.003	0.003	0.037	0.010
[P17]	0.000	0.001	0.022	0.031	0.009

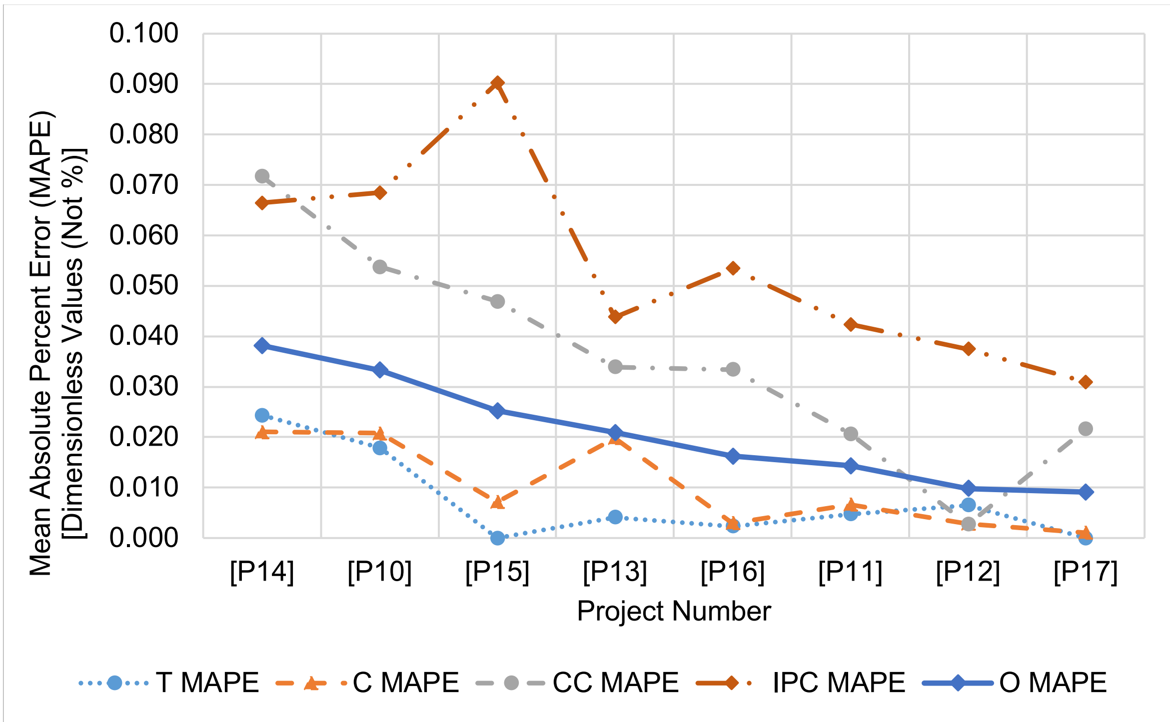
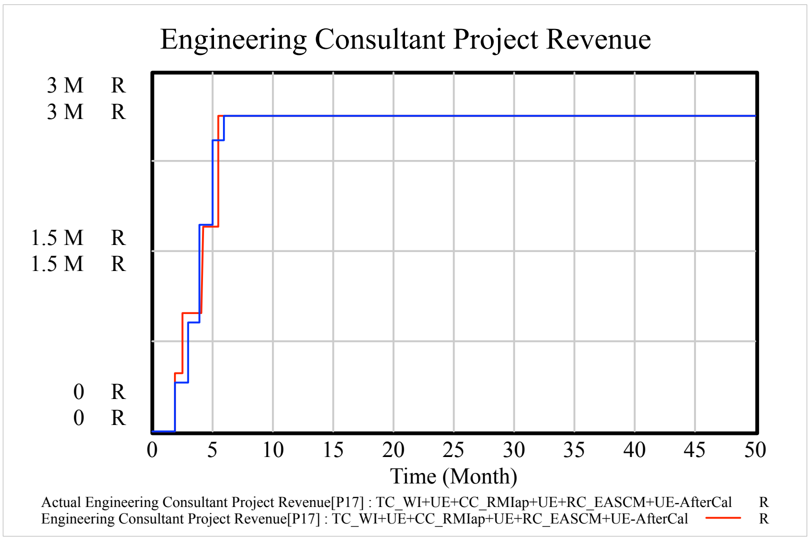


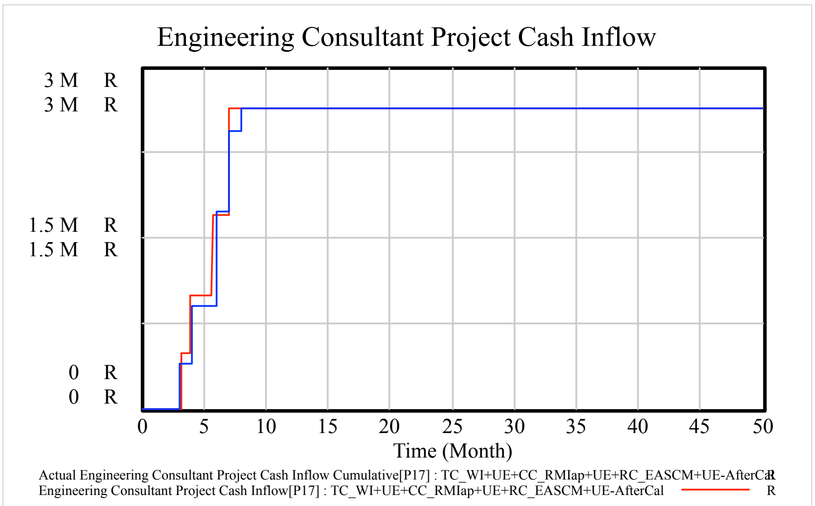
Figure 6.8: Calibration errors (dimensionless MAPE values) per project (asset renewal-related)

Figures 6.9 and 6.10 show the simulated output versus the actual observed data for the best-fit project (Project [P17]) and the worst-fit project (Project [P14]), respectively, among the 8 calibrated asset renewal-related projects.

Project cost curve (engineering consultant project revenue curve):



Project invoices payment curve (engineering consultant project cash inflow curve):

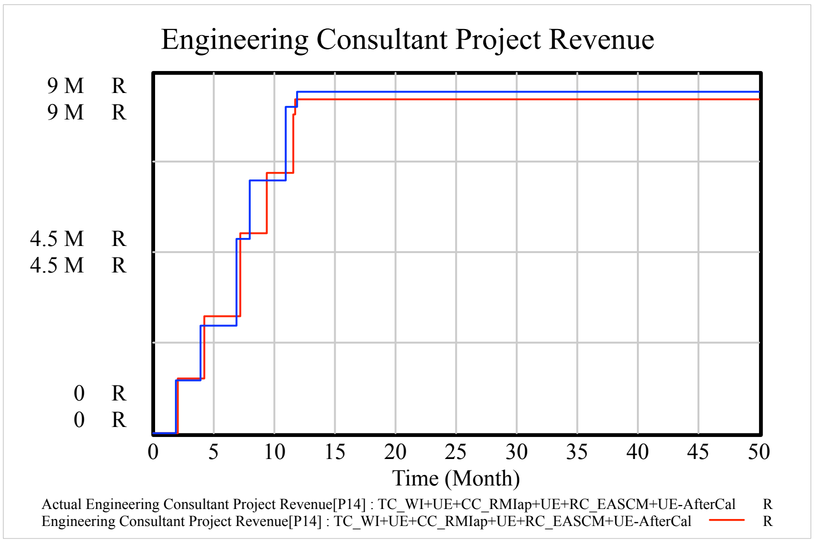


Project time schedule duration:
5.5 months (simulated);
5.5 months (actual)

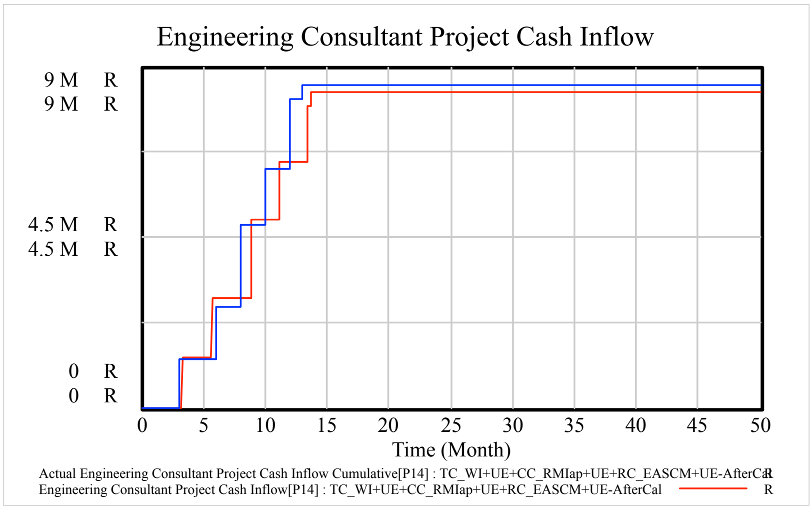
Project cost (engineering consultant project revenue):
R2.635 million (simulated);
R2.632 million (actual)

Figure 6.9: Simulated output vs actual data (best-fit, Project [P17]) (asset renewal-related)

Project cost curve (engineering consultant project revenue curve):



Project invoices payment curve (engineering consultant project cash inflow curve):



Project time schedule duration:
11.78 months (simulated);
11.50 months (actual)

Project cost (engineering consultant project revenue):
R8.321 million (simulated);
R8.500 million (actual)

Figure 6.10: Simulated output vs actual observed data (worst-fit, Project [P14]) (asset renewal-related projects)

6.5.4 Discussion

Section 6.3.2 defined and discussed 'model calibration', highlighting that real-world data gathered for two sets of unique raw water infrastructure projects were used to conduct two separate model calibrations on the system dynamics simulation model formulated in Chapter 5. Section 6.4 discussed the first model calibration that was conducted using data gathered for the first set of unique raw water infrastructure projects (10 asset management planning and support-related projects). Sections 6.5.1 to 6.5.3 discussed the second model calibration that was conducted using data gathered for the second set of unique raw water infrastructure projects (8 asset renewal-related projects) considered in this research study.

As discussed in Section 6.3.2, the two model calibrations were conducted so as to produce two calibrated system dynamics simulation models which would then be used to separately conduct similar simulation and optimisation experiments, with subsequent comparison of results from the two sets, in order to yield more valid provisional answers for research questions number 3 to 5 (posed in Section 1.6), as discussed later in Sections 6.6 to 6.8.

The second model calibration was conducted in exactly the same way as the first model calibration that was conducted, which was discussed in Section 6.4. Thus, the same expression of the calibration problem as a single optimization problem, the model calibration optimisation objective functions/payoffs (Equations 6.2 and 6.3), the parameters (model constants) estimated (10 project-specific parameters per project and 5 non-project-specific parameters, as shown in Table 6.6), the three-stage model calibration process, and the simulation model calibration configuration details (Appendix G) used for the first model calibration (conducted using the 10 asset management planning and support-related projects data), as discussed in Section 6.4.2, were all utilised in the second model calibration (conducted using the 8 asset renewal-related projects data).

It was necessary to follow the same calibration process considering that: the two model calibrations were being conducted (though separately) on exactly the same system dynamics simulation model formulated in Chapter 5; and the resultant two calibrated system dynamics simulation models would then be used to separately conduct similar simulation and optimisation experiments, with subsequent comparison of results from the two sets, so as to yield more valid provisional answers for research questions number 3 to 5 (posed in Section 1.6), as discussed later in Sections 6.6 to 6.8. It is also a novel contribution towards the enhancement of the existing system dynamics simulation model testing and validation procedures.

The only difference between the two model calibrations was the total number of parameters estimated: 105 (10 project-specific x 10 asset management planning and support-related projects + 5 non-project-specific) for the first calibration, and 85 (10 project-specific x 8 asset renewal-related projects + 5 non-project-specific) for the second calibration, owing to the difference in the number of projects considered.

While the second model calibration test results, as presented in Section 6.5.3, helped to build confidence in the model, none of the 8 raw water infrastructure asset renewal-related projects used in the model calibration provided a 100% match between the model simulated output and the real-world project data (dimensionless O MAPE ranged from 0.009 to 0.038). This is similar to the first model calibration test results (presented in Section 6.4.3 and discussed in Section 6.4.4), and possible alternative explanations for the difference between the simulated model outputs and the observed behaviours are similar to those discussed in Section 6.4.4.

The next section discusses how the two calibrated system dynamics simulation models (discussed in Sections 6.4 and 6.5) were used to separately conduct similar simulation experiments, with subsequent comparison of results from the two sets, in assessing the impact of the competition between two key project participants (the client and the engineering consultant) on project performance.

6.6. Impact of Competition on Project Performance

This section seeks to answer the following research question (posed in Section 1.6):

3. *How does the competition between the two key project participants (client and engineering consultant) influence project performance?*

Analysis of the impact of competition between the two key project participants (the client and the engineering consultant) on project performance was conducted in three stages. In the *first stage* (Sections 6.6.1 and 6.6.2), project-specific data gathered for the first set of unique raw water infrastructure projects (10 asset management planning and support-related) and the associated calibrated system dynamics simulation model, both discussed in Section 6.4, were used to conduct three sets of simulation experiments (Section 6.6.1).

Firstly, 36 different model simulations were run for each of the 10 projects, by varying combinations of active client project cost controls and their unintended effects. The model simulation outputs were then analysed to determine whether or not they supported the following dynamic hypothesis formulated in Section 4.9.3:

The client project cost controls, which are aimed at reducing/eliminating the 'project cost overrun' by reducing the 'estimated project cost at completion' (a 'win-lose' control in favour of the client), tend to generate some unintended and counteractive consequences (unintended effects) that increase the 'estimated project cost at completion' and the 'project cost overrun'.

Secondly, 46 different model simulations were run for each of the 10 projects, by varying combinations of active engineering consultant project revenue controls and their unintended effects. The model simulation outputs were then analysed to determine whether or not they supported the following dynamic hypothesis formulated in Section 4.9.3:

The engineering consultant project revenue controls, which are aimed at reducing/eliminating the 'project revenue shortfall' by increasing the 'estimated project cost at completion' (a 'win-lose' control in favour of the

> *engineering consultant), tend to generate some unintended and counteractive consequence (unintended effect) that decreases the 'estimated project cost at completion' and increases the 'project revenue shortfall'.*

Lastly, two model simulations were run for each of the 10 projects, namely: one without competition, where only the engineering consultant project time schedule control (work intensity) and its associated unintended effect were activated, no client project cost controls and their associated unintended effects were activated, and no engineering consultant project revenue controls and their associated unintended effects were activated; and the other with competition, where all the said controls and their unintended effects were activated. The model simulation outputs were then used to analyse the impact of the competition (i.e. combined impact of competing client project cost controls and their unintended effects, and engineering consultant project revenue controls and their unintended effects) on the project performance of each of the 10 projects. The impact was assessed through the determination of two impact ratios (impact ratio on project time schedule performance, and impact ratio on project cost performance) (Section 6.6.1). The descriptive statistics of the impact were then analysed to determine whether or not they supported the following dynamic hypothesis formulated in Section 4.9.3:

> *The client project cost controls and the engineering consultant project revenue controls tend to oppose (compete with) each other, generating some unintended and counteractive consequences (unintended effects) that negatively influence project performance (increasing both 'project time schedule delay' and 'project cost overrun').*

Subsequently, a multivariate Monte Carlo behaviour mode sensitivity analysis was conducted to assess, for each project, the sensitivity of the impact of the competition on project performance to uncertainty in key calibrated parameters (Section 6.6.2).

In the *second stage* (Sections 6.6.3 and 6.6.4), all the three sets of model simulation experiments, impact analysis and sensitivity analysis conducted in the preceding stage were repeated, but using data gathered for the second set of unique raw water infrastructure projects (8 asset renewal-related) and the associated calibrated system dynamics simulation model discussed in Section 6.5.

In the *third stage* (Section 6.6.5), a comparison of the key results (client project cost controls' counteractive and unintended effects, engineering consultant project revenue controls' counteractive and unintended effects, as well as polarity and behaviour mode sensitivity of the impact of the competition on project performance) from the preceding two stages is made, with appropriate conclusions drawn as to whether or not the above-mentioned associated dynamic hypotheses were supported by the two sets of projects considered, and an appropriate provisional answer to research question number 3 (posed in Section 1.6) provided.

The above-discussed three-stage analysis of the impact of competition on project performance, where the impact analysis and associated sensitivity analysis were conducted separately for each of the two sets of unique raw water infrastructure projects considered, with subsequent comparison of results from the two sets, assisted in enhancing the validity of the associated overall key research results (presented in Section 6.6.5), namely support for the stated dynamic hypotheses and a provisional answer for research question number 3 (posed in Section 1.6), which help to address some key associated gaps identified in the reviewed literature, as discussed in Chapters 1, 3 and 4. It is a novel contribution towards the enhancement of the existing system dynamics simulation model validation, in particular impact and sensitivity analyses, processes and procedures, and is, thus expected to benefit future system dynamics research studies.

The next sub-section discusses key results from the first stage of the impact analysis, which was conducted using data gathered for the first set of unique raw water infrastructure projects (10 asset management planning and support-related) and the calibrated system dynamics simulation model discussed in Section 6.4.

6.6.1 Impact Analysis (Infrastructure Asset Management Planning and Support Projects)

Project Participants Performance Targets

As discussed in Chapter 4 (Table 4.11 and Figure 4.31), the client and the engineering consultant set up their own individual performance targets, and take appropriate control actions aimed at protecting them, during project execution. Table 6.15 shows the client project cost targets and engineering consultant project revenue targets per project for the first set of unique raw water infrastructure projects (10 asset management planning and support-related) considered in this research study. These individual project participant performance targets were used in all the associated simulation experiments conducted in Sections 6.6 and 6.7.

Table 6.15: Project participants performance targets per project (asset management planning and support-related)

Project number	Initially planned		Client project cost performance target		Engineering consultant project revenue performance target	
	Project time schedule duration (months)	Project contract ceiling price (Z) (R million)	Client project cost variance % at completion target (a) (%)	Client project cost at completion target (U) (R million)	Engineering consultant project contract ceiling price % target (b) (%)	Engineering consultant project revenue at completion target (V) (R million)
P0	12	13.473	15	11.452	100	13.473
P1	12	15.022	15	12.769	95	14.271
P2	24	42.937	20	34.350	90	38.643
P3	9	5.752	5	5.464	100	5.752
P4	6	3.840	10	3.456	100	3.840
P5	9	5.992	10	5.393	100	5.992
P6	26	21.278	20	17.022	95	20.214
P7	7	3.817	5	3.626	100	3.817
P8	12	12.170	15	10.345	100	12.170
P9	12	10.590	10	9.531	100	10.59

The next sub-section assesses the client project cost controls' unintended effects, using the 10 unique asset management planning and support-related projects.

Model Simulations for Client Project Cost Controls and their Unintended Effects

Subsequent to the model calibration discussed in Section 6.4, a total of 36 different model simulations (using Vensim software) were run for each and every project, by varying the client project cost controls and their unintended effects (discussed in Section 5.7). The 36 simulations are as shown in Table 6.16. They were conducted using the associated calibrated system dynamics simulation model discussed in Section 6.4. The model was simulated, first without any client project cost controls (simulation run-name TC_WI+UE), then with individual client project cost controls (firstly without and then with the associated unintended effects, that also include the engineering consultant project revenue controls) as shown in Table 6.16. Next, the model was simulated with a combination of the client project cost controls (also, firstly without and then with the associated unintended effects).

Table 6.16: Descriptions of model simulations for client project cost controls and unintended effects

Model simulation run-name	Client project cost controls (CC)				Engineering consultant project revenue controls (RC)		
	R	M	Iap	UE	EA	SVM	UE
TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE	✓	✓	✓	✓	✓	✓	✓
TC_WI+UE+CC_RMIap+UE+RC_SVM+UE	✓	✓	✓	✓		✓	✓
TC_WI+UE+CC_RMIap+UE+RC_EA+UE	✓	✓	✓	✓	✓		✓
TC_WI+UE+CC_RMIap+UE	✓	✓	✓	✓			
TC_WI+UE+CC_RMIap	✓	✓	✓				
TC_WI+UE+CC_MIap+UE+RC_EASVM+UE		✓	✓	✓	✓	✓	✓
TC_WI+UE+CC_MIap+UE+RC_SVM+UE		✓	✓	✓		✓	✓
TC_WI+UE+CC_MIap+UE+RC_EA+UE		✓	✓	✓	✓		✓
TC_WI+UE+CC_MIap+UE		✓	✓	✓			
TC_WI+UE+CC_MIap		✓	✓				
TC_WI+UE+CC_RIap+UE+RC_EASVM+UE	✓		✓	✓	✓	✓	✓
TC_WI+UE+CC_RIap+UE+RC_SVM+UE	✓		✓	✓		✓	✓
TC_WI+UE+CC_RIap+UE+RC_EA+UE	✓		✓	✓	✓		✓
TC_WI+UE+CC_RIap+UE	✓		✓	✓			
TC_WI+UE+CC_RIap	✓		✓				
TC_WI+UE+CC_RM+UE+RC_EASVM+UE	✓	✓		✓	✓	✓	✓
TC_WI+UE+CC_RM+UE+RC_SVM+UE	✓	✓		✓		✓	✓
TC_WI+UE+CC_RM+UE+RC_EA+UE	✓	✓		✓	✓		✓
TC_WI+UE+CC_RM+UE	✓	✓		✓			
TC_WI+UE+CC_RM	✓	✓					
TC_WI+UE+CC_Iap+UE+RC_EASVM+UE			✓	✓	✓	✓	✓
TC_WI+UE+CC_Iap+UE+RC_SVM+UE			✓	✓		✓	✓
TC_WI+UE+CC_Iap+UE+RC_EA+UE			✓	✓	✓		✓
TC_WI+UE+CC_Iap+UE			✓	✓			
TC_WI+UE+CC_Iap			✓				
TC_WI+UE+CC_M+UE+RC_EASVM+UE		✓		✓	✓	✓	✓
TC_WI+UE+CC_M+UE+RC_SVM+UE		✓		✓		✓	✓
TC_WI+UE+CC_M+UE+RC_EA+UE		✓		✓	✓		✓
TC_WI+UE+CC_M+UE		✓		✓			
TC_WI+UE+CC_M		✓					
TC_WI+UE+CC_R+UE+RC_EASVM+UE	✓			✓	✓	✓	✓
TC_WI+UE+CC_R+UE+RC_SVM+UE	✓			✓		✓	✓
TC_WI+UE+CC_R+UE+RC_EA+UE	✓			✓	✓		✓
TC_WI+UE+CC_R+UE	✓			✓			
TC_WI+UE+CC_R	✓						
TC_WI+UE							

Key:

TC_WI+UE	:	Engineering consultant project time schedule control (work intensity) and associated unintended effects;
✓	:	Included (blank means excluded);
CC	:	Client project cost controls;
R	:	Project progress reports demand;
M	:	Project progress meetings demand;
Iap	:	Invoices approval and payment delay;
UE	:	Unintended effects;
RC	:	Engineering consultant project revenue controls;
EA	:	Effort adjustment;
SVM	:	Project scope variation motivations.

Table 6.17 shows the model simulations outputs (project time schedule duration and project cost) of client project cost controls and their unintended effects for each of the 36 model simulation runs conducted for Project P0, one of the 10 asset management planning and support-related projects.

The simulation results shown in Table 6.17 indicate that the short-term impact of all the considered client project cost controls looked positive, supporting the intended effect of a reduction in project cost overrun. For instance, using the first considered client project cost control, i.e. increasing the frequency of progress reports (simulation run TC_WI+UE+CC_R), resulted in a project cost saving of approximately 14% (i.e., project cost overrun of -14%). However, when all the unintended effects of the client project cost controls (i.e., decrease in productivity due to 'Less Time Spent On Real Work' and 'Engineering Consultant Project Revenue Controls', increase in work errors due to 'Haste Makes Waste', and decrease in project workforce due to 'Insufficient Operating Cash Flow For Engineering Consultant' – all of which result in a decrease in project work completion rate, as shown in Figure 4.31) were considered (simulation run TC_WI+UE+CC_R +UE+RC_EASVM+UE), the project cost (and project cost overrun) increased by 17%, as shown in Table 6.17. Thus, the long-term impact of the client project cost controls was counterintuitive, counteractive and unintended: instead of the project cost overrun decreasing, it increased. This is an example of a 'better-before-worse' result that is characteristic of dynamic complexity (Sterman, 2000).

The other asset management planning and support-related projects generally exhibited a similar 'better-before-worse' result as evident in Appendix H (Tables H.1.1 and H.1.2), which shows all the 36 model simulation outputs (project time schedule duration, project cost and engineering consultant project revenue) of the client project cost controls and their unintended effects for each of the 10 projects. Thus, the model simulation outputs supported the following counterintuitive dynamic hypothesis formulated in Section 4.9.3:

The client project cost controls, which are aimed at reducing/eliminating the 'project cost overrun' by reducing the 'estimated project cost at completion' (a 'win-lose' control in favour of the client), tend to generate some unintended and counteractive consequences (unintended effects) that increase the 'estimated project cost at completion' and the 'project cost overrun'.

As discussed in Chapters 4 and 5, in this research study: only time-based contracts with a ceiling price (Turner, 2004) between the client and the engineering consultant were considered; and only the time-based costs for the engineering consultant services were considered for the project cost. Hence, in this research study, the project revenue realised by the engineering consultant at project completion was assumed to be equal to the project cost incurred by the client at completion of the same project. Thus, from an engineering consultant project revenue performance perspective, the short-term impact of all the considered client project cost controls looked negative (the resulting negative project cost budget overrun is equivalent to a shortfall in the engineering consultant project revenue); while their long-term impact was positive (the resulting positive project cost budget overrun is equivalent to an increase in the engineering consultant project revenue).

Table 6.17: Model simulations outputs (time duration and cost) of client project cost controls and their unintended effects for Project P0

Model simulation run-name	Project time schedule duration (months)	Project cost (R million)	Compared with initial plan (time duration of 12 months, and cost budget of R13. 473m)	
			% Time schedule delay	% Cost budget over-run
TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE	16.12	15.910	34	18
TC_WI+UE+CC_RMIap+UE+RC_SVM+UE	16.44	16.070	37	19
TC_WI+UE+CC_RMIap+UE+RC_EA+UE	16.06	15.860	34	18
TC_WI+UE+CC_RMIap+UE	15.41	15.270	28	13
TC_WI+UE+CC_RMIap	10.06	11.590	-16	-14
TC_WI+UE+CC_MIap+UE+RC_EASVM+UE	15.69	14.040	31	4
TC_WI+UE+CC_MIap+UE+RC_SVM+UE	15.69	14.040	31	4
TC_WI+UE+CC_MIap+UE+RC_EA+UE	15.66	14.020	31	4
TC_WI+UE+CC_MIap+UE	14.53	13.660	21	1
TC_WI+UE+CC_MIap	10.06	11.590	-16	-14
TC_WI+UE+CC_RIap+UE+RC_EASVM+UE	13.31	13.100	11	-3
TC_WI+UE+CC_RIap+UE+RC_SVM+UE	13.31	13.100	11	-3
TC_WI+UE+CC_RIap+UE+RC_EA+UE	13.22	13.080	10	-3
TC_WI+UE+CC_RIap+UE	12.31	12.620	3	-6
TC_WI+UE+CC_RIap	10.06	11.590	-16	-14
TC_WI+UE+CC_RM+UE+RC_EASVM+UE	22.09	25.450	84	89

Model simulation run-name	Project time schedule duration (months)	Project cost (R million)	Compared with initial plan (time duration of 12 months, and cost budget of R13. 473m)	
			% Time schedule delay	% Cost budget over-run
TC_WI+UE+CC_RM+UE+RC_SVM+UE	22.12	25.490	84	89
TC_WI+UE+CC_RM+UE+RC_EA+UE	22.09	25.450	84	89
TC_WI+UE+CC_RM+UE	13.72	15.800	14	17
TC_WI+UE+CC_RM	10.06	11.590	-16	-14
TC_WI+UE+CC_Iap+UE+RC_EASVM+UE	13.59	12.080	13	-10
TC_WI+UE+CC_Iap+UE+RC_SVM+UE	13.50	12.050	13	-11
TC_WI+UE+CC_Iap+UE+RC_EA+UE	13.59	12.100	13	-10
TC_WI+UE+CC_Iap+UE	13.25	11.910	10	-12
TC_WI+UE+CC_Iap	10.12	11.660	-16	-13
TC_WI+UE+CC_M+UE+RC_EASVM+UE	13.38	15.410	12	14
TC_WI+UE+CC_M+UE+RC_SVM+UE	13.41	15.440	12	15
TC_WI+UE+CC_M+UE+RC_EA+UE	13.38	15.410	12	14
TC_WI+UE+CC_M+UE	12.97	14.940	8	11
TC_WI+UE+CC_M	10.06	11.590	-16	-14
TC_WI+UE+CC_R+UE+RC_EASVM+UE	13.66	15.730	14	17
TC_WI+UE+CC_R+UE+RC_SVM+UE	19.06	21.960	59	63
TC_WI+UE+CC_R+UE+RC_EA+UE	13.66	15.730	14	17
TC_WI+UE+CC_R+UE	12.88	14.830	7	10
TC_WI+UE+CC_R	10.06	11.590	-16	-14
TC_WI+UE	12.50	14.400	4	7

The next sub-section assesses the engineering consultant project revenue controls' unintended effects, using the 10 unique asset management planning and support-related projects.

Model Simulations for Engineering Consultant Project Revenue Controls and their Unintended Effects

Subsequent to the 36 model simulations, per project, of client project cost controls and their unintended effects discussed in the preceding sub-section, a further 46 different model simulations were run for each and every project, by varying the engineering consultant project revenue controls and their unintended effects (discussed in Section 5.8). The 46 different simulations are as shown in Table 6.18. They were conducted using the associated calibrated system dynamics simulation model discussed in Section 6.4. The model was simulated, first without any engineering consultant project revenue controls (simulation run-name TC_WI+UE), then with individual engineering consultant project revenue controls (firstly without and then with the associated unintended effects, i.e. client project cost controls), as shown in Table 6.18. Next, the model was simulated with both the engineering consultant project revenue controls activated (also, firstly without and then with the unintended effects).

Table 6.18: Descriptions of model simulations for engineering consultant project revenue controls and unintended effects

Model simulation run-name	Engineering consultant project revenue controls (RC)		Client project cost controls (CC)			
	EA	SVM	R	M	Iap	UE
TC_WI+UE+RC_EASVM+CC_RMIap+UE	✓	✓	✓	✓	✓	✓
TC_WI+UE+RC_EASVM+CC_RMIap	✓	✓	✓	✓	✓	
TC_WI+UE+RC_EASVM+CC_MIap+UE	✓	✓		✓	✓	✓
TC_WI+UE+RC_EASVM+CC_MIap	✓	✓		✓	✓	
TC_WI+UE+RC_EASVM+CC_RIap+UE	✓	✓	✓		✓	✓
TC_WI+UE+RC_EASVM+CC_RIap	✓	✓	✓		✓	
TC_WI+UE+RC_EASVM+CC_RM+UE	✓	✓	✓	✓		✓
TC_WI+UE+RC_EASVM+CC_RM	✓	✓	✓	✓		
TC_WI+UE+RC_EASVM+CC_Iap+UE	✓	✓			✓	✓
TC_WI+UE+RC_EASVM+CC_Iap	✓	✓			✓	
TC_WI+UE+RC_EASVM+CC_M+UE	✓	✓		✓		✓
TC_WI+UE+RC_EASVM+CC_M	✓	✓		✓		
TC_WI+UE+RC_EASVM+CC_R+UE	✓	✓	✓			✓
TC_WI+UE+RC_EASVM+CC_R	✓	✓	✓			
TC_WI+UE+RC_EASVM	✓	✓				
TC_WI+UE+RC_SVM+CC_RMIap+UE		✓	✓	✓	✓	✓
TC_WI+UE+RC_SVM+CC_RMIap		✓	✓	✓	✓	
TC_WI+UE+RC_SVM+CC_MIap+UE		✓		✓	✓	✓
TC_WI+UE+RC_SVM+CC_MIap		✓		✓	✓	
TC_WI+UE+RC_SVM+CC_RIap+UE		✓	✓		✓	✓
TC_WI+UE+RC_SVM+CC_RIap		✓	✓		✓	
TC_WI+UE+RC_SVM+CC_RM+UE		✓	✓	✓		✓
TC_WI+UE+RC_SVM+CC_RM		✓	✓	✓		
TC_WI+UE+RC_SVM+CC_Iap+UE		✓			✓	✓
TC_WI+UE+RC_SVM+CC_Iap		✓			✓	
TC_WI+UE+RC_SVM+CC_M+UE		✓		✓		✓
TC_WI+UE+RC_SVM+CC_M		✓		✓		
TC_WI+UE+RC_SVM+CC_R+UE		✓	✓			✓
TC_WI+UE+RC_SVM+CC_R		✓	✓			
TC_WI+UE+RC_SVM		✓				
TC_WI+UE+RC_EA+CC_RMIap+UE	✓		✓	✓	✓	✓

Model simulation run-name	Engineering consultant project revenue controls (RC)		Client project cost controls (CC)			
	EA	SVM	R	M	Iap	UE
TC_WI+UE+RC_EA+CC_RMIap	✓		✓	✓	✓	
TC_WI+UE+RC_EA+CC_MIap+UE	✓			✓	✓	✓
TC_WI+UE+RC_EA+CC_MIap	✓			✓	✓	
TC_WI+UE+RC_EA+CC_RIap+UE	✓		✓		✓	✓
TC_WI+UE+RC_EA+CC_RIap	✓		✓		✓	
TC_WI+UE+RC_EA+CC_RM+UE	✓		✓	✓		✓
TC_WI+UE+RC_EA+CC_RM	✓		✓	✓		
TC_WI+UE+RC_EA+CC_Iap+UE	✓				✓	✓
TC_WI+UE+RC_EA+CC_Iap	✓				✓	
TC_WI+UE+RC_EA+CC_M+UE	✓			✓		✓
TC_WI+UE+RC_EA+CC_M	✓			✓		
TC_WI+UE+RC_EA+CC_R+UE	✓		✓			✓
TC_WI+UE+RC_EA+CC_R	✓		✓			
TC_WI+UE+RC_EA	✓					
TC_WI+UE						

Key:

TC_WI+UE	:	Engineering consultant project time schedule control (work intensity) and associated unintended effects;
✓	:	Included (blank means excluded);
CC	:	Client project cost controls;
R	:	Project progress reports demand;
M	:	Project progress meetings demand;
Iap	:	Invoices approval and payment delay;
UE	:	Unintended effects;
RC	:	Engineering consultant project revenue controls;
EA	:	Effort adjustment;
SVM	:	Project scope variation motivations.

Table 6.19 shows the model simulations outputs (project time schedule duration and project cost) of engineering consultant project revenue controls and their unintended effects for each of the 46 simulation runs conducted for Project P0, one of the 10 asset management planning and support-related projects.

As discussed in Chapters 4 and 5, in this research study: only time-based contracts with a ceiling price (Turner, 2004) between the client and the engineering consultant were considered; and only the time-based costs for the engineering consultant services were considered for the project cost. Hence, in this research study, the project revenue realised by the engineering consultant at project completion was assumed to be equal to the project cost incurred by the client at completion of the same project. The simulation results shown in Table 6.19 indicate that the short-term impact of all the considered engineering consultant project revenue controls looked positive, supporting the intended effect of a reduction in the engineering consultant project revenue shortfall. For instance, using the first considered engineering consultant project revenue control, i.e. effort adjustment (simulation run TC_WI+UE+RC_EA), resulted in a positive project cost budget overrun (which mean an increase in the engineering consultant project revenue, and a decrease in the engineering consultant project revenue shortfall) of approximately 7%.

When all the unintended effects of the engineering consultant project revenue controls, i.e., all the three client project cost controls (increasing the frequency of both progress meetings and reports, and delaying approval and payment of the engineering consultant's invoices – all of which result in an increase in project work completion rate, as shown in Figure 4.31), were considered (simulation run TC_WI+UE+RC_EA+CC_RMIap), there was, however, an engineering consultant project revenue shortfall (negative project cost budget overrun) of approximately 12%, as shown in Table 6.19. Thus, the long-term impact of the engineering consultant project revenue controls was counterintuitive, counteractive and unintended: instead of the engineering consultant project revenue shortfall decreasing, it increased. This is also a 'better-before-worse' result, that is characteristic of dynamic complexity (Sterman, 2000).

The other asset management planning and support-related projects generally exhibited a similar 'better-before-worse' result as evident in Appendix H (Tables H.1.3 and H.1.4), which shows all the 46 model simulations outputs (project time schedule duration, project cost and engineering consultant project revenue) of engineering consultant project revenue controls and their unintended effects for each of the 10 projects. Thus, the model simulation outputs supported the following counterintuitive dynamic hypothesis formulated in Section 4.9.3:

> *The engineering consultant project revenue controls, which are aimed at reducing/eliminating the 'project revenue shortfall' by increasing the 'estimated project cost at completion' (a 'win-lose' control in favour of the engineering consultant), tend to generate some unintended and counteractive consequence (unintended effect) that decreases the 'estimated project cost at completion' and increases the 'project revenue shortfall'.*

From a project cost performance perspective, however, the short-term impact of all the considered engineering consultant project revenue controls looked negative (they yielded a positive project cost budget overrun); while their long-term impact was positive (they yielded a negative project cost budget overrun, which is a cost saving), as shown in Table 6.19.

Table 6.19: Model simulations outputs (time duration and cost) of engineering consultant project revenue controls and their unintended effects for Project P0

Model simulation run-name	Project time schedule duration (months)	Project cost (R million)	Compared with initial plan (time duration of 12 months, and cost budget of R13. 473m)	
			% Time schedule delay	% Cost budget over-run
TC_WI+UE+RC_EASVM+CC_RMIap+UE	16.12	15.910	34%	18%
TC_WI+UE+RC_EASVM+CC_RMIap	10.31	11.880	-14%	-12%
TC_WI+UE+RC_EASVM+CC_MIap+UE	15.69	14.040	31%	4%
TC_WI+UE+RC_EASVM+CC_MIap	10.31	11.880	-14%	-12%
TC_WI+UE+RC_EASVM+CC_RIap+UE	13.31	13.100	11%	-3%
TC_WI+UE+RC_EASVM+CC_RIap	10.31	11.880	-14%	-12%
TC_WI+UE+RC_EASVM+CC_RM+UE	22.09	25.450	84%	89%
TC_WI+UE+RC_EASVM+CC_RM	10.31	11.880	-14%	-12%
TC_WI+UE+RC_EASVM+CC_Iap+UE	13.59	12.080	13%	-10%
TC_WI+UE+RC_EASVM+CC_Iap	10.34	11.920	-14%	-12%
TC_WI+UE+RC_EASVM+CC_M+UE	13.38	15.410	12%	14%
TC_WI+UE+RC_EASVM+CC_M	10.31	11.880	-14%	-12%
TC_WI+UE+RC_EASVM+CC_R+UE	13.66	15.730	14%	17%
TC_WI+UE+RC_EASVM+CC_R	10.31	11.880	-14%	-12%
TC_WI+UE+RC_EASVM	12.50	14.400	4%	7%
TC_WI+UE+RC_SVM+CC_RMIap+UE	16.44	16.070	37%	19%
TC_WI+UE+RC_SVM+CC_RMIap	10.31	11.880	-14%	-12%
TC_WI+UE+RC_SVM+CC_MIap+UE	15.69	14.040	31%	4%
TC_WI+UE+RC_SVM+CC_MIap	10.31	11.880	-14%	-12%
TC_WI+UE+RC_SVM+CC_RIap+UE	13.31	13.100	11%	-3%
TC_WI+UE+RC_SVM+CC_RIap	10.31	11.880	-14%	-12%
TC_WI+UE+RC_SVM+CC_RM+UE	22.12	25.490	84%	89%
TC_WI+UE+RC_SVM+CC_RM	10.31	11.880	-14%	-12%
TC_WI+UE+RC_SVM+CC_Iap+UE	13.50	12.050	13%	-11%
TC_WI+UE+RC_SVM+CC_Iap	10.31	11.880	-14%	-12%
TC_WI+UE+RC_SVM+CC_M+UE	13.41	15.440	12%	15%
TC_WI+UE+RC_SVM+CC_M	10.31	11.880	-14%	-12%
TC_WI+UE+RC_SVM+CC_R+UE	19.06	21.960	59%	63%
TC_WI+UE+RC_SVM+CC_R	10.31	11.880	-14%	-12%
TC_WI+UE+RC_SVM	12.50	14.400	4%	7%
TC_WI+UE+RC_EA+CC_RMIap+UE	16.06	15.860	34%	18%
TC_WI+UE+RC_EA+CC_RMIap	10.31	11.880	-14%	-12%
TC_WI+UE+RC_EA+CC_MIap+UE	15.66	14.020	31%	4%
TC_WI+UE+RC_EA+CC_MIap	10.31	11.880	-14%	-12%
TC_WI+UE+RC_EA+CC_RIap+UE	13.22	13.080	10%	-3%
TC_WI+UE+RC_EA+CC_RIap	10.31	11.880	-14%	-12%

Model simulation run-name	Project time schedule duration (months)	Project cost (R million)	Compared with initial plan (time duration of 12 months, and cost budget of R13. 473m)	
			% Time schedule delay	% Cost budget over-run
TC_WI+UE+RC_EA+CC_RM+UE	22.09	25.450	84%	89%
TC_WI+UE+RC_EA+CC_RM	10.31	11.880	-14%	-12%
TC_WI+UE+RC_EA+CC_Iap+UE	13.59	12.100	13%	-10%
TC_WI+UE+RC_EA+CC_Iap	10.34	11.920	-14%	-12%
TC_WI+UE+RC_EA+CC_M+UE	13.38	15.410	12%	14%
TC_WI+UE+RC_EA+CC_M	10.31	11.880	-14%	-12%
TC_WI+UE+RC_EA+CC_R+UE	13.66	15.730	14%	17%
TC_WI+UE+RC_EA+CC_R	10.31	11.880	-14%	-12%
TC_WI+UE+RC_EA	12.50	14.400	4%	7%
TC_WI+UE	12.50	14.400	4%	7%

The next sub-section assesses the impact of competition (i.e. competing client project cost controls and their unintended effects, and engineering consultant project revenue controls and their unintended effects) on project performance, using the 10 unique asset management planning and support-related projects.

Analysis of the Impact of Competition on Project Performance

The reviewed literature showed that: there are many measures of project performance (Section 3.3.1), yet current project dynamics models are limited to project performance (mainly time schedule duration) control actions of mainly the engineering consultant or construction contractor; and control actions taken by the client to protect project performance, and control actions taken by the engineering consultant and construction contractor to protect their individual business performance targets during project execution are sparingly covered (Section 3.11). Also, in the reviewed literature, no appropriate system dynamics project model could be identified that considered: competition among project participants, with their different and competing performance measures and targets during project execution; and how such competition influences project performance (Section 3.11).

In this research study, two measures of project performance (project time duration and project cost) were used as simulation model outputs, similar to the models of De Marco (2006), Ford et al. (2007), and Parvan et al. (2015)). However, unlike in any of the said previous models, the system dynamics simulation model formulated in this study (discussed in Chapters 4 and 5) also captured the competition between two key project participants (client and engineering consultant) in the form of two sets of competing project controls (aimed at win-lose results), namely client project cost controls and their associated unintended effects, and engineering consultant project revenue controls and their associated unintended effects. This sub-section analyses how such competition influences the said two measures of project performance. This novel contribution, made by this study, expands existing project dynamics models, deepening our understanding of project dynamics, and assists towards addressing the above-mentioned gaps identified in the reviewed literature.

To assess the impact of the competition between the two key project participants (client and engineering consultant) on project performance (as measured by project time schedule duration and project cost), two model simulations (conducted using the associated calibrated system dynamics simulation model discussed in Section 6.4) were considered in this research study, namely:

- TC_WI+UE (*Without competition)*: where only the engineering consultant project time schedule control (work intensity) and its associated unintended effect were activated. No client project cost controls and their associated unintended effects were activated, and no engineering consultant project revenue controls and their associated unintended effects were activated; and
- TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE (*With competition*): where the engineering consultant project time schedule control (work intensity) and its associated unintended effect, all the client project cost controls and their associated unintended effects, as well as all the engineering consultant project revenue controls and their associated unintended effects were all activated.

Table 6.20 shows, for each of the 10 unique asset management planning and support-related projects, the initially planned project time duration and project cost, as well as their corresponding simulated outputs for the two model simulation runs. As is evident in Table 6.20: project time schedule performance was worse in the ‘With competition’ simulation run than in the ‘Without competition’ simulation run for all (except Project P3) the considered projects; whilst project cost performance was worse in the ‘With competition’ simulation run than in the ‘Without competition’ simulation run for all (except Projects P3 and P4) the considered projects.

Table 6.20: Planned project time duration and cost, and corresponding simulated outputs without and with competition (asset management planning and support-related projects)

Project number	Planned		Without competition (simulation run: TC_WI+UE)		With competition (simulation run: TC_WI+UE+CC_RMIap+UE +RC_EASVM+UE)	
	Project time schedule duration (months)	Project cost (R million)	Project time schedule duration (months)	Project cost (R million)	Project time schedule duration (months)	Project cost (R million)
P0	12	13.473	12.5	14.400	16.12	15.910
P1	12	15.022	12.09	15.140	18.19	16.820
P2	24	42.937	25.09	44.890	32.75	45.510
P3	9	5.752	9.78	6.251	9.72	6.059
P4	6	3.840	6.22	3.980	7.50	3.854
P5	9	5.992	8.84	5.888	13.22	6.942
P6	26	21.278	27.34	22.380	31.25	22.630
P7	7	3.817	5.88	3.203	7.75	3.517
P8	12	12.170	12.12	12.300	15.66	14.360
P9	12	10.590	12.09	10.670	15.53	11.660

In this research study, the *schedule performance index (SPI)* is a measure of schedule efficiency and is determined by the ratio of the planned project time schedule duration to the actual/simulated project time schedule duration, similar to Parvan (2012). An SPI of: less than 1 indicates the project is behind schedule (inefficient); 1 indicates the project is on schedule (efficient); and greater than 1 indicates the project is ahead of schedule (highly efficient) (Anbari, 2003; Project Management Institute, 2017).

The *cost performance index (CPI)* is a measure of cost efficiency and is determined by the ratio of the planned project cost to the actual/simulated project cost, similar to Anbari (2003), Parvan (2012) and Project Management Institute (2017). A CPI of: less than 1 indicates the project is over budget (inefficient); 1 indicates the project is on budget (efficient); and greater than 1 indicates the project is under budget (highly efficient) (Anbari, 2003; Project Management Institute, 2017).

In this research study, the *impact ratio on project performance* is a measure of the decrease/increase (deterioration/improvement) of a project performance index (SPI or CPI) as a result of competition between the client and the engineering consultant during project execution. Put differently, the *impact ratio on project performance* indicates the decrease/increase below/above what the project performance index (SPI or CPI) would have been (if there was no competition).

The impact of the competition on project time schedule performance was determined by: *impact ratio on project time schedule performance* = SPI (without competition) / SPI (with competition). The impact of the competition on project cost performance was determined by: *impact ratio on project cost performance* = CPI (without competition) / CPI (with competition). These formulations are comparable to those used by Parvan (2012) who assessed the impact of building information modelling on project performance.

An *impact ratio on project performance* (a measure of the impact of the competition on project performance, in terms of project time schedule duration and project cost) of: less than 1 indicates that the competition positively influences (improves) the project performance; 1 indicates that the competition has no impact on the project performance; and greater than 1 indicates that the competition negatively influences (worsens) the project performance.

Table 6.21 shows, for each of the 10 unique asset management planning and support-related projects considered in this research study, the SPI and CPI (without and with competition) and the resulting impact ratios (of the competition between the client and the engineering consultant during project execution) on project time schedule performance and on project cost performance. This assessment of the impact/influence of competition between two key project participants (with their different and competing performance measures and targets during project execution) on project performance (as measured by project time schedule duration and project cost) is another novel contribution made by this research study. It assists towards addressing a related gap identified in the reviewed literature, namely no appropriate study could be identified that specifically investigated the influence of such competition on project performance, as discussed in Chapters 1, 3, and 4.

The competition between the client and the engineering consultant during project execution negatively influenced the project time schedule performance of all the projects (except Project P3), with Project P1 being the worst affected with an impact ratio of 1.50, as shown in Table 6.21. The competition negatively influenced the project cost performance of all the projects (save for Projects P3 and P4), with Project P5 being the worst affected with an impact ratio of 1.18.

Table 6.21: SPI and CPI (without and with competition), and competition impact ratios per project (asset management planning and support-related)

Project number	Project time schedule performance			Project cost performance		
	Schedule performance index (SPI)		Impact ratio	Cost performance index (CPI)		Impact ratio
	Without competition (simulation run: TC_WI+UE)	With competition (simulation run: TC_WI+UE+CC_RMlap+UE+RC_EASVM+UE)		Without competition (simulation run: TC_WI+UE)	With competition (simulation run: TC_WI+UE+CC_RMlap+UE+RC_EASVM+UE)	
P0	0.96	0.74	1.29	0.94	0.85	1.10
P1	0.99	0.66	1.50	0.99	0.89	1.11
P2	0.96	0.73	1.31	0.96	0.94	1.01
P3	0.92	0.93	0.99	0.92	0.95	0.97
P4	0.96	0.80	1.21	0.96	1.00	0.97
P5	1.02	0.68	1.49	1.02	0.86	1.18
P6	0.95	0.83	1.14	0.95	0.94	1.01
P7	1.19	0.90	1.32	1.19	1.09	1.10
P8	0.99	0.77	1.29	0.99	0.85	1.17
P9	0.99	0.77	1.28	0.99	0.91	1.09

Table 6.22 shows the overall descriptive statistics for the SPI and CPI (without and with competition) and the associated impact ratios (of the competition between the client and the engineering consultant during project execution) on both project time schedule performance and project cost performance for the 10 unique asset management planning and support-related projects considered in this research study. On average, the competition between the client and the engineering consultant during project execution negatively influenced project performance: both the project time schedule performance and the project cost performance have mean impact ratios that are greater than 1 (i.e. 1.28 and 1.07, respectively). This finding supports the following related dynamic hypothesis formulated in Section 4.9.3:

> *The client project cost controls and the engineering consultant project revenue controls tend to oppose (compete with) each other, generating some unintended and counteractive consequences (unintended effects) that negatively influence project performance (increasing both ‘project time schedule delay’ and ‘project cost overrun’).*

Table 6.22: Descriptive statistics for SPI and CPI (without and with competition), and competition impact ratios (asset management planning and support-related projects)

Statistic	Project time schedule performance			Project cost performance		
	Schedule performance index (SPI)		Impact ratio	Cost performance index (CPI)		Impact ratio
	Without competition (simulation run: TC_WI+UE)	With competition (simulation run: TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE)		Without competition (simulation run: TC_WI+UE)	With competition (simulation run: TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE)	
Median	0.98	0.77	1.29	0.98	0.92	1.10
Mean	0.99	0.78	1.28	0.99	0.93	1.07
Standard Deviation	0.07	0.09	0.15	0.08	0.07	0.08
Minimum	0.92	0.66	0.99	0.92	0.85	0.97
Maximum	1.19	0.93	1.50	1.19	1.09	1.18

The next sub-section assesses the sensitivity of the impact of the competition on project performance, as determined in this sub-section, to uncertainty/changes in some of the key calibrated model parameters.

6.6.2 Behaviour Mode Sensitivity Analysis (Infrastructure Asset Management Planning and Support Projects)

Parametric Sensitivity Analysis Overview

In system dynamics, parametric sensitivity analysis entails assessing the robustness and sensitivity of a system dynamics simulation model's outputs (and conclusions drawn therefrom) to uncertainties in the calibrated model parameters (Sterman, 2000). In this Section 6.6, it was important to assess the sensitivity of the impact of competition on project performance to uncertainty/changes in key calibrated model parameters, as this helps to enhance the validity of the conclusion drawn regarding the associated dynamic hypothesis formulated in Section 4.9.3 (and also presented in the preceding sub-section) and the provisional answer provided for the associated research question number 3 (posed in Section 1.6).

The sensitivity of the impact of competition on project performance determined in Section 6.6.1 using the first set of unique raw water infrastructure projects considered in this research study is assessed in this sub-section; while that of the impact of competition on project performance determined in Section 6.6.3 using the second set of unique raw water infrastructure projects is assessed in Section 6.6.4. The impact analysis and associated sensitivity analysis are, thus, conducted separately for each of the two sets of projects. Subsequently, in Section 6.6.5, the key research results (i.e., polarity and behaviour mode sensitivity of the impact of competition on project performance) for the two sets of projects are then compared, with appropriate overall conclusion drawn regarding the associated dynamic hypothesis formulated in Section 4.9.3 and a provisional answer for research question number 3 (posed in Section 1.6) provided (which help to address a related key gap identified in the reviewed literature, as discussed in Chapters 1, 3 and 4).

The above-discussed process followed in this research study in assessing the impact of competition on project performance, and the sensitivity thereof, using two sets of unique projects separately, with subsequent comparison of the key research results, assisted in enhancing the validity of the associated overall key research results (as presented in Section 6.6.5). It is a novel contribution towards the enhancement of the existing system dynamics simulation model validation, in particular impact and sensitivity analyses, processes and procedures, and is, thus expected to benefit future system dynamics research studies.

There are three types of parametric sensitivity, namely: "numerical sensitivity" (exhibited when the simulated model output values change with changes in the values of the model parameters); "behaviour mode sensitivity" (exhibited when the simulated model output behaviour patterns change with changes in the values of the model parameters); and "policy sensitivity" (exhibited when the simulated impact or desirability of a policy is reversed when the values of the model parameters change) (Sterman, 2000).

Sterman (2000) further highlighted that the choice of the type of parametric sensitivity analysis to conduct is dependent upon the purpose of the model. As indicated in Section 4.2 (and as is evident in the research questions posed in Section 1.6), the purpose of this research study and of the system dynamics model formulated therein is centred around: investigating the influence/impact (essentially behaviour mode) of the competition between the two key project participants (the client and the engineering consultant) on project performance and on the business performance of the engineering consultant; and investigating how to improve/ minimise the competition so as to yield 'win-win' results. Accordingly, *behaviour mode sensitivity analyses* were conducted in this sub-section and in Sections 6.6.4, 6.7.2 and 6.7.4.

The basic modes of dynamic behaviour (and the basic feedback structures that generate them, shown in brackets) are *growth* (positive feedback), *goal seeking* (negative feedback), and *oscillations, including damped oscillations, limit cycles and chaos* (negative feedback with time delays); while the complex modes of dynamic behaviour are *S-shaped growth, S-shaped growth with overshoot and collapse,* and *overshoot and collapse* (all of which are a result of nonlinear interaction of the basic feedback structures) (Sterman, 2000).

Behaviour Mode Sensitivity

A multivariate Monte Carlo behaviour mode sensitivity analysis was conducted on the calibrated system dynamics simulation model to assess the sensitivity of the impact of competition on project performance, as determined in the preceding sub-section, to uncertainty/changes in some of the key calibrated model parameters. As discussed in the preceding sub-section, the impact of the competition on project performance was assessed through the determination of two impact ratios:

- *impact ratio* on *project time schedule performance* (determined as the ratio of the schedule performance index when there is no competition to the schedule performance index when there is competition); and
- *impact ratio on project cost performance* (determined as the ratio of the cost performance index when there is no competition to the cost performance index when there is competition).

The sensitivity analysis was therefore limited to only those calibrated parameters whose values changed between the two simulation runs of interest (TC_WI+UE, without competition; and TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE, with competition). Such calibrated model parameters that were used in the sensitivity analysis are: *progress reports demand policy; progress meetings demand policy; invoice approval and payment delay policy; effort adjustment policy; project scope variation motivations policy; progress reports demand adjustment delay; progress meetings demand adjustment delay; invoices approval and payment delay adjustment delay; engineering consultant effort adjustment delay; and project scope variation demand adjustment delay*.

Using the Monte Carlo sensitivity analysis module of Vensim DSS software, a minimum and a maximum value (approximately -30% and +30% of the calibrated value, respectively) as well as a random uniform probability distribution were specified for each parameter. The multivariate sensitivity analysis entailed automatically randomly varying all the above mentioned 10 calibrated model parameters in a total of 200 simulations (all using the simulation run TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE, with competition) per project; in each case saving the *schedule performance index* and the *cost performance index*.

Figures 6.11 and 6.12 show the results of the sensitivity analysis per project, that is, the sensitivities of the *schedule performance index* and the *cost performance index,* respectively, to the uncertainty/changes in the considered 10 parametric assumptions. The two figures show that both the *schedule performance index* and the *cost performance index* exhibited no behaviour mode sensitivity (though there were effects in absolute values, i.e., exhibited numerical sensitivity): both the base case (based on calibrated parameter values, and represented by the blue single line) and the random cases (based on the 200 sets of randomly selected parameter values, represented by the solid envelopes) exhibited an *S-shaped growth with overshoot and collapse* behaviour mode for all the considered projects.

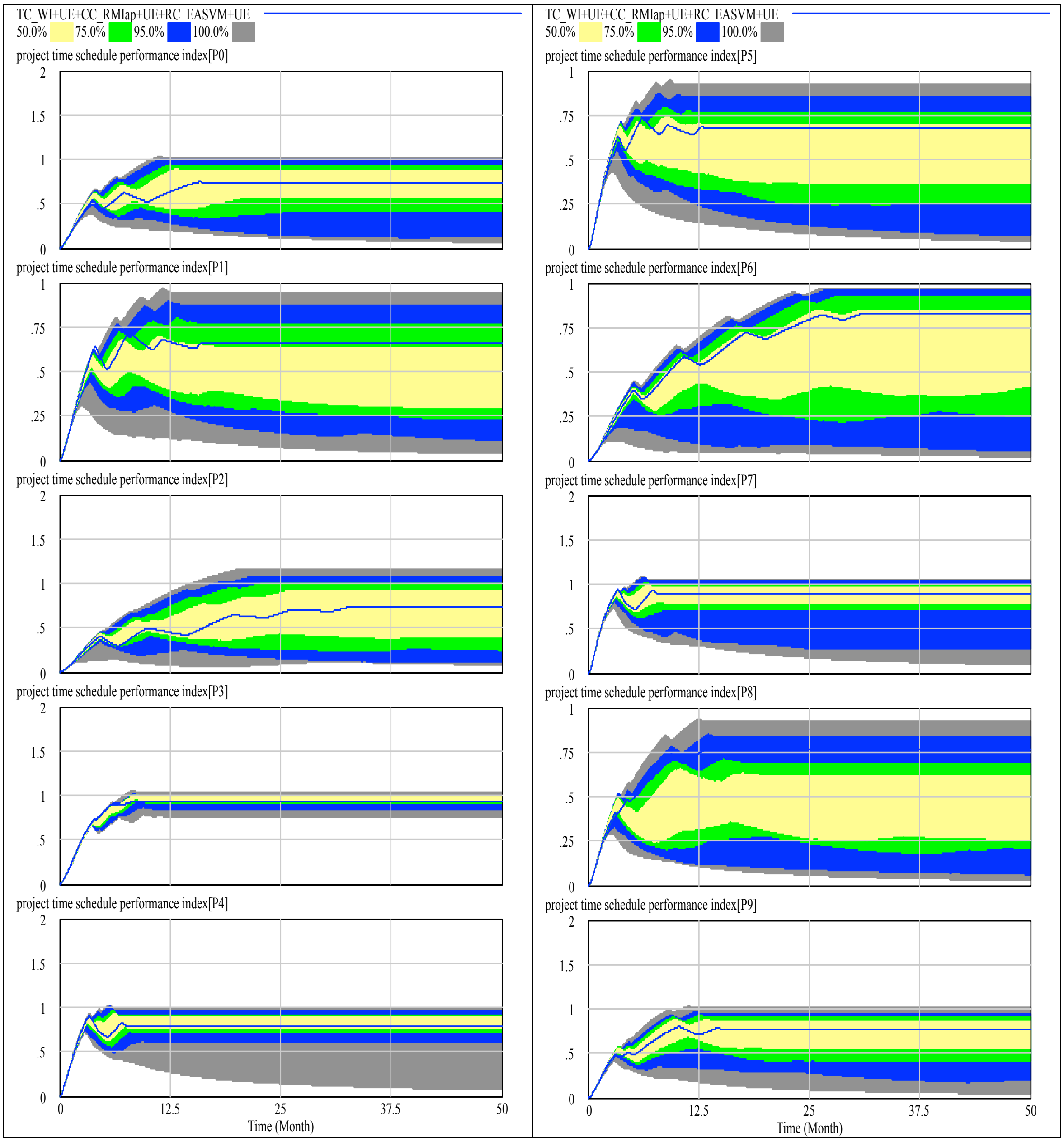


Figure 6.11: Sensitivity of schedule performance index (with competition) per project (asset management planning and support-related)

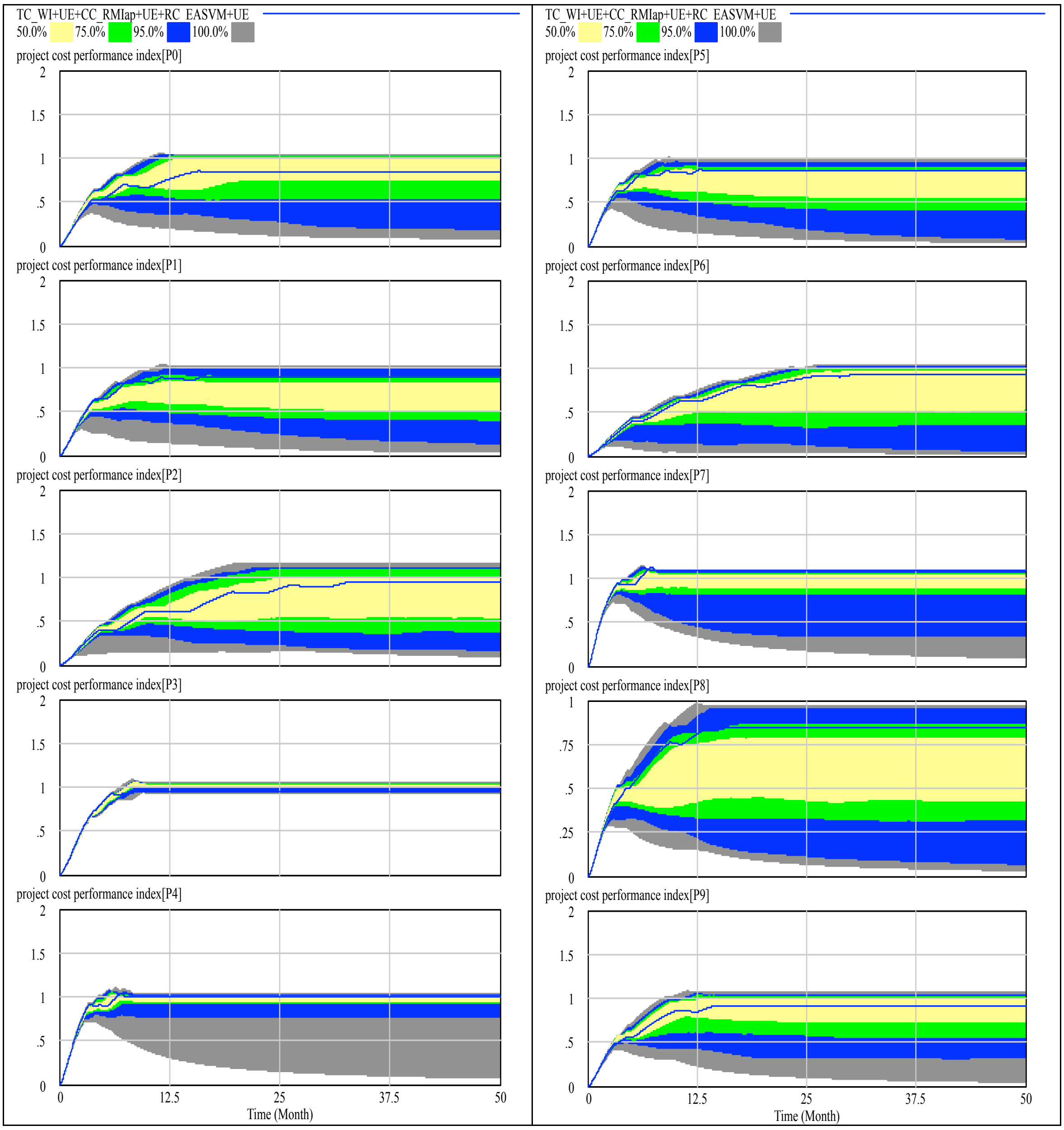


Figure 6.12: Sensitivity of cost performance index (with competition) per project (asset management planning and support-related)

The next sub-section discusses key results from the second stage of the impact analysis, which was conducted using data gathered for the second set of unique raw water infrastructure projects (asset renewal-related, made up of 8 projects) and the calibrated system dynamics simulation model discussed in Section 6.5.

6.6.3 Impact Analysis (Infrastructure Asset Renewal Projects)

Project Participants Performance Targets

As discussed in Chapter 4 (Table 4.11 and Figure 4.31), the client and the engineering consultant set up their own individual performance targets, and take appropriate control actions aimed at protecting them, during project execution. Table 6.23 shows the client project cost targets and engineering consultant project revenue targets per project for the second set of unique raw water infrastructure projects (asset renewal-related, made up of 8 projects) considered in this research study. These individual project participant performance targets were used in all the associated simulation experiments conducted in Sections 6.6 and 6.7.

Table 6.23: Project participants performance targets per project (asset renewal-related)

Project number	Initially planned		Client project cost performance target		Engineering consultant project revenue performance target	
	Project time schedule duration (months)	Project contract ceiling price (Z) (R million)	Client project cost variance % at completion target (a) (%)	Client project cost at completion target (U) (R million)	Engineering consultant project contract ceiling price % target (b) (%)	Engineering consultant project revenue at completion target (V) (R million)
P10	10.00	6.521	15	5.543	95	6.195
P11	5.00	2.857	10	2.571	100	2.857
P12	4.00	2.535	5	2.409	100	2.535
P13	6.00	4.327	10	3.894	100	4.327
P14	10.00	7.592	15	6.453	90	6.832
P15	6.00	3.312	10	2.981	100	3.312
P16	8.00	6.670	15	5.670	95	6.337
P17	5.00	2.632	5	2.501	100	2.632

The next sub-section assesses the client project cost controls' counteractive and unintended effects, using the 8 unique asset renewal-related projects.

Model Simulations for Client Project Cost Controls and their Unintended Effects

Subsequent to the model calibration discussed in Section 6.5, a total of 36 different model simulations (using Vensim software) were run for each and every project, by varying the client project cost controls and their unintended effects (discussed in Section 5.7). The 36 different simulations are as described in Section 6.6.1 and shown in Table 6.16. They were conducted using the associated calibrated system dynamics simulation model discussed in Section 6.5.

Table 6.24 shows the model simulations outputs (project time schedule duration and project cost) of client project cost controls and their unintended effects for each of the 36 model simulation runs conducted for Project P10, one of the 8 asset renewal-related projects considered in this research study.

The simulation results shown in Table 6.24 indicate that the short-term impact of all the considered client project cost controls looked positive, supporting the intended effect of a reduction in project cost overrun. For instance, using the second considered client project cost control, i.e. increasing the frequency of progress meetings (simulation run TC_WI+UE+CC_M), resulted in a cost saving of approximately 13% (i.e., project cost overrun of -13%). However, when all the unintended effects of the client project cost control (i.e., decrease in productivity due to 'Less Time Spent On Real Work' and 'Engineering Consultant Project Revenue Controls', increase in work errors due to 'Haste Makes Waste', and decrease in project workforce due to 'Insufficient Operating Cash Flow For Engineering Consultant' – all of which result in a decrease in project work completion rate, as shown in Figure 4.31) were considered (simulation run TC_WI+UE+CC_M+UE+RC_EASVM+UE), the project cost (and project cost overrun) increased by 9%, as shown in Table 6.24. Thus, the long-term impact of client project cost controls was counterintuitive, counteractive and unintended: instead of the project cost overrun decreasing, it increased. This is an example of a 'better-before-worse' result that is characteristic of dynamic complexity (Sterman, 2000).

The other asset renewal-related projects generally exhibited a similar 'better-before-worse' result as evident in Appendix H (Tables H.2.1 and H.2.2), which shows all the 36 simulations outputs (project time duration, project cost and engineering consultant project revenue) of the client project cost controls and their unintended effects for each of the 8 projects. Thus, the model simulation outputs supported the following counterintuitive dynamic hypothesis formulated in Section 4.9.3:

> *The client project cost controls, which are aimed at reducing/eliminating the 'project cost overrun' by reducing the 'estimated project cost at completion' (a 'win-lose' control in favour of the client), tend to generate some unintended and counteractive consequences (unintended effects) that increase the 'estimated project cost at completion' and the 'project cost overrun'.*

As discussed in Chapters 4 and 5, in this research study: only time-based contracts with a ceiling price (Turner, 2004) between the client and the engineering consultant were considered; and only the time-based costs for the engineering consultant services were considered for the project cost. Hence, in this research study, the project revenue realised by the engineering consultant at project completion was assumed to be equal to the project cost incurred by the client at completion of the same project. Thus, from an engineering consultant project revenue performance perspective, however, the short-term impact of all the considered client project cost controls looked negative (the resulting negative project cost budget overrun is equivalent to a shortfall in the engineering consultant project revenue); while their long-term impact was positive (the resulting positive project cost budget overrun is equivalent to an increase in the engineering consultant project revenue).

Table 6.24: Model simulations outputs (time duration and cost) of client project cost controls and their unintended effects for Project P10

Model simulation run-name	Project time schedule duration (months)	Project cost (R million)	Compared with initial plan (time duration of 10 months, and cost budget of R6.521m)	
			% Time schedule delay	% Cost budget over-run
TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE	14.25	7.344	43	13
TC_WI+UE+CC_RMIap+UE+RC_SVM+UE	14.25	7.344	43	13
TC_WI+UE+CC_RMIap+UE+RC_EA+UE	14.25	7.344	43	13
TC_WI+UE+CC_RMIap+UE	14.16	7.297	42	12
TC_WI+UE+CC_RMIap	8.75	5.706	-13	-12
TC_WI+UE+CC_MIap+UE+RC_EASVM+UE	15.88	7.090	59	9
TC_WI+UE+CC_MIap+UE+RC_SVM+UE	15.88	7.090	59	9
TC_WI+UE+CC_MIap+UE+RC_EA+UE	15.88	7.090	59	9
TC_WI+UE+CC_MIap+UE	15.81	7.069	58	8
TC_WI+UE+CC_MIap	8.75	5.706	-13	-12
TC_WI+UE+CC_RIap+UE+RC_EASVM+UE	14.38	7.069	44	8
TC_WI+UE+CC_RIap+UE+RC_SVM+UE	14.38	7.069	44	8
TC_WI+UE+CC_RIap+UE+RC_EA+UE	14.38	7.069	44	8
TC_WI+UE+CC_RIap+UE	14.12	7.022	41	8
TC_WI+UE+CC_RIap	8.75	5.706	-13	-12
TC_WI+UE+CC_RM+UE+RC_EASVM+UE	18.66	12.170	87	87
TC_WI+UE+CC_RM+UE+RC_SVM+UE	18.66	12.170	87	87
TC_WI+UE+CC_RM+UE+RC_EA+UE	18.66	12.170	87	87
TC_WI+UE+CC_RM+UE	18.62	12.140	86	86
TC_WI+UE+CC_RM	8.75	5.706	-13	-12
TC_WI+UE+CC_Iap+UE+RC_EASVM+UE	14.59	6.233	46	-4
TC_WI+UE+CC_Iap+UE+RC_SVM+UE	14.59	6.233	46	-4
TC_WI+UE+CC_Iap+UE+RC_EA+UE	14.59	6.233	46	-4
TC_WI+UE+CC_Iap+UE	14.44	6.195	44	-5
TC_WI+UE+CC_Iap	8.81	5.746	-12	-12
TC_WI+UE+CC_M+UE+RC_EASVM+UE	10.88	7.091	9	9
TC_WI+UE+CC_M+UE+RC_SVM+UE	10.88	7.091	9	9
TC_WI+UE+CC_M+UE+RC_EA+UE	10.88	7.091	9	9
TC_WI+UE+CC_M+UE	10.84	7.071	8	8
TC_WI+UE+CC_M	8.72	5.685	-13	-13
TC_WI+UE+CC_R+UE+RC_EASVM+UE	18.84	12.290	88	88
TC_WI+UE+CC_R+UE+RC_SVM+UE	18.84	12.290	88	88
TC_WI+UE+CC_R+UE+RC_EA+UE	18.84	12.290	88	88
TC_WI+UE+CC_R+UE	18.81	12.270	88	88
TC_WI+UE+CC_R	8.75	5.706	-13	-12
TC_WI+UE	10.53	6.867	5	5

The next sub-section assesses the engineering consultant project revenue controls' unintended effects, using the 8 unique asset renewal-related projects.

Model Simulations for Engineering Consultant Project Revenue Controls and their Unintended Effects

Subsequent to the 36 model simulations, per project, of client project cost controls and their unintended effects discussed in the preceding sub-section, a further 46 different model simulations were run for each and every project, by varying the engineering consultant project revenue controls and their unintended effects (discussed in Section 5.8). The 46 different simulations are as described in Section 6.6.1 and shown in Table 6.18. They were conducted using the associated calibrated system dynamics simulation model discussed in Section 6.5.

Table 6.25 shows the model simulations outputs (project time schedule duration and project cost) of engineering consultant project revenue controls and their unintended effects for each of the 46 model simulation runs conducted for Project P10, one of the 8 asset renewal-related projects considered.

As discussed in Chapters 4 and 5, in this research study: only time-based contracts with a ceiling price (Turner, 2004) between the client and the engineering consultant were considered; and only the time-based costs for the engineering consultant services were considered for the project cost. Hence, in this research study, the project revenue realised by the engineering consultant at project completion was assumed to be equal to the project cost incurred by the client at completion of the same project. The simulation results shown in Table 6.25 indicate that the short-term impact of all the considered engineering consultant project revenue controls looked positive, supporting the intended effect of a reduction in the engineering consultant project revenue shortfall. For instance, using the first considered engineering consultant project revenue control, i.e. effort adjustment (simulation run TC_WI+UE+RC_EA), resulted in a positive project cost budget overrun (which mean an increase in the engineering consultant project revenue, and a decrease in the engineering consultant project revenue shortfall) of approximately 5%.

When all the unintended effects of the engineering consultant project revenue controls, i.e., all the three client project cost controls (i.e. increasing the frequency of both progress meetings and reports, and delaying approval and payment of the engineering consultant's invoices – all of which result in an increase in project work completion rate, as shown in Figure 4.31), were considered (simulation run TC_WI+UE+RC_EA+CC_RMIap), there was, however, an engineering consultant project revenue shortfall (negative project cost budget overrun) of approximately 11%, as shown in Table 6.25. Thus, the long-term impact of the engineering consultant project revenue controls was counterintuitive, counteractive and unintended: instead of the engineering consultant project revenue shortfall decreasing, it increased. This is also a ‘better-before-worse’ result that is characteristic of dynamic complexity (Sterman, 2000).

The other asset renewal-related projects generally exhibited a similar ‘better-before-worse’ result as evident in Appendix H (Tables H.2.3 and H.2.4), which shows all the 46 simulations outputs (project time duration, cost and engineering consultant project revenue) of engineering consultant project revenue controls and their unintended effects for each of the 8 projects. Thus, the simulation outputs supported the following counterintuitive dynamic hypothesis formulated in Section 4.9.3:

> *The engineering consultant project revenue controls, which are aimed at reducing/eliminating the ‘project revenue shortfall’ by increasing the ‘estimated project cost at completion’ (a ‘win-lose’ control in favour of the engineering consultant), tend to generate some unintended and counteractive consequence (unintended effect) that decreases the ‘estimated project cost at completion’ and increases the ‘project revenue shortfall’.*

From a project cost performance perspective, however, the short-term impact of all the considered engineering consultant project revenue controls looked negative (they yielded a positive project cost budget overrun); while their long-term impact was positive (they yielded a negative project cost budget overrun, which is a cost saving), as shown in Table 6.25.

Table 6.25: Model simulations outputs (time duration and cost) of engineering consultant project revenue controls and their unintended effects for Project P10

Model simulation run-name	Project time schedule duration (months)	Project cost (R million)	Compared with initial plan (time duration of 10 months, and cost budget of R6.521m)	
			% Time schedule delay	% Cost budget over-run
TC_WI+UE+RC_EASVM+CC_RMIap+UE	14.25	7.344	43%	13%
TC_WI+UE+RC_EASVM+CC_RMIap	8.88	5.787	-11%	-11%
TC_WI+UE+RC_EASVM+CC_MIap+UE	15.88	7.090	59%	9%
TC_WI+UE+RC_EASVM+CC_MIap	8.84	5.767	-12%	-12%
TC_WI+UE+RC_EASVM+CC_RIap+UE	14.38	7.069	44%	8%
TC_WI+UE+RC_EASVM+CC_RIap	8.88	5.787	-11%	-11%
TC_WI+UE+RC_EASVM+CC_RM+UE	18.66	12.170	87%	87%
TC_WI+UE+RC_EASVM+CC_RM	8.88	5.787	-11%	-11%
TC_WI+UE+RC_EASVM+CC_Iap+UE	14.59	6.233	46%	-4%
TC_WI+UE+RC_EASVM+CC_Iap	8.91	5.808	-11%	-11%

Model simulation run-name	Project time schedule duration (months)	Project cost (R million)	Compared with initial plan (time duration of 10 months, and cost budget of R6.521m)	
			% Time schedule delay	% Cost budget over-run
TC_WI+UE+RC_EASVM+CC_M+UE	10.88	7.091	9%	9%
TC_WI+UE+RC_EASVM+CC_M	8.84	5.767	-12%	-12%
TC_WI+UE+RC_EASVM+CC_R+UE	18.84	12.290	88%	88%
TC_WI+UE+RC_EASVM+CC_R	8.88	5.787	-11%	-11%
TC_WI+UE+RC_EASVM	10.53	6.867	5%	5%
TC_WI+UE+RC_SVM+CC_RMIap+UE	14.25	7.344	43%	13%
TC_WI+UE+RC_SVM+CC_RMIap	8.88	5.787	-11%	-11%
TC_WI+UE+RC_SVM+CC_MIap+UE	15.88	7.090	59%	9%
TC_WI+UE+RC_SVM+CC_MIap	8.84	5.767	-12%	-12%
TC_WI+UE+RC_SVM+CC_RIap+UE	14.38	7.069	44%	8%
TC_WI+UE+RC_SVM+CC_RIap	8.88	5.787	-11%	-11%
TC_WI+UE+RC_SVM+CC_RM+UE	18.66	12.170	87%	87%
TC_WI+UE+RC_SVM+CC_RM	8.88	5.787	-11%	-11%
TC_WI+UE+RC_SVM+CC_Iap+UE	14.59	6.233	46%	-4%
TC_WI+UE+RC_SVM+CC_Iap	8.91	5.808	-11%	-11%
TC_WI+UE+RC_SVM+CC_M+UE	10.88	7.091	9%	9%
TC_WI+UE+RC_SVM+CC_M	8.84	5.767	-12%	-12%
TC_WI+UE+RC_SVM+CC_R+UE	18.84	12.290	88%	88%
TC_WI+UE+RC_SVM+CC_R	8.88	5.787	-11%	-11%
TC_WI+UE+RC_SVM	10.53	6.867	5%	5%
TC_WI+UE+RC_EA+CC_RMIap+UE	14.25	7.344	43%	13%
TC_WI+UE+RC_EA+CC_RMIap	8.88	5.787	-11%	-11%
TC_WI+UE+RC_EA+CC_MIap+UE	15.88	7.090	59%	9%
TC_WI+UE+RC_EA+CC_MIap	8.84	5.767	-12%	-12%
TC_WI+UE+RC_EA+CC_RIap+UE	14.38	7.069	44%	8%
TC_WI+UE+RC_EA+CC_RIap	8.88	5.787	-11%	-11%
TC_WI+UE+RC_EA+CC_RM+UE	18.66	12.170	87%	87%
TC_WI+UE+RC_EA+CC_RM	8.88	5.787	-11%	-11%
TC_WI+UE+RC_EA+CC_Iap+UE	14.59	6.233	46%	-4%
TC_WI+UE+RC_EA+CC_Iap	8.91	5.808	-11%	-11%
TC_WI+UE+RC_EA+CC_M+UE	10.88	7.091	9%	9%
TC_WI+UE+RC_EA+CC_M	8.84	5.767	-12%	-12%
TC_WI+UE+RC_EA+CC_R+UE	18.84	12.290	88%	88%
TC_WI+UE+RC_EA+CC_R	8.88	5.787	-11%	-11%
TC_WI+UE+RC_EA	10.53	6.867	5%	5%
TC_WI+UE	10.53	6.867	5%	5%

The next sub-section assesses the impact of competition (i.e. competing client project cost controls and their unintended effects, and engineering consultant project revenue controls and their unintended effects) on project performance, using the 8 unique asset renewal-related projects.

Analysis of the Impact of Competition on Project Performance

As discussed in Section 6.6.1: two measures of project performance (project time schedule duration and project cost) were considered in this research study; and to assess the impact of the competition between the two key project participants (the client and the engineering consultant) on project performance (as measured by project time schedule duration and project cost), two model simulation runs were considered, namely: TC_WI+UE (*Without competition)*; and TC_WI+UE+ CC_RMIap+UE+RC_EASVM+UE (*With competition*). The two model simulations were conducted using the associated calibrated system dynamics simulation model discussed in Section 6.5.

Table 6.26 shows, for each of the 8 unique raw water infrastructure asset renewal-related projects considered, the initially planned project time schedule duration and project cost, as well as their corresponding simulated outputs for the two model simulation runs. As is evident in Table 6.26: project time schedule performance was worse in the 'With competition' simulation run than in the 'Without competition' simulation run for all the considered 8 projects; whilst project cost performance was worse in the 'With competition' simulation run than in the 'Without competition' simulation run for 4 (P10, P14, P15 and P16) of the 8 considered projects.

Table 6.26: Planned project time duration and cost, and corresponding simulated outputs without and with competition (asset renewal-related projects)

Project number	Planned		Without competition (simulation run: TC_WI+UE)		With competition (simulation run: TC_WI+UE+CC_RMIap+UE +RC_EASVM+UE)	
	Project time schedule duration (months)	Project cost (R million)	Project time schedule duration (months)	Project cost (R million)	Project time schedule duration (months)	Project cost (R million)
P10	10.00	6.521	10.53	6.867	14.25	7.344
P11	5.00	2.857	5.41	3.089	6.47	2.876
P12	4.00	2.535	4.72	2.991	4.78	2.807
P13	6.00	4.327	6.59	4.755	7.53	4.754
P14	10.00	7.592	10.69	8.113	11.78	8.321
P15	6.00	3.312	6.63	3.657	8.00	3.781
P16	8.00	6.670	7.53	6.279	13.03	8.126
P17	5.00	2.632	5.28	2.780	5.50	2.635

Refer to Section 6.6.1 for the definitions and interpretations of *schedule performance index (SPI), cost performance index (CPI)* and *impact ratio on project performance.* Table 6.27 shows, for each of the 8 unique raw water infrastructure asset renewal-related projects considered, the SPI and CPI (without and with competition) and the resulting impact ratios (of the competition between the client and the engineering consultant during project execution) on project time schedule performance and on project cost performance. As highlighted in Section 6.6.1, this assessment of the impact/influence of the competition between the two key project participants (with their different and competing performance measures and targets during project execution) on project performance (as measured by project time duration and cost) is another novel contribution made by this study. It assists towards addressing a related gap identified in the reviewed literature, namely no appropriate study could be identified that specifically investigated the influence of such competition on project performance, as discussed in Chapters 1, 3, and 4.

The competition between the client and the engineering consultant during project execution negatively influenced (impact ratio greater than 1) the project time schedule performance of all the 8 projects, with Project P16 being the worst affected with an impact ratio of 1.73, as shown in Table 6.27.

The competition: negatively influenced the project cost performance of 4 (P10, P14, P15 and P16) of the 8 considered projects, with Project P16 being the worst affected with an impact ratio of 1.29; had no influence (impact ratio equal to 1) on the project cost performance of Project P13; and positively influenced the project cost performance of 3 projects (P11, P12 and P17), as also shown in Table 6.27.

Table 6.27: SPI and CPI (without and with competition), and competition impact ratios per project (asset renewal-related)

Project number	Project time schedule performance			Project cost performance		
	Schedule performance index (SPI)		Impact ratio	Cost performance index (CPI)		Impact ratio
	Without competition (simulation run: TC_WI+UE)	With competition (simulation run: TC_WI+UE+CC_RMlap+UE+RC_EASVM+UE)		Without competition (simulation run: TC_WI+UE)	With competition (simulation run: TC_WI+UE+CC_RMlap+UE+RC_EASVM+UE)	
P10	0.95	0.70	1.35	0.95	0.89	1.07
P11	0.92	0.77	1.20	0.92	0.99	0.93
P12	0.85	0.84	1.01	0.85	0.90	0.94
P13	0.91	0.80	1.14	0.91	0.91	1.00
P14	0.94	0.85	1.10	0.94	0.91	1.03
P15	0.91	0.75	1.21	0.91	0.88	1.03
P16	1.06	0.61	1.73	1.06	0.82	1.29
P17	0.95	0.91	1.04	0.95	1.00	0.95

Table 6.28 shows the overall descriptive statistics for the SPI and CPI (without and with competition) and the associated impact ratios (of the competition between the client and the engineering consultant during project execution) on both project time schedule performance and project cost performance for the 8 unique raw water infrastructure asset renewal-related projects considered in this study. On average, the competition negatively influenced project performance: the mean impact ratios on both the project time schedule performance and the project cost performance were greater than 1 (i.e. 1.22 and 1.03, respectively). This finding supports the following related dynamic hypothesis formulated in Section 4.9.3:

> *The client project cost controls and the engineering consultant project revenue controls tend to oppose (compete with) each other, generating some unintended and counteractive consequences (unintended effects) that negatively influence project performance (increasing both 'project time schedule delay' and 'project cost overrun').*

Table 6.28: Descriptive statistics for SPI and CPI (without and with competition), and competition impact ratios (asset renewal-related projects)

<table>
<tr><th rowspan="3">Statistic</th><th colspan="3">Project time schedule performance</th><th colspan="3">Project cost performance</th></tr>
<tr><th colspan="2">Schedule performance index (SPI)</th><th rowspan="2">Impact ratio</th><th colspan="2">Cost performance index (CPI)</th><th rowspan="2">Impact ratio</th></tr>
<tr><th>Without competition (simulation run: TC_WI+UE)</th><th>With competition (simulation run: TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE)</th><th>Without competition (simulation run: TC_WI+UE)</th><th>With competition (simulation run: TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE)</th></tr>
<tr><td>Median</td><td>0.93</td><td>0.78</td><td>1.17</td><td>0.93</td><td>0.91</td><td>1.01</td></tr>
<tr><td>Mean</td><td>0.94</td><td>0.78</td><td>1.22</td><td>0.94</td><td>0.91</td><td>1.03</td></tr>
<tr><td>Standard Deviation</td><td>0.06</td><td>0.09</td><td>0.23</td><td>0.06</td><td>0.06</td><td>0.12</td></tr>
<tr><td>Minimum</td><td>0.85</td><td>0.61</td><td>1.01</td><td>0.85</td><td>0.82</td><td>0.93</td></tr>
<tr><td>Maximum</td><td>1.06</td><td>0.91</td><td>1.73</td><td>1.06</td><td>1.00</td><td>1.29</td></tr>
</table>

The next sub-section assesses the sensitivity of the impact of the competition on project performance, as determined in this sub-section, to uncertainty/changes in some of the key calibrated model parameters.

6.6.4 Behaviour Mode Sensitivity Analysis (Infrastructure Asset Renewal Projects)

Parametric Sensitivity Analysis Overview

Refer to Section 6.6.2 for an overview of: parametric sensitivity analysis, including its definition, different types thereof, how to select a particular type of sensitivity analysis; and the basic modes of dynamic behaviour (and the basic feedback structures that generate them). In this sub-section, the behaviour mode sensitivity of the impact of competition on project performance determined in Section 6.6.3 using the second set of unique raw water infrastructure projects (8 asset renewal-related projects) considered in this research study is assessed.

Behaviour Mode Sensitivity

The process followed in conducting the behaviour mode sensitivity analysis in this sub-section was the same as that described and followed in Section 6.6.2. Figures 6.13 and 6.14 show the results of the sensitivity analysis per project; that is, the sensitivities of the *schedule performance index* and the *cost performance index,* respectively, to the uncertainty/changes in the considered 10 parametric assumptions. The two figures show that both the *schedule performance index* and the *cost performance index* exhibited no behaviour mode sensitivity (though there were effects in absolute values, i.e., exhibited numerical sensitivity): both the base case (based on calibrated parameter values, and represented by the blue single line) and the random cases (based on the 200 sets of randomly selected parameter values, represented by the solid envelopes) exhibited an *S-shaped growth with overshoot and collapse* behaviour mode for all the considered projects.

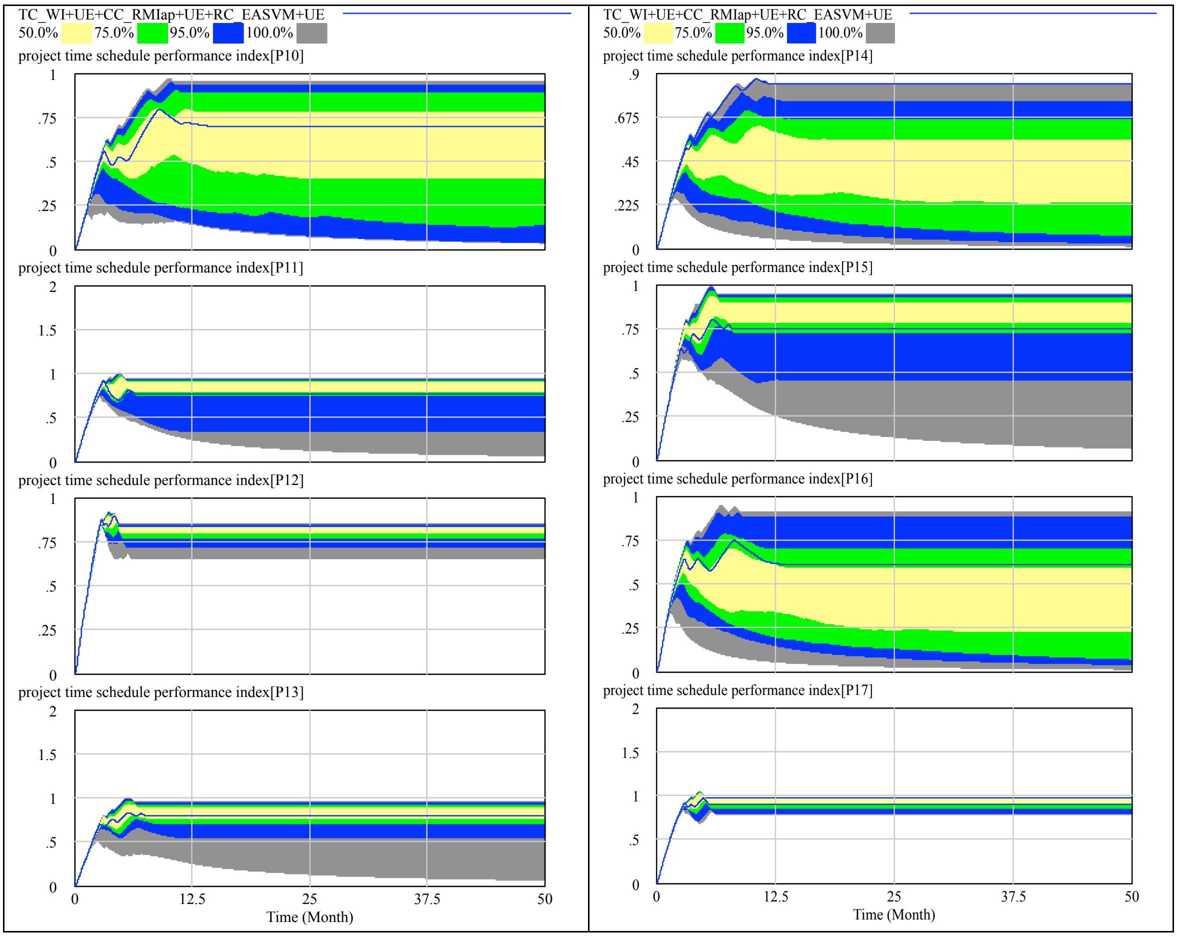


Figure 6.13: Sensitivity of schedule performance index (with competition) per project (asset renewal-related)

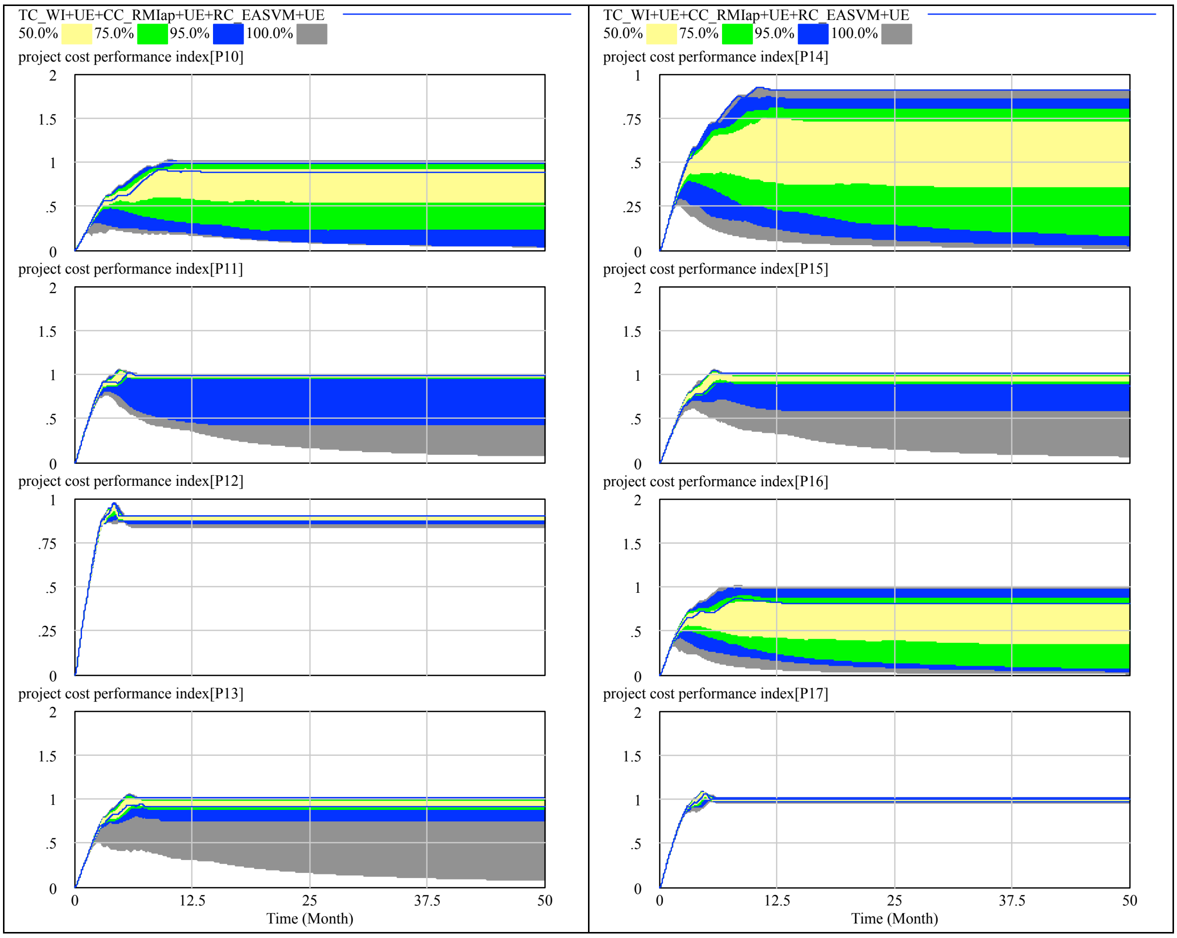


Figure 6.14: Sensitivity of cost performance index (with competition) per project (asset renewal-related)

The next sub-section is the third stage of the impact analysis, i.e., comparison of the key results from the preceding two stages of the impact analysis, providing a provisional answer to research question number 3 (posed in Section 1.6).

6.6.5 Comparisons and Discussions (Impact and Behaviour Mode Sensitivity)

Subsequent to the model calibrations discussed in Sections 6.4 and 6.5, the next step was to analyse the impact of competition between the two key project participants (the client and the engineering consultant) on project performance. This was conducted in three stages, described in detail at the beginning of Section 6.6.

In the *first stage* (Sections 6.6.1 and 6.6.2), three sets of simulation experiments were conducted using the data gathered for the first set of unique raw water infrastructure projects (asset management planning and support-related, made up of 10 projects) and the associated calibrated system dynamics simulation model, both discussed in Section 6.4. In each case, the model simulation outputs were then analysed to determine whether or not they supported a related dynamic hypothesis formulated in Section 4.9.3. The impact of the competition (i.e. combined impact of competing client project cost controls and their unintended effects, and engineering consultant project revenue controls and their unintended effects) on the project performance was assessed through the determination of two impact ratios (impact ratio on project time schedule performance, and impact ratio on project cost performance), for each of the 10 projects and on average (Section 6.6.1). Subsequently, a multivariate Monte Carlo behaviour mode sensitivity analysis was conducted to assess, for each project, the sensitivity of the impact on project performance to uncertainty in key calibrated model parameters (Section 6.6.2).

In the *second stage* (Sections 6.6.3 and 6.6.4), all the three sets of model simulation experiments, impact analysis and sensitivity analysis conducted in the preceding stage were repeated, but using data gathered for the second set of unique raw water infrastructure projects (asset renewal-related, made up of 8 projects) and the associated calibrated system dynamics simulation model discussed in Section 6.5.

The *third stage* is this sub-section (Section 6.6.5), where a comparison of the key results (client project cost controls' counteractive and unintended effects, engineering consultant project revenue controls' counteractive and unintended effects, as well as polarity and behaviour mode sensitivity of the impact of the competition on project performance) from the preceding two stages is made, with appropriate conclusions drawn as to whether or not the associated dynamic hypotheses formulated in Section 4.9.3 were supported by the two sets of projects considered, and an appropriate provisional answer to research question number 3 (posed in Section 1.6) is provided.

The above-summarised three-stage analysis of the impact of competition on project performance, where the impact analysis and associated sensitivity analysis were conducted separately for each of the two sets of unique raw water infrastructure projects considered, with subsequent comparison of results from the two sets, assisted in enhancing the validity of the associated overall key research results (presented later in this Section 6.6.5), namely support for the related dynamic hypotheses and a provisional answer for research question number 3 (posed in Section 1.6), which help to address some key associated gaps identified in the reviewed literature, as discussed in Chapters 1, 3 and 4. It is a novel contribution towards the enhancement of the existing system dynamics simulation model validation, in particular impact and sensitivity analyses, processes and procedures, and is, thus expected to benefit future system dynamics research studies.

The next two sub-sections compare and discuss the individual project participant controls' counteractive and unintended effects for the two sets of unique raw water infrastructure projects considered in the current research study.

Client Project Cost Controls' Unintended Effects

The client project cost controls simulation results for both sets of unique raw water infrastructure projects considered [10 asset management planning and support-related (Section 6.6.1), and 8 asset renewal-related (Section 6.6.3)] suggested a 'better-before-worse' result that is characteristic of dynamic complexity (Sterman, 2000). The short-term impact of all the considered client project cost controls supported the intended effect of a reduction in project cost overrun. However, when all the unintended effects of the client project cost controls (i.e., decrease in productivity due to 'Less Time Spent On Real Work' and 'Engineering Consultant Project Revenue Controls', increase in work errors due to 'Haste Makes Waste', and decrease in project workforce due to 'Insufficient Operating Cash Flow For Engineering Consultant' – all of which result in a decrease in project work completion rate, as shown in Figure 4.31) were considered, the long-term impact of the client project cost controls was counterintuitive, counteractive and unintended: instead of the project cost overrun decreasing, it increased.

The simulation results from both sets of projects considered, thus, supported the following counterintuitive dynamic hypothesis formulated in Section 4.9.3:

> *The client project cost controls, which are aimed at reducing/eliminating the 'project cost overrun' by reducing the 'estimated project cost at completion' (a 'win-lose' control in favour of the client), tend to generate some unintended and counteractive consequences (unintended effects) that increase the 'estimated project cost at completion' and the 'project cost overrun'.*

Engineering Consultant Project Revenue Controls' Unintended Effects

As discussed in Chapters 4 and 5, in this research study: only time-based contracts with a ceiling price (Turner, 2004) between the client and the engineering consultant were considered; and only the time-based costs for the engineering consultant services were considered for project cost. Hence, in this study, the project revenue realised by the engineering consultant at project completion was assumed to be equal to the project cost incurred by the client at completion of the same project.

The engineering consultant project revenue controls simulation results for both sets of unique raw water infrastructure projects considered (10 asset management planning and support-related projects (Section 6.6.1), and 8 asset renewal-related projects (Section 6.6.3)) suggested a 'better-before-worse' result characteristic of dynamic complexity (Sterman, 2000). The short-term impact of the considered engineering consultant project revenue controls supported the intended effect of a reduction in engineering consultant project revenue shortfall. However, when all the unintended effects of the engineering consultant project revenue controls (i.e., all the three client project cost controls, namely increasing the frequency of both progress meetings and reports, and delaying approval and payment of the engineering consultant's invoices – all of which result in an increase in project work completion rate, as shown in Figure 4.31) were considered, the long-term impact of the engineering consultant project revenue controls was counterintuitive, counteractive and unintended: instead of the engineering consultant project revenue shortfall decreasing, it increased.

The simulation results from both sets of projects considered, thus, supported the following counterintuitive dynamic hypothesis formulated in Section 4.9.3:

> *The engineering consultant project revenue controls, which are aimed at reducing/eliminating the 'project revenue shortfall' by increasing the 'estimated project cost at completion' (a 'win-lose' control in favour of the engineering consultant), tend to generate some unintended and counteractive consequence (unintended effect) that decreases the 'estimated project cost at completion' and increases the 'project revenue shortfall'.*

The next sub-section compares and discusses the impact of the competition (i.e. competing client project cost controls and their unintended effects, and engineering consultant project revenue controls and their unintended effects) on project performance for the two sets of projects considered in this research study.

Analysis of the Impact of Competition on Project Performance

The reviewed literature showed that: there are many measures of project performance (Section 3.3.1), yet current project dynamics models are limited to project performance (mainly time schedule duration) control actions of mainly the engineering consultant or construction contractor; and control actions taken by the client to protect project performance, and control actions taken by the engineering consultant and construction contractor to protect their individual business performance targets during project execution are sparingly covered (Section 3.11). Also, in the reviewed literature, no appropriate system dynamics project model could be identified that considered: competition among project participants, with their different and competing performance measures and targets during project execution; and how such competition influences project performance (Section 3.11).

In this research study, two measures of project performance (project time schedule duration and project cost) were used as simulation model outputs, similar to the models of De Marco (2006), Ford et al. (2007), and Parvan et al. (2015)). However, unlike in any of the said previous models, the system dynamics simulation model formulated in this research study (as discussed in Chapters 4 and 5) also captured the competition between two key project participants (the client and the engineering consultant) in the form of two sets of competing project controls (aimed at win-lose results), namely client project cost controls and their associated unintended effects, and engineering consultant project revenue controls and their associated unintended effects. This sub-section analyses how such competition influences the said two measures of project performance. This novel contribution, made by this research study, expands the existing project dynamics models, deepening our understanding of project dynamics, and assists towards addressing the above-mentioned gaps identified in the reviewed literature.

In this research study, the impact of the competition between the two key project participants (the client and the engineering consultant) during project execution on project performance was assessed through the determination of the *impact ratio on project performance,* which is a measure of the decrease/increase (deterioration/ improvement) of a project performance index (SPI or CPI) as a result of the competition. Put differently, the *impact ratio on project performance* indicates the decrease/increase below/above what the project performance index (SPI or CPI) would have been (if there was no competition). Two impact ratios were determined, in line with the two measures of project performance used in this research study as discussed in Sections 6.6.1 and 6.6.3, namely:

- *impact ratio* on *project time schedule performance* (determined as the ratio of the project schedule performance index when there is no competition to the project schedule performance index when there is competition); and
- *impact ratio on project cost performance* (determined as the ratio of the project cost performance index when there is no competition to the project cost performance index when there is competition).

Noteworthy is that an *impact ratio on project performance* (a measure of the impact of the competition on project performance, in terms of project time schedule duration and project cost) of: less than 1 indicates that the competition positively influences (improves) the project performance; 1 indicates that the competition has no impact on the project performance; and greater than 1 indicates that the competition negatively influences (worsens) the project performance.

Tables 6.29 and 6.30 show the number of projects that were negatively, positively and not influenced (in terms of project time schedule performance and project cost performance, respectively) by the competition between the client and the engineering consultant for the two sets of unique raw water infrastructure projects (10 asset management planning and support-related, and 8 asset renewal-related) considered in this research study. Refer to Tables 6.21 and 6.27 for more details regarding the individual projects' SPI and CPI (without and with competition) and the resulting impact ratios of the competition on project time schedule performance and on project cost performance. This assessment of the impact/influence of competition between two key project participants (with their different and competing performance measures and targets during project execution) on project performance (as measured by project time schedule duration and project cost) is another novel contribution made by this research study. It assists towards addressing a related gap identified in the reviewed literature, namely no appropriate study could be identified that specifically investigated the influence of such competition on project performance, as discussed in Chapters 1, 3, and 4.

The competition negatively influenced (impact ratio greater than 1) the project time schedule performance of: most (9/10) of the asset management planning and support-related projects; and all the 8 asset renewal-related projects considered, as shown in Table 6.29.

The competition negatively influenced (impact ratio greater than 1) the project cost performance of: most (8/10) of the asset management planning and support-related projects; and half (4/8) of the asset renewal-related projects considered, as shown in Table 6.30. However, it positively influenced (impact ratio less than 1) the project cost performance of: 2 asset management planning and support-related projects; and 3 asset renewal-related projects.

Table 6.29: Impact of competition on project time schedule performance per project set

Impact of competition	Number of projects influenced		
	Asset management planning and support-related projects	Asset renewal-related projects	Total
Negative (impact ratio > 1)	9	8	**17**
Positive (impact ratio < 1)	1	-	**1**
None (impact ratio = 1)	-	-	**-**
Total	**10**	**8**	**18**

Table 6.30: Impact of competition on project cost performance per project set

Impact of competition	Number of projects influenced		
	Asset management planning and support-related projects	Asset renewal-related projects	Total
Negative (impact ratio > 1)	8	4	**12**
Positive (impact ratio < 1)	2	3	**5**
None (impact ratio = 1)	-	1	**1**
Total	**10**	**8**	**18**

Table 6.31 (refer to Tables 6.22 and 6.28 for more details) shows the descriptive statistics for the impact ratios of the competition on project time schedule

performance and on project cost performance for the two sets of unique raw water infrastructure projects (10 asset management planning and support-related, and 8 asset renewal-related) considered in this study. For both sets of projects, the mean values for the impact ratios on both the project time schedule performance and on the project cost performance were greater than 1. This means that, on average, the competition negatively influenced both project time schedule performance and project cost performance for both sets of projects considered.

The mean impact ratio on project time schedule performance was much higher than that on project cost performance for both sets of projects, as shown in Table 6.31. This means that the competition much more negatively influenced project time schedule performance than project cost performance, in both sets of projects considered. For instance, on average, the competition led to a 28% project time schedule delay and a much lower 7% project cost overrun for the asset management planning and support-related projects. A similar pattern is evident for the asset renewal-related projects, as shown in Table 6.31.

Table 6.31: Descriptive statistics for competition impact ratios on project performance per project set

Statistic	Impact ratio on project time schedule performance		Impact ratio on project cost performance	
	Asset management planning and support-related projects	Asset renewal-related projects	Asset management planning and support-related projects	Asset renewal-related projects
Median	1.29	1.17	1.10	1.01
Mean	1.28	1.22	1.07	1.03
Standard Deviation	0.15	0.23	0.08	0.12
Minimum	0.99	1.01	0.97	0.93
Maximum	1.50	1.73	1.18	1.29

Multivariate Monte Carlo behaviour mode sensitivity analyses were conducted to assess the sensitivity of the impact of the competition on project performance (measured by project time schedule performance and project cost performance) to uncertainty/changes in 10 key calibrated model parameters for each of the two sets of unique projects (10 asset management planning and support-related, and 8 asset renewal-related) considered, as discussed in Sections 6.6.2 and 6.6.4. The results of the sensitivity analyses showed that both the *schedule performance index* and the *cost performance index* exhibited no behaviour mode sensitivity (though there were effects in absolute values, i.e., exhibited numerical sensitivity): both the base case (based on calibrated parameter values) and the random cases (based on 200 sets of randomly selected parameter values) exhibited an *S-shaped growth with overshoot and collapse* behaviour mode for all the considered 18 projects.

The above-discussed key research results suggested no difference, in terms of the polarity (which is negative) and behaviour mode insensitivity of the impact of the competition on project performance, between the two sets of unique raw water infrastructure projects considered in this research study. They supported the following dynamic hypothesis formulated in Section 4.9.3:

> *The client project cost controls and the engineering consultant project revenue controls tend to oppose (compete with) each other, generating some unintended and counteractive consequences (unintended effects) that negatively influence project performance (increasing both 'project time schedule delay' and 'project cost overrun').*

Accordingly, a provisional answer for research question number 3 (posed in Section 1.6) is as follows:

<u>Research Question:</u>

3. *How does the competition between the two key project participants (client and engineering consultant) influence project performance?*

<u>Provisional Answer:</u>

> *The competition between the two key project participants (client and engineering consultant) during project execution negatively influences project performance (it results in project time schedule delay and project cost overrun, and thus, it negatively influences both project time schedule performance and project cost performance, both of which are the key measures of project performance considered in this research study).*

Some previous researchers and scholars, such as Lyneis and Ford (2007), Mohammed et al. (2009), and Sutterfield et al. (2007) highlighted that the use of competition (aimed at win-lose results), as a conflict-handling style, is quite common among project participants during project execution. Yet, no appropriate study could be identified in the reviewed existing literature, as discussed in Chapter 3, that specifically investigated how such competition influences project performance. Thus, the analysis of the impact/influence of competition between two key project participants (the client and the engineering consultant, with their different and competing performance measures and targets during project execution) on project performance (as measured by project time schedule duration and project cost), as conducted in this Section 6.6, is one of the novel contributions made by this research study. The above-stated key research findings, particularly support for the stated dynamic hypothesis from two different sets of unique raw water infrastructure projects, and the stated provisional answer for research question number 3 (posed in Section 1.6) help towards addressing the above-mentioned gap identified in the reviewed literature, and deepens our understanding of project dynamics.

The next section discusses how the two calibrated system dynamics simulation models (discussed in Sections 6.4 and 6.5) were used to separately conduct similar simulation experiments, with subsequent comparison of their results, in assessing the impact of the competition between two key project participants (client and engineering consultant) on the business performance of the engineering consultant.

6.7. Impact of Competition on the Engineering Consultant's Business Performance

This section seeks to answer the following research question (posed in Section 1.6):

4. *How does the competition between the two key project participants (client and engineering consultant) influence the business performance of the engineering consultant?*

Analysis of the impact of competition between the two key project participants (the client and engineering consultant) on the business performance of the engineering consultant was conducted in three stages, similar to the analysis of the impact of the competition on project performance as described in Section 6.6.

In the *first stage* (Sections 6.7.1 and 6.7.2), data gathered for the first set of unique raw water infrastructure projects (10 asset management planning and support-related) and the associated calibrated system dynamics simulation model discussed in Section 6.4 were used to conduct the three sets of simulation experiments and sensitivity analysis similar to Sections 6.6.1 and 6.6.2. The impact of the competition (i.e. combined impact of competing client project cost controls and their unintended effects, and engineering consultant project revenue controls and their unintended effects) on the engineering consultant's project business performance, for each of the 10 projects, was assessed through the determination of two impact ratios (impact ratio on project time schedule performance, and impact ratio on the engineering consultant's project revenue performance) (Section 6.7.1). The descriptive statistics of the impact were then analysed to determine whether or not they supported the following dynamic hypothesis formulated in Section 4.9.3:

> *The client project cost controls and the engineering consultant project revenue controls tend to oppose (compete with) each other, generating some unintended and counteractive consequences (unintended effects) that negatively influence the engineering consultant's project business performance (increasing both 'project time schedule delay' and 'project revenue shortfall').*

Subsequently, a multivariate Monte Carlo behaviour mode sensitivity analysis was conducted to assess, for each project, the sensitivity of the impact of the competition on the engineering consultant's project business performance to uncertainty in key calibrated parameters (Section 6.6.2).

In the *second stage* (Sections 6.7.3 and 6.7.4), all the three sets of model simulation experiments, impact analysis and sensitivity analysis conducted in the preceding stage were repeated, but using data gathered for the second set of unique raw water infrastructure projects (8 asset renewal-related) and the associated calibrated system dynamics simulation model discussed in Section 6.5.

In the *third stage* (Section 6.7.5), a comparison of the key results (i.e., polarity and behaviour mode sensitivity of the impact of the competition on the engineering consultant's project business performance) from the preceding two stages was made, with appropriate conclusions drawn as to whether or not the said dynamic hypothesis was supported by the two sets of projects, and an appropriate provisional answer to research question number 4 (posed in Section 1.6) was then provided.

The above-described three-stage analysis of the impact of the competition on the engineering consultant's project business performance, where the impact analysis and associated sensitivity analysis were conducted separately for each of the two sets of unique raw water infrastructure projects considered, with subsequent comparison of results from the two sets, assisted in enhancing the validity of the overall key research results presented in Section 6.7.5, namely support for the stated dynamic hypothesis and a provisional answer for research question number 4 (posed in Section 1.6), which help to address associated gaps identified in the reviewed literature, as discussed in Chapters 1, 3 and 4. It is a novel contribution towards the enhancement of the existing system dynamics simulation model validation, in particular impact and sensitivity analyses, processes and procedures, and is, thus expected to benefit future system dynamics research studies. The next sub-section discusses key results from the first stage of the impact analysis.

6.7.1 Impact Analysis (Infrastructure Asset Management Planning and Support Projects)

Project Participants Performance Targets

As discussed in Chapter 4 (Table 4.11 and Figure 4.31), the client and the engineering consultant set up their own individual performance targets, and take appropriate control actions aimed at protecting them, during project execution. Table 6.15 in Section 6.6.1 shows the client project cost targets and engineering consultant project revenue targets per project for the first set of unique raw water infrastructure projects (10 asset management planning and support-related) considered in this research study. These individual project participant performance targets were used in all the associated simulation experiments conducted in Sections 6.6 and 6.7. The next sub-section assesses the client project cost controls' counteractive and unintended effects for the same set of projects.

Model Simulations for Client Project Cost Controls and their Unintended Effects

As discussed in Section 6.6.1, subsequent to the model calibration discussed in Section 6.4, a total of 36 different model simulations were run for each project, by varying the client project cost controls and their unintended effects. The 36 different simulations are as shown in Table 6.16 (Section 6.6.1). They were conducted using the calibrated system dynamics simulation model discussed in Section 6.4.

Table 6.32 shows the model simulations outputs (project time schedule duration and engineering consultant project revenue) of client project cost controls and their unintended effects for each of the 36 model simulation runs conducted for Project P0, one of the 10 asset management planning and support-related projects considered. In this research study, as discussed in Chapters 4 and 5: only time-based contracts with a ceiling price (Turner, 2004) between the client and the engineering consultant were considered; and only the time-based costs for the engineering consultant services were considered for the project cost. Hence, in this research study, the project revenue realised by the engineering consultant at project completion was assumed to be equal to the project cost incurred by the client at completion of the same project.

As discussed in Section 6.6.1: the short-term impact of all the considered client project cost controls looked positive for the client, supporting the intended effect of a reduction in project cost overrun; while their long-term impact was counterintuitive, counteractive and unintended: instead of the project cost overrun decreasing, it increased.

The simulation results shown in Table 6.32, however, indicate the reverse for the engineering consultant project revenue: the short-term impact of all the considered client project cost controls looked negative for the engineering consultant project revenue performance. For instance, using the first considered client project cost control, i.e. increasing the frequency of progress reports (simulation run TC_WI+UE+CC_R), resulted in a shortfall in the engineering consultant project revenue of approximately 14%. However, when all the unintended effects of the client project cost controls (i.e., decrease in productivity due to ‘Less Time Spent On Real Work’ and ‘Engineering Consultant Project Revenue Controls’, increase in work errors due to ‘Haste Makes Waste’, and decrease in project workforce due to ‘Insufficient Operating Cash Flow For Engineering Consultant’ – all of which result in a decrease in project work completion rate, as shown in Figure 4.31) were considered (simulation run TC_WI+UE+CC_R+UE+RC_EASVM+UE), the engineering consultant project revenue increased by 17%, as shown in Table 6.32. Thus, the long-term impact of all the client project cost controls looked positive for the engineering consultant.

The other asset management planning and support-related projects generally exhibited a similar trend as evident in Appendix H (Tables H.1.1 and H.1.2), which shows all the 36 model simulations outputs (project time schedule duration, project cost and engineering consultant project revenue) of client project cost controls and their unintended effects for each of the 10 projects.

Table 6.32: Model simulations outputs (time duration and engineering consultant project revenue) of client project cost controls and unintended effects for Project P0

Model simulation run-name	Project time schedule duration (months)	Engineering consultant project revenue (R million)	Compared with initial plan (time duration of 12 months, and project revenue target of R13. 473m)	
			% Time schedule delay	% Revenue shortfall
TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE	16.12	15.910	34	-18
TC_WI+UE+CC_RMIap+UE+RC_SVM+UE	16.44	16.070	37	-19
TC_WI+UE+CC_RMIap+UE+RC_EA+UE	16.06	15.860	34	-18
TC_WI+UE+CC_RMIap+UE	15.41	15.270	28	-13
TC_WI+UE+CC_RMIap	10.06	11.590	-16	14
TC_WI+UE+CC_MIap+UE+RC_EASVM+UE	15.69	14.040	31	-4
TC_WI+UE+CC_MIap+UE+RC_SVM+UE	15.69	14.040	31	-4
TC_WI+UE+CC_MIap+UE+RC_EA+UE	15.66	14.020	31	-4
TC_WI+UE+CC_MIap+UE	14.53	13.660	21	-1
TC_WI+UE+CC_MIap	10.06	11.590	-16	14
TC_WI+UE+CC_RIap+UE+RC_EASVM+UE	13.31	13.100	11	3
TC_WI+UE+CC_RIap+UE+RC_SVM+UE	13.31	13.100	11	3
TC_WI+UE+CC_RIap+UE+RC_EA+UE	13.22	13.080	10	3
TC_WI+UE+CC_RIap+UE	12.31	12.620	3	6
TC_WI+UE+CC_RIap	10.06	11.590	-16	14
TC_WI+UE+CC_RM+UE+RC_EASVM+UE	22.09	25.450	84	-89
TC_WI+UE+CC_RM+UE+RC_SVM+UE	22.12	25.490	84	-89
TC_WI+UE+CC_RM+UE+RC_EA+UE	22.09	25.450	84	-89
TC_WI+UE+CC_RM+UE	13.72	15.800	14	-17
TC_WI+UE+CC_RM	10.06	11.590	-16	14
TC_WI+UE+CC_Iap+UE+RC_EASVM+UE	13.59	12.080	13	10
TC_WI+UE+CC_Iap+UE+RC_SVM+UE	13.50	12.050	13	11
TC_WI+UE+CC_Iap+UE+RC_EA+UE	13.59	12.100	13	10
TC_WI+UE+CC_Iap+UE	13.25	11.910	10	12
TC_WI+UE+CC_Iap	10.12	11.660	-16	13
TC_WI+UE+CC_M+UE+RC_EASVM+UE	13.38	15.410	12	-14
TC_WI+UE+CC_M+UE+RC_SVM+UE	13.41	15.440	12	-15

Model simulation run-name	Project time schedule duration (months)	Engineering consultant project revenue (R million)	Compared with initial plan (time duration of 12 months, and project revenue target of R13. 473m)	
			% Time schedule delay	% Revenue shortfall
TC_WI+UE+CC_M+UE+RC_EA+UE	13.38	15.410	12	-14
TC_WI+UE+CC_M+UE	12.97	14.940	8	-11
TC_WI+UE+CC_M	10.06	11.590	-16	14
TC_WI+UE+CC_R+UE+RC_EASVM+UE	13.66	15.730	14	-17
TC_WI+UE+CC_R+UE+RC_SVM+UE	19.06	21.960	59	-63
TC_WI+UE+CC_R+UE+RC_EA+UE	13.66	15.730	14	-17
TC_WI+UE+CC_R+UE	12.88	14.830	7	-10
TC_WI+UE+CC_R	10.06	11.590	-16	14
TC_WI+UE	12.50	14.400	4	-7

The next sub-section assesses the engineering consultant project revenue controls' unintended effects, using the 10 unique asset management planning and support-related projects.

Model Simulations for Engineering Consultant Project Revenue Controls and their Unintended Effects

As discussed in Section 6.6.1, subsequent to the 36 model simulations, per project, of client project cost controls and their unintended effects discussed in the preceding sub-section, a further 46 different model simulations were run for each project, by varying the engineering consultant project revenue controls and their unintended effects. The 46 different simulations are as shown in Table 6.18. They were conducted using the associated calibrated system dynamics simulation model discussed in Section 6.4.

Table 6.33 shows the model simulations outputs (project time schedule duration and engineering consultant project revenue) of engineering consultant project revenue controls and their unintended effects for each of the 46 model simulation runs conducted for Project P0, one of the 10 asset management planning and support-related projects considered.

As discussed in Section 6.6.1, from a project cost performance perspective: the short-term impact of all the engineering consultant project revenue controls was negative (they yielded a positive project cost budget overrun); while their long-term impact was positive (they yielded a negative project cost budget overrun, which is a cost saving). Also, as discussed in Section 6.6.1 (and evident in Table 6.33): the short-term impact of all the considered engineering consultant project revenue controls was positive, supporting the intended effect of a reduction in the engineering consultant project revenue shortfall; while their long-term impact was counterintuitive, counteractive and unintended: instead of the engineering consultant project revenue shortfall decreasing, it increased. This is also a 'better-before-worse' result that is characteristic of dynamic complexity (Sterman, 2000).

The other asset management planning and support-related projects generally exhibited a similar 'better-before-worse' result as evident in Appendix H (Tables H.1.3 and H.1.4), which shows all the 46 model simulations outputs (project time schedule duration, project cost and engineering consultant project revenue) of engineering consultant project revenue and unintended effects for each of the 10 projects. Thus, the model simulation outputs supported the following counterintuitive dynamic hypothesis formulated in Section 4.9.3:

> *The engineering consultant project revenue controls, which are aimed at reducing/eliminating the 'project revenue shortfall' by increasing the 'estimated project cost at completion' (a 'win-lose' control in favour of the engineering consultant), tend to generate some unintended and counteractive consequence (unintended effect) that decreases the 'estimated project cost at completion' and increases the 'project revenue shortfall'.*

Table 6.33: Model simulations outputs (time duration and engineering consultant project revenue) of engineering consultant project revenue controls and their unintended effects for Project P0

Model simulation run-name	Project time schedule duration (months)	Engineering consultant project revenue (R million)	Compared with initial plan (time duration of 12 months, and project revenue target of R13. 473m)	
			% Time schedule delay	% Revenue shortfall
TC_WI+UE+RC_EASVM+CC_RMIap+UE	16.12	15.910	34%	-18%
TC_WI+UE+RC_EASVM+CC_RMIap	10.31	11.880	-14%	12%
TC_WI+UE+RC_EASVM+CC_MIap+UE	15.69	14.040	31%	-4%
TC_WI+UE+RC_EASVM+CC_MIap	10.31	11.880	-14%	12%
TC_WI+UE+RC_EASVM+CC_RIap+UE	13.31	13.100	11%	3%
TC_WI+UE+RC_EASVM+CC_RIap	10.31	11.880	-14%	12%
TC_WI+UE+RC_EASVM+CC_RM+UE	22.09	25.450	84%	-89%
TC_WI+UE+RC_EASVM+CC_RM	10.31	11.880	-14%	12%
TC_WI+UE+RC_EASVM+CC_Iap+UE	13.59	12.080	13%	10%
TC_WI+UE+RC_EASVM+CC_Iap	10.34	11.920	-14%	12%

Model simulation run-name	Project time schedule duration (months)	Engineering consultant project revenue (R million)	Compared with initial plan (time duration of 12 months, and project revenue target of R13. 473m)	
			% Time schedule delay	% Revenue shortfall
TC_WI+UE+RC_EASVM+CC_M+UE	13.38	15.410	12%	-14%
TC_WI+UE+RC_EASVM+CC_M	10.31	11.880	-14%	12%
TC_WI+UE+RC_EASVM+CC_R+UE	13.66	15.730	14%	-17%
TC_WI+UE+RC_EASVM+CC_R	10.31	11.880	-14%	12%
TC_WI+UE+RC_EASVM	12.50	14.400	4%	-7%
TC_WI+UE+RC_SVM+CC_RMIap+UE	16.44	16.070	37%	-19%
TC_WI+UE+RC_SVM+CC_RMIap	10.31	11.880	-14%	12%
TC_WI+UE+RC_SVM+CC_MIap+UE	15.69	14.040	31%	-4%
TC_WI+UE+RC_SVM+CC_MIap	10.31	11.880	-14%	12%
TC_WI+UE+RC_SVM+CC_RIap+UE	13.31	13.100	11%	3%
TC_WI+UE+RC_SVM+CC_RIap	10.31	11.880	-14%	12%
TC_WI+UE+RC_SVM+CC_RM+UE	22.12	25.490	84%	-89%
TC_WI+UE+RC_SVM+CC_RM	10.31	11.880	-14%	12%
TC_WI+UE+RC_SVM+CC_Iap+UE	13.50	12.050	13%	11%
TC_WI+UE+RC_SVM+CC_Iap	10.31	11.880	-14%	12%
TC_WI+UE+RC_SVM+CC_M+UE	13.41	15.440	12%	-15%
TC_WI+UE+RC_SVM+CC_M	10.31	11.880	-14%	12%
TC_WI+UE+RC_SVM+CC_R+UE	19.06	21.960	59%	-63%
TC_WI+UE+RC_SVM+CC_R	10.31	11.880	-14%	12%
TC_WI+UE+RC_SVM	12.50	14.400	4%	-7%
TC_WI+UE+RC_EA+CC_RMIap+UE	16.06	15.860	34%	-18%
TC_WI+UE+RC_EA+CC_RMIap	10.31	11.880	-14%	12%
TC_WI+UE+RC_EA+CC_MIap+UE	15.66	14.020	31%	-4%
TC_WI+UE+RC_EA+CC_MIap	10.31	11.880	-14%	12%
TC_WI+UE+RC_EA+CC_RIap+UE	13.22	13.080	10%	3%
TC_WI+UE+RC_EA+CC_RIap	10.31	11.880	-14%	12%
TC_WI+UE+RC_EA+CC_RM+UE	22.09	25.450	84%	-89%
TC_WI+UE+RC_EA+CC_RM	10.31	11.880	-14%	12%
TC_WI+UE+RC_EA+CC_Iap+UE	13.59	12.100	13%	10%
TC_WI+UE+RC_EA+CC_Iap	10.34	11.920	-14%	12%
TC_WI+UE+RC_EA+CC_M+UE	13.38	15.410	12%	-14%
TC_WI+UE+RC_EA+CC_M	10.31	11.880	-14%	12%
TC_WI+UE+RC_EA+CC_R+UE	13.66	15.730	14%	-17%
TC_WI+UE+RC_EA+CC_R	10.31	11.880	-14%	12%
TC_WI+UE+RC_EA	12.50	14.400	4%	-7%
TC_WI+UE	12.50	14.400	4%	-7%

The next sub-section assesses the impact of the competition (i.e., competing client project cost controls and their unintended effects, and engineering consultant project revenue controls and their unintended effects) on the engineering consultant's business performance, using the 10 unique asset management planning and support-related projects.

Analysis of the Impact of Competition on the Engineering Consultant's Business Performance

The reviewed literature showed that: there are many measures of engineering consultant project business performance (Section 3.3.2); current project dynamics models are limited to project performance (mainly time duration) control actions of mainly the engineering consultant or construction contractor; and control actions taken by the client to protect project performance, and control actions taken by the engineering consultant and construction contractor to protect their individual business performance targets during project execution are sparingly covered (Section 3.11). Also, in the reviewed literature, no appropriate system dynamics project model could be identified that considered: competition among project participants, with their different and competing performance measures and targets during project execution; and how such competition influences the engineering consultant's project business performance (Section 3.11).

As discussed in Chapters 4 and 5, the system dynamics simulation model of competition between two key project participants (the client and the engineering consultant) formulated in this research study included two measures (project time schedule duration and engineering consultant project revenue) of the engineering consultant's project business performance. It also captured the competition in the form of two sets of competing project controls (aimed at win-lose results), namely client project cost controls and their associated unintended effects, and engineering consultant project revenue controls and their associated unintended effects. This sub-section analyses how such competition influences the said two measures of the engineering consultant's project business performance. This novel contribution, made by this research study, expands the existing project dynamics models, deepening our understanding of project dynamics, and assists towards addressing the above-mentioned gaps identified in the reviewed literature.

To assess the impact of the competition between the two key project participants (the client and the engineering consultant) on the engineering consultant's project business performance (measured by project time schedule duration and engineering consultant project revenue), two model simulation runs were considered, namely:

- TC_WI+UE (*Without competition)*: where only the engineering consultant project time schedule control (work intensity) and its associated unintended effect were activated. No client project cost controls and their associated unintended effects were activated, and no engineering consultant project revenue controls and their associated unintended effects were activated; and
- TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE (*With competition*): where the engineering consultant project time schedule control (work intensity) and its associated unintended effect, all the client project cost controls and their associated unintended effects, and all the engineering consultant project revenue controls and their associated unintended effects were all activated.

The two model simulations were conducted using the associated calibrated system dynamics simulation model discussed in Section 6.4. Table 6.34 shows, for each of the 10 unique asset management planning and support-related projects considered, the initially planned project time schedule duration and engineering consultant project revenue, as well as their corresponding simulated outputs for the two model simulation runs. As is evident in Table 6.34: project time schedule duration performance was worse in the 'With competition' simulation run than in the 'Without competition' simulation run for all (except Project P3) the considered projects; whilst the engineering consultant project revenue performance was better in the 'With competition' simulation run than in the 'Without competition' simulation run for all (except Projects P3 and P4) the considered projects.

Table 6.34: Planned project time duration and engineering consultant's project revenue, and corresponding simulated outputs with and without competition (asset management planning and support-related projects)

Project number	Planned		Without competition (simulation run: TC_WI+UE)		With competition (simulation run: TC_WI+UE+CC_RMIap+UE +RC_EASVM+UE)	
	Project time schedule duration (months)	Engineering consultant project revenue (R million)	Project time schedule duration (months)	Engineering consultant project revenue (R million)	Project time schedule duration (months)	Engineering consultant project revenue (R million)
P0	12	13.473	12.5	14.400	16.12	15.910
P1	12	15.022	12.09	15.140	18.19	16.820
P2	24	42.937	25.09	44.890	32.75	45.510
P3	9	5.752	9.781	6.251	9.719	6.059
P4	6	3.840	6.219	3.980	7.5	3.854
P5	9	5.992	8.844	5.888	13.22	6.942
P6	26	21.278	27.34	22.380	31.25	22.630
P7	7	3.817	5.875	3.203	7.75	3.517
P8	12	12.170	12.12	12.300	15.66	14.360
P9	12	10.590	12.09	10.670	15.53	11.660

Section 6.6.1 discusses the meanings and formulations of the *schedule performance index (SPI), cost performance index (CPI),* and the *impact ratio on project performance.* In this research study, the *revenue performance index (RPI)* is a measure of the engineering consultant project revenue efficiency and is determined by the ratio of the planned engineering consultant project revenue to the actual/simulated engineering consultant project revenue.

Also, in this research study, the *impact ratio on the engineering consultant's project business performance* is a measure of the deterioration/improvement of an engineering consultant's project business project performance index (SPI or RPI) as a result of competition between the client and the engineering consultant during project execution. Put differently, the *impact ratio on the engineering consultant's project business performance* indicates the decrease/increase below/above what the engineering consultant's project business performance index (SPI or RPI) would have been (if there was no competition).

The impact of the competition between the two key project participants (client and engineering consultant) during project execution on the engineering consultant's project business performance was assessed, in this research study, through the determination of two impact ratios, namely:

- *impact ratio* on *project time schedule performance,* determined as the ratio of the project schedule performance index (SPI) without competition to the project SPI with competition; and
- *impact ratio on engineering consultant project revenue performance*, determined as the ratio of the project revenue performance index (RPI) without competition to the project RPI with competition.

An *impact ratio on project time schedule performance* (a measure of the impact of the competition on the engineering consultant's project business performance, in terms of project time schedule duration) of: less than 1 indicates that the competition positively influences (improves) the engineering consultant's project business performance; 1 indicates that the competition has no impact the engineering consultant's project business performance; and greater than 1 indicates that the competition negatively influences (worsens) the engineering consultant's project business performance. In contrast, an *impact ratio on the engineering consultant project revenue performance* (a measure of the impact of the competition on the engineering consultant project business performance, in terms of project revenue) of: less than 1 indicates that the competition negatively influences (worsens) the project business performance; 1 indicates that the competition has no impact on the engineering consultant project business performance; and greater than 1 indicates that the competition positively influences (improves) the engineering consultant project business performance.

Table 6.35 shows, for each of the 10 asset management planning and support related projects, the SPI and RPI (without and with competition) and the resulting impact ratios (of the competition between the client and the engineering consultant during project execution) on the engineering consultant's project time schedule performance and project revenue performance. This assessment of the impact/ influence of the competition between two key project participants (with their different and competing performance measures and targets during project execution) on the engineering consultant's project business performance (as measured by project time schedule duration and project revenue) is another novel contribution made by this research study. It assists towards addressing a related gap identified in the reviewed literature, namely no appropriate study could be identified that specifically investigated the influence of such competition on the engineering consultant's project business performance, as discussed in Chapters 1, 3, and 4.

The competition between the client and the engineering consultant during project execution negatively influenced the project time schedule performance of all the projects (except Project P3), with Project P1 being the worst affected with an impact ratio of 1.50, as shown in Table 6.35. However, it positively influenced the engineering consultant project revenue performance of all the considered projects (except for Projects P3 and P4), with Project P5 being the best affected with an impact ratio of 1.18.

Table 6.35: SPI and RPI (without and with competition), and competition impact ratios per project (asset management planning and support-related)

Project number	Engineering consultant project time schedule performance			Engineering consultant project revenue performance		
	Schedule performance index (SPI)		Impact ratio	Revenue performance index (RPI)		Impact ratio
	Without competition (simulation run: TC_WI+UE)	With competition (simulation run: TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE)		Without competition (simulation run: TC_WI+UE)	With competition (simulation run: TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE)	
P0	0.96	0.74	1.29	0.94	0.85	1.10
P1	0.99	0.66	1.50	0.99	0.89	1.11
P2	0.96	0.73	1.31	0.96	0.94	1.01
P3	0.92	0.93	0.99	0.92	0.95	0.97
P4	0.96	0.80	1.21	0.96	1.00	0.97
P5	1.02	0.68	1.49	1.02	0.86	1.18
P6	0.95	0.83	1.14	0.95	0.94	1.01
P7	1.19	0.90	1.32	1.19	1.09	1.10
P8	0.99	0.77	1.29	0.99	0.85	1.17
P9	0.99	0.77	1.28	0.99	0.91	1.09

Table 6.36 shows the overall descriptive statistics for the SPI and RPI (without and with competition) and the associated impact ratios (of the competition between the client and the engineering consultant during project execution) on the engineering consultant's project time schedule performance and project revenue performance for the 10 unique asset management planning and support-related projects.

Table 6.36: Descriptive statistics for SPI and RPI (without and with competition), and competition impact ratios (asset management planning and support-related)

Statistic	Engineering consultant project time schedule performance			Engineering consultant project revenue performance		
	Schedule performance index (SPI)		Impact ratio	Revenue performance index (RPI)		Impact ratio
	Without competition (simulation run: TC_WI+UE)	With competition (simulation run: TC_WI+UE+CC_RMlap+UE+RC_EASVM+UE)		Without competition (simulation run: TC_WI+UE)	With competition (simulation run: TC_WI+UE+CC_RMlap+UE+RC_EASVM+UE)	
Median	0.98	0.77	1.29	0.98	0.92	1.10
Mean	0.99	0.78	1.28	0.99	0.93	1.07
Standard Deviation	0.07	0.09	0.15	0.08	0.07	0.08
Minimum	0.92	0.66	0.99	0.92	0.85	0.97
Maximum	1.19	0.93	1.50	1.19	1.09	1.18

On average, the competition between the client and the engineering consultant during project execution negatively influenced the project time schedule performance as the mean impact ratio was greater than 1 (i.e. 1.28), as shown in Table 6.36. However, on average, it positively influenced the engineering consultant project revenue performance as the mean impact ratio was greater than 1 (i.e. 1.07).

Noteworthy is that the 7% average increase in the engineering consultant project revenue was much lower than the 28% average increase in the project time schedule duration. Even though the engineering consultant project revenue at project completion increased (was higher than that initially planned), the average net increase in the project revenue was much lower than (and not commensurate with) the average net increase in the project time schedule duration (since only time-based contracts were considered), and, thus the engineering consultant actually lost out. Hence, in the final analysis, on average the competition between the two key project participants (the client and engineering consultant) negatively influenced the engineering consultant's project business performance. This finding supports the following related dynamic hypothesis formulated in Section 4.9.3:

The client project cost controls and the engineering consultant project revenue controls tend to oppose (compete with) each other, generating some *unintended and counteractive consequences (unintended effects) that negatively influence the engineering consultant's project business performance (increasing both 'project time schedule delay' and 'project revenue shortfall').*

The next sub-section assesses the sensitivity of the impact of the competition on the engineering consultant's project business performance, as determined in this sub-section, to uncertainty in some of the key calibrated model parameters.

6.7.2 Behaviour Mode Sensitivity Analysis (Infrastructure Asset Management Planning and Support Projects)

Parametric Sensitivity Analysis Overview

Refer to Section 6.6.2 for an overview of: parametric sensitivity analysis, including its definition, different types thereof, how to select a particular type of sensitivity analysis; and the basic modes of dynamic behaviour (and the basic feedback structures that generate them). In this Section 6.7, it was important to assess the sensitivity of the impact of the competition on the engineering consultant's project business performance to uncertainty in key calibrated model parameters, as this helps to enhance the validity of the conclusion drawn regarding the associated dynamic hypothesis formulated in Section 4.9.3 (and also presented in the preceding sub-section) and the provisional answer provided for the associated research question number 4 (posed in Section 1.6).

The sensitivity of the impact of the competition on the engineering consultant's project business performance determined in Section 6.7.1 using the first set of unique raw water infrastructure projects considered in this research study is assessed in this sub-section; while that of the impact of the competition on the engineering consultant's project business performance determined in Section 6.7.3 using the second set of unique raw water infrastructure projects is assessed in Section 6.7.4. The impact analysis and associated sensitivity analysis are, thus, conducted separately for each of the two sets of projects. Subsequently, in Section 6.7.5, the key research results (i.e., polarity and behaviour mode sensitivity of the impact of competition on the engineering consultant's project business performance) for the two sets of projects are then compared, with an appropriate overall conclusion drawn regarding the associated dynamic hypothesis formulated in Section 4.9.3 and a provisional answer for research question number 4 (posed in Section 1.6) provided (which help to address a related key gap identified in the reviewed literature, as discussed in Chapters 1, 3 and 4).

The above-discussed process followed in this study in assessing the impact of the competition on the engineering consultant's project business performance, and the sensitivity thereof, using two sets of unique projects separately, with subsequent comparison of key results, assisted in enhancing the validity of the associated overall key research results (as presented in Section 6.7.5). It is a novel contribution towards the enhancement of the existing system dynamics simulation model validation, in particular impact and sensitivity analyses, processes and procedures, and is, thus expected to benefit future system dynamics research studies.

Behaviour Mode Sensitivity

The process followed in conducting the behaviour mode sensitivity analysis in this sub-section was the same as that described and followed in Section 6.6.2, but with the *cost performance index* replaced by the *engineering consultant project revenue performance index*. This was because: whereas Section 6.6.2 focussed on the sensitivity of the impact of the competition on project performance (which is influenced by the sensitivities of the *schedule performance index* and the *cost performance index*, since time schedule duration and cost were used as the measures of project performance as discussed in Section 6.6.1); this Section 6.7.2 focusses on the sensitivity of the impact of the competition on the engineering consultant's project business performance (which is influenced by the sensitivities of the *schedule performance index* and the *engineering consultant project revenue performance index*, since time schedule duration and project revenue were used as the measures of the engineering consultant's project business performance in this research study as discussed in Section 6.7.1).

Figure 6.11 in Section 6.6.2 and Figure 6.15 show the results of the sensitivity analysis per project; that is, the sensitivities of the *schedule performance index* and the *engineering consultant project revenue performance index,* respectively, to the uncertainty/changes in the considered 10 parametric assumptions. The two figures show that both the *schedule performance index* and the *engineering consultant project revenue performance index* exhibited no behaviour mode sensitivity (though there were effects in absolute values, i.e., exhibited numerical sensitivity): both the base case (based on calibrated parameter values, and represented by the blue single line) and the random cases (based on the 200 sets of randomly selected parameter values, represented by the solid envelopes) exhibit an *S-shaped growth with overshoot and collapse* behaviour mode for all the considered projects.

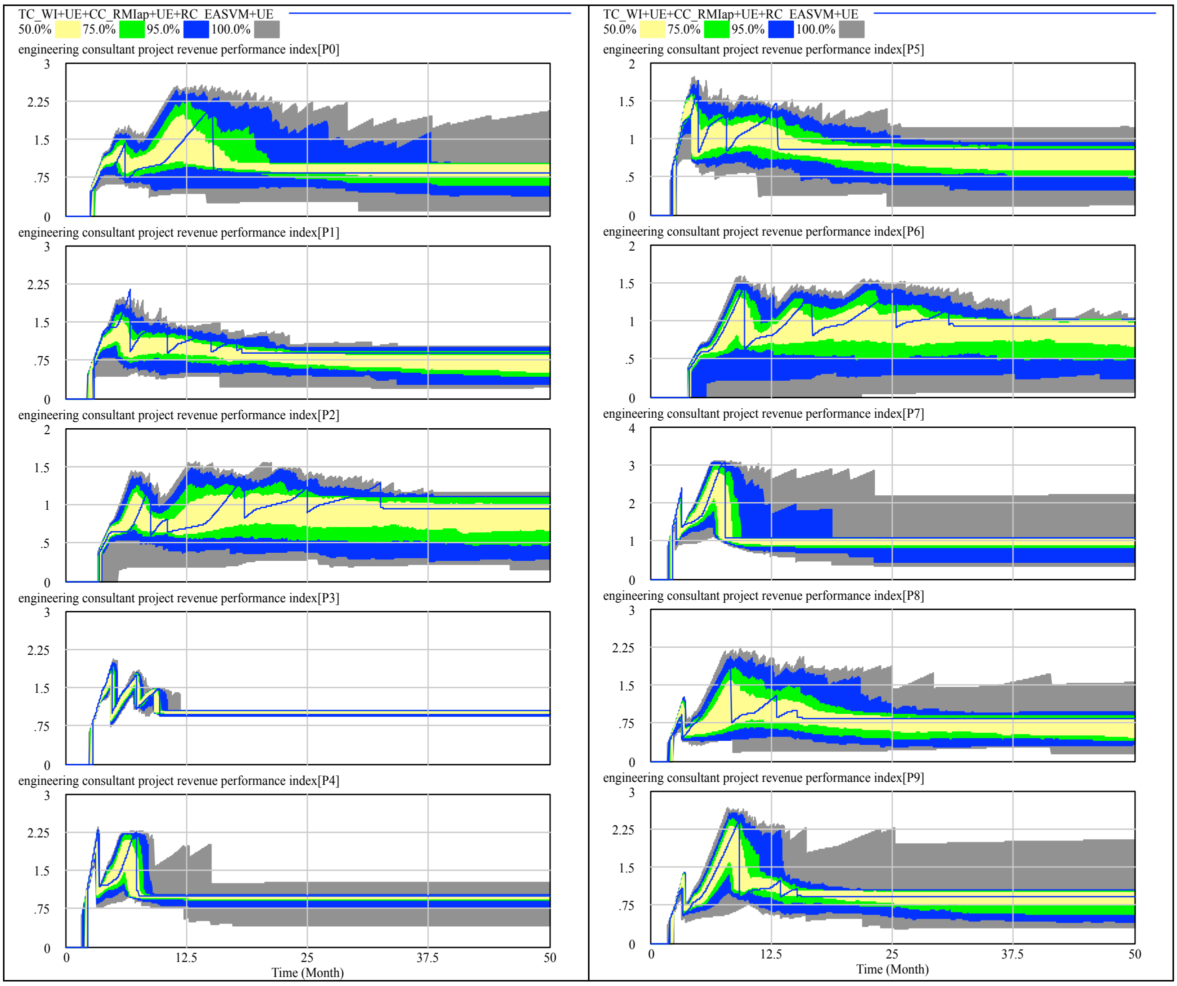


Figure 6.15: Sensitivity of engineering consultant project revenue performance index (with competition) per project (asset management planning and support-related)

The next sub-section discusses key results from the second stage of the impact analysis, which was conducted using data gathered for the second set of unique raw water infrastructure projects (asset renewal-related, made up of 8 projects) and the calibrated system dynamics simulation model discussed in Section 6.5.

6.7.3 Impact Analysis (Infrastructure Asset Renewal Projects)

Project Participants Performance Targets

As discussed in Chapter 4 (Table 4.11 and Figure 4.31), the client and the engineering consultant set up their own individual performance targets, and take appropriate control actions aimed at protecting them, during project execution. Table 6.23 in Section 6.6.3 shows the client project cost targets and engineering consultant project revenue targets per project for the second set of unique raw water infrastructure projects (8 asset renewal-related) considered in this research study. These individual project participant performance targets were used in all the associated simulation experiments conducted in Sections 6.6 and 6.7. The next sub-section assesses the client project cost controls' counteractive and unintended effects for the same set of projects.

Model Simulations for Client Project Cost Controls and their Unintended Effects

As discussed in Section 6.6.3, subsequent to the model calibration discussed in Section 6.5, a total of 36 different model simulations were run for each project, by varying the client project cost controls and their unintended effects. The 36 different simulations are shown in Table 6.16. They were conducted using the associated calibrated system dynamics simulation model discussed in Section 6.5.

Table 6.37 shows the model simulations outputs (project time schedule duration and engineering consultant project revenue) of client project cost controls and their unintended effects for each of the 36 model simulation runs conducted for Project P10, one of the 8 asset renewal-related projects considered. In this research study, as discussed in Chapters 4 and 5: only time-based contracts with a ceiling price (Turner, 2004) between the client and the engineering consultant were considered; and only the time-based costs for the engineering consultant services were considered for the project cost. Hence, in this research study, the project revenue realised by the engineering consultant at project completion was assumed to be equal to the project cost incurred by the client at completion of the same project.

As discussed in Section 6.6.3: the short-term impact of all the considered client project cost controls looked positive for the client, supporting the intended effect of a reduction in project cost overrun; whereas their long-term impact was counterintuitive, counteractive and unintended: instead of the project cost overrun decreasing, it increased.

The simulation results shown in Table 6.37, however, indicate the reverse for the engineering consultant project revenue: the short-term impact of all the considered client project cost controls looked negative for the engineering consultant project revenue performance. For instance, using the second considered client project cost control, i.e. increasing the frequency of progress meetings (simulation run TC_WI+UE+CC_M), resulted in an engineering consultant project revenue shortfall of 13%. However, when all the unintended effects of the client project cost controls (i.e., decrease in productivity due to 'Less Time Spent On Real Work' and 'Engineering Consultant Project Revenue Controls', increase in work errors due to 'Haste Makes Waste', and decrease in project workforce due to 'Insufficient Operating Cash Flow For Engineering Consultant' – all of which result in a decrease in project work completion rate, as shown in Figure 4.31) were considered (simulation run TC_WI+UE+CC_M+UE+RC_EASVM+UE), the engineering consultant project revenue increased by 9%, as shown in Table 6.37. Thus, the long-term impact of all the considered client project cost controls looked positive for the engineering consultant.

The other asset renewal-related projects generally exhibited a similar trend as evident in Appendix H (Tables H.2.1 and H.2.2), which shows all the 36 model simulations outputs (project time schedule duration, project cost and engineering consultant project revenue) of client project cost controls and their unintended effects for each of the 8 projects.

Table 6.37: Model simulations outputs (time duration and engineering consultant project revenue) of client project cost controls and unintended effects for Project P10

Model simulation run-name	Project time schedule duration (months)	Engineering consultant project revenue (R million)	Compared with initial plan (time schedule duration of 10 months, and project revenue target of R6.521m)	
			% Time schedule delay	% Revenue shortfall
TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE	14.25	7.344	43	-13
TC_WI+UE+CC_RMIap+UE+RC_SVM+UE	14.25	7.344	43	-13
TC_WI+UE+CC_RMIap+UE+RC_EA+UE	14.25	7.344	43	-13
TC_WI+UE+CC_RMIap+UE	14.16	7.297	42	-12
TC_WI+UE+CC_RMIap	8.75	5.706	-13	12
TC_WI+UE+CC_MIap+UE+RC_EASVM+UE	15.88	7.090	59	-9
TC_WI+UE+CC_MIap+UE+RC_SVM+UE	15.88	7.090	59	-9
TC_WI+UE+CC_MIap+UE+RC_EA+UE	15.88	7.090	59	-9
TC_WI+UE+CC_MIap+UE	15.81	7.069	58	-8
TC_WI+UE+CC_MIap	8.75	5.706	-13	12
TC_WI+UE+CC_RIap+UE+RC_EASVM+UE	14.38	7.069	44	-8
TC_WI+UE+CC_RIap+UE+RC_SVM+UE	14.38	7.069	44	-8
TC_WI+UE+CC_RIap+UE+RC_EA+UE	14.38	7.069	44	-8
TC_WI+UE+CC_RIap+UE	14.12	7.022	41	-8
TC_WI+UE+CC_RIap	8.75	5.706	-13	12
TC_WI+UE+CC_RM+UE+RC_EASVM+UE	18.66	12.170	87	-87
TC_WI+UE+CC_RM+UE+RC_SVM+UE	18.66	12.170	87	-87
TC_WI+UE+CC_RM+UE+RC_EA+UE	18.66	12.170	87	-87
TC_WI+UE+CC_RM+UE	18.62	12.140	86	-86
TC_WI+UE+CC_RM	8.75	5.706	-13	12
TC_WI+UE+CC_Iap+UE+RC_EASVM+UE	14.59	6.233	46	4
TC_WI+UE+CC_Iap+UE+RC_SVM+UE	14.59	6.233	46	4
TC_WI+UE+CC_Iap+UE+RC_EA+UE	14.59	6.233	46	4
TC_WI+UE+CC_Iap+UE	14.44	6.195	44	5
TC_WI+UE+CC_Iap	8.81	5.746	-12	12

Model simulation run-name	Project time schedule duration (months)	Engineering consultant project revenue (R million)	Compared with initial plan (time schedule duration of 10 months, and project revenue target of R6.521m)	
			% Time schedule delay	% Revenue shortfall
TC_WI+UE+CC_M+UE+RC_EASVM+UE	10.88	7.091	9	-9
TC_WI+UE+CC_M+UE+RC_SVM+UE	10.88	7.091	9	-9
TC_WI+UE+CC_M+UE+RC_EA+UE	10.88	7.091	9	-9
TC_WI+UE+CC_M+UE	10.84	7.071	8	-8
TC_WI+UE+CC_M	8.72	5.685	-13	13
TC_WI+UE+CC_R+UE+RC_EASVM+UE	18.84	12.290	88	-88
TC_WI+UE+CC_R+UE+RC_SVM+UE	18.84	12.290	88	-88
TC_WI+UE+CC_R+UE+RC_EA+UE	18.84	12.290	88	-88
TC_WI+UE+CC_R+UE	18.81	12.270	88	-88
TC_WI+UE+CC_R	8.75	5.706	-13	12
TC_WI+UE	10.53	6.867	5	-5

The next sub-section assesses the engineering consultant project revenue controls' unintended effects, using the 8 unique asset renewal-related projects.

Model Simulations for Engineering Consultant Project Revenue Controls and their Unintended Effects

As discussed in Section 6.6.3, subsequent to the 36 model simulations, per project, of client project cost controls and their unintended effects discussed in the preceding sub-section, a further 46 different model simulations were run for each project, by varying the engineering consultant project revenue controls and their unintended effects. The 46 simulations are as shown in Table 6.18. They were conducted using the calibrated system dynamics simulation model discussed in Section 6.5.

Table 6.38 shows the model simulations outputs (project time schedule duration and engineering consultant project revenue) of engineering consultant project revenue controls and their unintended effects for each of the 46 model simulation runs conducted for Project P10, one of the 8 asset renewal-related projects considered. As discussed in Section 6.6.3, from a project cost performance perspective: the short-term impact of all the considered engineering consultant project revenue controls was negative (they yielded a positive project cost budget overrun); whereas their long-term impact was positive (they yielded a negative project cost budget overrun, which is a cost saving). Also, as discussed in Section 6.6.3 (and evident in Table 6.38): the short-term impact of all the considered engineering consultant project revenue controls was positive, supporting the intended effect of a reduction in engineering consultant project revenue shortfall; whereas their long-term impact was counterintuitive, counteractive and unintended: instead of the engineering consultant project revenue shortfall decreasing, it increased. This is also a 'better-before-worse' result that is characteristic of dynamic complexity (Sterman, 2000).

The other asset renewal-related projects generally exhibited a similar 'better-before-worse' result as evident in Appendix H (Tables H.2.3 and H.2.4), which shows the 46 simulations outputs (project time schedule duration, project cost and engineering consultant project revenue) of engineering consultant project revenue and unintended effects for each of the 8 projects. Thus, the simulation outputs supported the following counterintuitive dynamic hypothesis formulated in Section 4.9.3:

> *The engineering consultant project revenue controls, which are aimed at reducing/eliminating the 'project revenue shortfall' by increasing the 'estimated project cost at completion' (a 'win-lose' control in favour of the engineering consultant), tend to generate some unintended and counteractive consequence (unintended effect) that decreases the 'estimated project cost at completion' and increases the 'project revenue shortfall'.*

Table 6.38: Model simulations outputs (time duration and engineering consultant project revenue) of engineering consultant project revenue controls and their unintended effects for Project P10

Model simulation run-name	Project time schedule duration (months)	Engineering consultant project revenue (R million)	Compared with initial plan (time schedule duration of 10 months, and project revenue target of R6.521m)	
			% Time schedule delay	% Revenue shortfall
TC_WI+UE+RC_EASVM+CC_RMIap+UE	14.25	7.344	43%	-13%
TC_WI+UE+RC_EASVM+CC_RMIap	8.88	5.787	-11%	11%
TC_WI+UE+RC_EASVM+CC_MIap+UE	15.88	7.090	59%	-9%
TC_WI+UE+RC_EASVM+CC_MIap	8.84	5.767	-12%	12%
TC_WI+UE+RC_EASVM+CC_RIap+UE	14.38	7.069	44%	-8%
TC_WI+UE+RC_EASVM+CC_RIap	8.88	5.787	-11%	11%
TC_WI+UE+RC_EASVM+CC_RM+UE	18.66	12.170	87%	-87%
TC_WI+UE+RC_EASVM+CC_RM	8.88	5.787	-11%	11%
TC_WI+UE+RC_EASVM+CC_Iap+UE	14.59	6.233	46%	4%
TC_WI+UE+RC_EASVM+CC_Iap	8.91	5.808	-11%	11%
TC_WI+UE+RC_EASVM+CC_M+UE	10.88	7.091	9%	-9%
TC_WI+UE+RC_EASVM+CC_M	8.84	5.767	-12%	12%
TC_WI+UE+RC_EASVM+CC_R+UE	18.84	12.290	88%	-88%

Model simulation run-name	Project time schedule duration (months)	Engineering consultant project revenue (R million)	Compared with initial plan (time schedule duration of 10 months, and project revenue target of R6.521m)	
			% Time schedule delay	% Revenue shortfall
TC_WI+UE+RC_EASVM+CC_R	8.88	5.787	-11%	11%
TC_WI+UE+RC_EASVM	10.53	6.867	5%	-5%
TC_WI+UE+RC_SVM+CC_RMIap+UE	14.25	7.344	43%	-13%
TC_WI+UE+RC_SVM+CC_RMIap	8.88	5.787	-11%	11%
TC_WI+UE+RC_SVM+CC_MIap+UE	15.88	7.090	59%	-9%
TC_WI+UE+RC_SVM+CC_MIap	8.84	5.767	-12%	12%
TC_WI+UE+RC_SVM+CC_RIap+UE	14.38	7.069	44%	-8%
TC_WI+UE+RC_SVM+CC_RIap	8.88	5.787	-11%	11%
TC_WI+UE+RC_SVM+CC_RM+UE	18.66	12.170	87%	-87%
TC_WI+UE+RC_SVM+CC_RM	8.88	5.787	-11%	11%
TC_WI+UE+RC_SVM+CC_Iap+UE	14.59	6.233	46%	4%
TC_WI+UE+RC_SVM+CC_Iap	8.91	5.808	-11%	11%
TC_WI+UE+RC_SVM+CC_M+UE	10.88	7.091	9%	-9%
TC_WI+UE+RC_SVM+CC_M	8.84	5.767	-12%	12%
TC_WI+UE+RC_SVM+CC_R+UE	18.84	12.290	88%	-88%
TC_WI+UE+RC_SVM+CC_R	8.88	5.787	-11%	11%
TC_WI+UE+RC_SVM	10.53	6.867	5%	-5%
TC_WI+UE+RC_EA+CC_RMIap+UE	14.25	7.344	43%	-13%
TC_WI+UE+RC_EA+CC_RMIap	8.88	5.787	-11%	11%
TC_WI+UE+RC_EA+CC_MIap+UE	15.88	7.090	59%	-9%
TC_WI+UE+RC_EA+CC_MIap	8.84	5.767	-12%	12%
TC_WI+UE+RC_EA+CC_RIap+UE	14.38	7.069	44%	-8%
TC_WI+UE+RC_EA+CC_RIap	8.88	5.787	-11%	11%
TC_WI+UE+RC_EA+CC_RM+UE	18.66	12.170	87%	-87%
TC_WI+UE+RC_EA+CC_RM	8.88	5.787	-11%	11%
TC_WI+UE+RC_EA+CC_Iap+UE	14.59	6.233	46%	4%
TC_WI+UE+RC_EA+CC_Iap	8.91	5.808	-11%	11%
TC_WI+UE+RC_EA+CC_M+UE	10.88	7.091	9%	-9%
TC_WI+UE+RC_EA+CC_M	8.84	5.767	-12%	12%
TC_WI+UE+RC_EA+CC_R+UE	18.84	12.290	88%	-88%
TC_WI+UE+RC_EA+CC_R	8.88	5.787	-11%	11%
TC_WI+UE+RC_EA	10.53	6.867	5%	-5%
TC_WI+UE	10.53	6.867	5%	-5%

The next sub-section assesses the impact of the competition (i.e., competing client project cost controls and their unintended effects, and engineering consultant project revenue controls and their unintended effects) on the engineering consultant's business performance, using the 8 asset renewal-related projects.

Analysis of the Impact of Competition on the Engineering Consultant's Business Performance

As discussed in Section 6.7.1: two measures (project time schedule duration and engineering consultant project revenue) of the engineering consultant's project business performance were considered in this study; and to assess the impact of the competition between the two key project participants (the client and engineering consultant) on the engineering consultant's project business performance, two model simulations (without, and with competition) conducted using the calibrated system dynamics simulation model discussed in Section 6.5 were considered.

Table 6.39 shows, for each of the 8 asset renewal-related projects, the initially planned project time schedule duration and engineering consultant project revenue, as well as their corresponding simulated outputs for the two model simulation runs. As is evident in Table 6.39: project time schedule duration performance was worse in the 'With competition' simulation than in the 'Without competition' simulation for all the 8 projects considered; whilst the engineering consultant project revenue performance was better in the 'With competition' simulation run than in the 'Without competition' simulation run for 4 (P10, P14, P15 and P16) of the 8 projects.

Table 6.39: Planned project time duration and engineering consultant's project revenue, and corresponding simulated outputs with and without competition (asset renewal-related projects)

Project number	Planned		Without competition (simulation run: TC_WI+UE)		With competition (simulation run: TC_WI+UE+CC_RMIap+UE +RC_EASVM+UE)	
	Project time schedule duration (months)	Engineering consultant project revenue (R million)	Project time schedule duration (months)	Engineering consultant project revenue (R million)	Project time schedule duration (months)	Engineering consultant project revenue (R million)
P10	10.00	6.521	10.53	6.867	14.25	7.344
P11	5.00	2.857	5.41	3.089	6.47	2.876
P12	4.00	2.535	4.72	2.991	4.78	2.807
P13	6.00	4.327	6.59	4.755	7.53	4.754
P14	10.00	7.592	10.69	8.113	11.78	8.321
P15	6.00	3.312	6.63	3.657	8.00	3.781
P16	8.00	6.670	7.53	6.279	13.03	8.126
P17	5.00	2.632	5.28	2.780	5.50	2.635

Refer to Section 6.6.1 for the definition and interpretation of *schedule performance index (SPI),* and Section 6.7.1 for the definitions and interpretations of *impact ratio* on *project time schedule performance, revenue performance index (RPI)* and *impact ratio on the engineering consultant project revenue performance*.

Table 6.40 shows, for each of the 8 raw water infrastructure asset renewal-related projects considered, the SPI and RPI (without and with competition) and the resulting impact ratios (of the competition between the client and the engineering consultant during project execution) on the engineering consultant's project time schedule performance and project revenue performance. As highlighted in Section 6.7.1, this assessment of the impact/influence of the competition between two key project participants (with their different and competing performance measures and targets during project execution) on the engineering consultant's project business performance (as measured by project time schedule duration and project revenue) is another novel contribution made by this research study. It assists towards addressing a related gap identified in the reviewed literature, namely no appropriate study could be identified that specifically investigated the influence of such competition on the engineering consultant's project business performance, as discussed in Chapters 1, 3, and 4.

The competition between the client and the engineering consultant during project execution negatively influenced (impact ratio greater than 1) the project time schedule performance of all the 8 projects, with Project P16 being the worst affected with an impact ratio of 1.73, as shown in Table 6.40.

The competition: positively influenced the engineering consultant project revenue performance of 4 (P10, P14, P15 and P16) of the 8 projects considered, with Project P16 being the best affected with an impact ratio of 1.29; had no influence (impact ratio equal to 1) on the engineering consultant project revenue performance of Project P13; and negatively influenced the engineering consultant project revenue performance of 3 projects (P11, P12 and P17), as also shown in Table 6.40.

Table 6.40: SPI and RPI (without and with competition) and competition impact ratios per project (asset renewal-related)

Project number	Engineering consultant project time schedule performance			Engineering consultant project revenue performance		
	Schedule performance index (SPI)		Impact ratio	Revenue performance index (RPI)		Impact ratio
	Without competition (simulation run: TC_WI+UE)	With competition (simulation run: TC_WI+UE+CC_RMlap+UE+RC_EASVM+UE)		Without competition (simulation run: TC_WI+UE)	With competition (simulation run: TC_WI+UE+CC_RMlap+UE+RC_EASVM+UE)	
P10	0.95	0.70	1.35	0.95	0.89	1.07
P11	0.92	0.77	1.20	0.92	0.99	0.93
P12	0.85	0.84	1.01	0.85	0.90	0.94
P13	0.91	0.80	1.14	0.91	0.91	1.00
P14	0.94	0.85	1.10	0.94	0.91	1.03
P15	0.91	0.75	1.21	0.91	0.88	1.03
P16	1.06	0.61	1.73	1.06	0.82	1.29
P17	0.95	0.91	1.04	0.95	1.00	0.95

Table 6.41 shows the overall descriptive statistics for the SPI and RPI (without and with competition) and the associated impact ratios (of the competition between the client and the engineering consultant during project execution) on the engineering consultant's project time schedule performance and project revenue performance for the 8 unique raw water infrastructure asset renewal-related projects. On average, the competition between the client and the engineering consultant during project execution negatively influenced the project time schedule performance as the associated mean impact ratio was greater than 1 (i.e. 1.22), as shown in Table 6.41. However, on average, it positively influenced the engineering consultant project revenue performance as the associated mean impact ratio was greater than 1 (i.e. 1.03).

Noteworthy is that the 3% average increase in the engineering consultant project revenue was much lower than the 22% average increase in the project time schedule duration. Even though the engineering consultant project revenue at project completion increased (was higher than that initially planned), the average net increase in the project revenue was much lower than (and not commensurate with) the average net increase in the project time schedule duration (since only time-based contracts were considered), and, thus the engineering consultant actually lost out. Hence, in the final analysis, on average the competition between the two key project participants (the client and engineering consultant) negatively influenced the engineering consultant's project business performance. This finding supports the following related dynamic hypothesis formulated in Section 4.9.3:

The client project cost controls and the engineering consultant project revenue controls tend to oppose (compete with) each other, generating some unintended and counteractive consequences (unintended effects) that negatively influence the engineering consultant's project business performance (increasing both 'project time schedule delay' and 'project revenue shortfall').

Table 6.41: Descriptive statistics for SPI and RPI (without and with competition), and competition impact ratios (asset renewal-related projects)

Statistic	Engineering consultant project time schedule performance			Engineering consultant project revenue performance		
	Schedule performance index (SPI)		Impact ratio	Revenue performance index (RPI)		Impact ratio
	Without competition (simulation run: TC_WI+UE)	With competition (simulation run: TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE)		Without competition (simulation run: TC_WI+UE)	With competition (simulation run: TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE)	
Median	0.93	0.78	1.17	0.93	0.91	1.01
Mean	0.94	0.78	1.22	0.94	0.91	1.03
Standard Deviation	0.06	0.09	0.23	0.06	0.06	0.12
Minimum	0.85	0.61	1.01	0.85	0.82	0.93
Maximum	1.06	0.91	1.73	1.06	1.00	1.29

The next sub-section assesses the sensitivity of the impact of the competition on the engineering consultant's project business performance, as determined in this sub-section, to uncertainty in some of the key calibrated model parameters.

6.7.4 Behaviour Mode Sensitivity Analysis (Infrastructure Asset Renewal Projects)

Parametric Sensitivity Analysis Overview

Refer to Section 6.6.2 for an overview of: parametric sensitivity analysis, including its definition, different types thereof, how to select a particular type of sensitivity analysis; and the basic modes of dynamic behaviour (and the basic feedback structures that generate them). In this sub-section, the behaviour mode sensitivity of the impact of competition on the engineering consultant's project business performance determined in Section 6.7.3 using the second set of unique raw water infrastructure projects (8 asset renewal-related projects) considered in this research study is assessed.

Behaviour Mode Sensitivity

The process followed in conducting the behaviour mode sensitivity analysis in this sub-section was the same as that described and followed in Section 6.6.2, but with the *cost performance index* replaced by the *engineering consultant project revenue performance index*. This was because: whereas Section 6.6.2 focussed on the sensitivity of the impact of the competition on project performance (which is influenced by the sensitivities of the *schedule performance index* and the *cost performance index*, since time schedule duration and cost were used as the measures of project performance as discussed in Section 6.6.1); this Section 6.7.4 (like Section 6.7.2) focusses on the sensitivity of the impact of the competition on the engineering consultant's project business performance (which is influenced by the sensitivities of the *schedule performance index* and the *engineering consultant project revenue performance index*, since time schedule duration and project revenue were used as the measures of the engineering consultant's project business performance in this research study as discussed in Section 6.7.1).

Figure 6.13 in Section 6.6.4 and Figure 6.16 show the results of the sensitivity analysis per project; that is, the sensitivities of the *schedule performance index* and the *engineering consultant project revenue performance index,* respectively, to the uncertainty/ changes in the considered 10 parametric assumptions. The two figures show that both the *schedule performance index* and the *engineering consultant project revenue performance index* exhibited no behaviour mode sensitivity (though there were effects in absolute values, i.e., exhibited numerical sensitivity): both the base case (based on calibrated parameter values, and represented by the blue single line) and the random cases (based on the 200 sets of randomly selected parameter values, represented by the solid envelopes) exhibit an *S-shaped growth with overshoot and collapse* behaviour mode for all the considered projects.

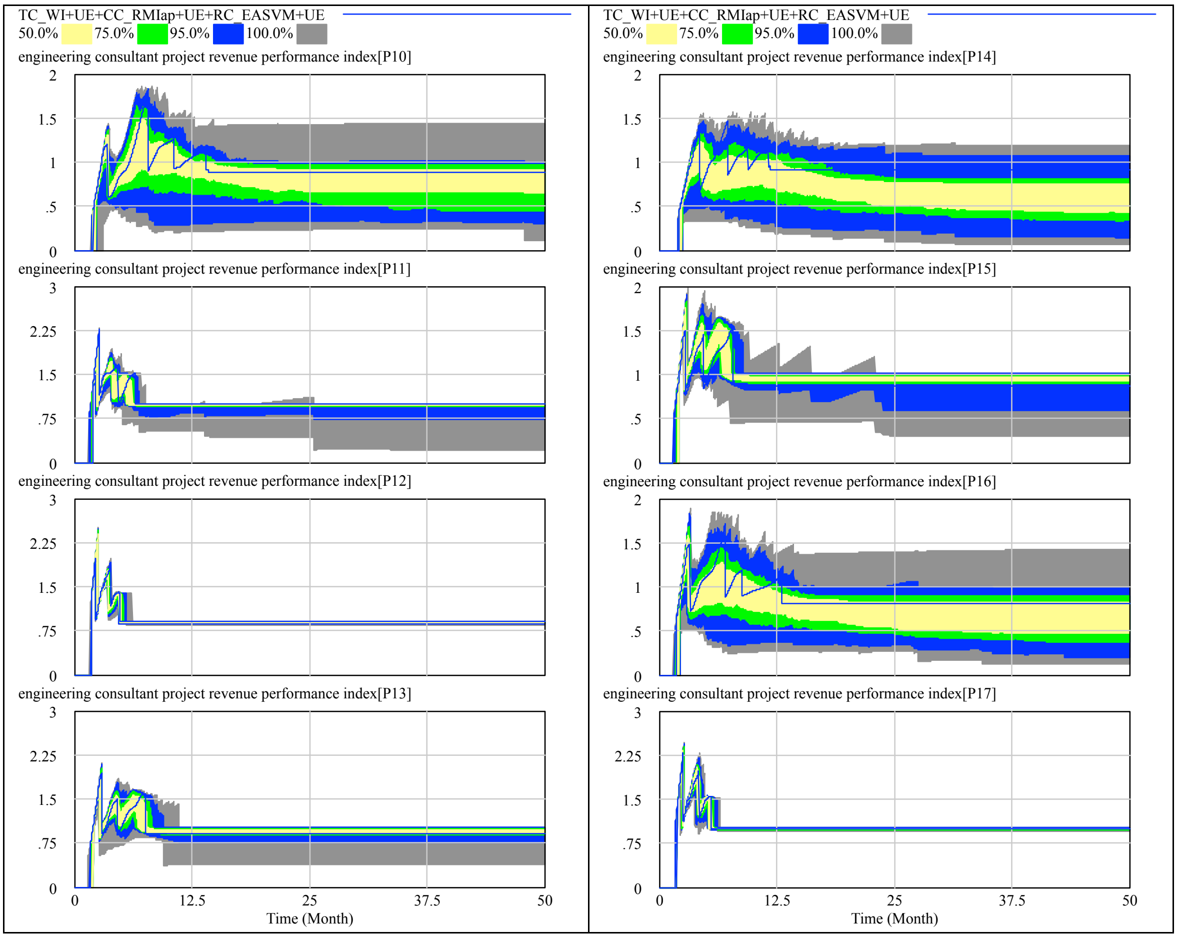


Figure 6.16: Sensitivity of engineering consultant project revenue performance index (with competition) per project (asset renewal-related)

The next sub-section is the third stage of the impact analysis, i.e., comparison of the key results from the preceding two stages of the impact analysis, providing a provisional answer to research question number 4 (posed in Section 1.6).

6.7.5 Comparisons and Discussions (Impact and Behaviour Mode Sensitivity)

Subsequent to the analysis of the impact of competition between the two key project participants (the client and the engineering consultant) on project performance discussed in Section 6.6, the next step in this research study was to analyse the impact of the same competition on the business performance of the engineering consultant. This was conducted in three stages, similar to the analysis of the impact of the competition on project performance described in Section 6.6, as described in detail at the beginning of Section 6.7.

In the *first stage* (Sections 6.7.1 and 6.7.2), data gathered for the first set of unique raw water infrastructure projects (10 asset management planning and support-related) and the associated calibrated system dynamics simulation model discussed in Section 6.4 were used to conduct three sets of simulation experiments and sensitivity analysis similar to Sections 6.6.1 and 6.6.2. The impact of the competition (i.e. combined impact of competing client project cost controls and their unintended effects, and engineering consultant project revenue controls and their unintended effects) on the engineering consultant's project business performance, for each of the 10 projects and on average, was assessed through the determination of two impact ratios (impact ratio on project time schedule performance, and impact ratio on the engineering consultant's project revenue performance) (Section 6.7.1). Subsequently, a multivariate Monte Carlo behaviour mode sensitivity analysis was conducted to assess, for each project, the sensitivity of the impact of the competition on the engineering consultant's project business performance to uncertainty in selected key calibrated parameters (Section 6.6.2).

In the *second stage* (Sections 6.7.3 and 6.7.4), all the three sets of model simulation experiments, impact analysis and sensitivity analysis conducted in the preceding stage were repeated, but using data gathered for the second set of unique raw water infrastructure projects (8 asset renewal-related) and the associated calibrated system dynamics simulation model discussed in Section 6.5.

The *third stage* is this sub-section (Section 6.7.5), where a comparison of the key results (client project cost controls' counteractive and unintended effects, engineering consultant project revenue controls' counteractive and unintended effects, and polarity and behaviour mode sensitivity of the impact of the competition on the engineering consultant's project business performance) from the preceding two stages is made, with appropriate conclusions drawn as to whether or not the associated dynamic hypotheses were supported by the two sets of projects, and an appropriate provisional answer to research question number 4 (posed in Section 1.6) provided.

The above-summarised three-stage analysis of the impact of the competition on the engineering consultant's project business performance, where the impact analysis and associated sensitivity analysis were conducted separately for each of the two sets of unique raw water infrastructure projects considered, with subsequent comparison of results from the two sets, assisted in enhancing the validity of the associated overall key research results (presented later in this Section 6.7.5), namely support for the related dynamic hypothesis and a provisional answer for research question number 4 (posed in Section 1.6), which help to address associated gaps identified in the reviewed literature, as discussed in Chapters 1, 3 and 4. It is a novel contribution towards the enhancement of the existing system dynamics simulation model validation, in particular impact and sensitivity analyses, processes and procedures, and is, thus expected to benefit future system dynamics research studies.

The next section compares the individual project participant controls' unintended effects for the two sets of projects considered.

Individual Project Participant Controls' Unintended Effects

As discussed in Sections 6.6.5, the client project cost controls simulation results for both sets of unique raw water infrastructure projects (10 asset management planning and support-related projects (Sections 6.6.1 and 6.7.1), and 8 asset renewal-related projects (Sections 6.6.3 and 6.7.3)) suggested a 'better-before-worse' result that is characteristic of dynamic complexity (Sterman, 2000). The short-term impact of all the considered client project cost controls was positive for the client, supporting the intended effect of a reduction in project cost overrun; whereas their long-term impact (when all their unintended effects were considered) was counterintuitive, counteractive and unintended: instead of the project cost overrun decreasing, it increased. Thus, the simulation results for both sets of projects supported a related dynamic hypothesis formulated in Section 4.9.3 as discussed in Section 6.6.5.

As discussed in Chapters 4 and 5, in this research study: only time-based contracts with a ceiling price (Turner, 2004) between the client and the engineering consultant were considered; and only the time-based costs for the engineering consultant services were considered for project cost. Hence, in this study, the project revenue realised by the engineering consultant at project completion was assumed to be equal to the project cost incurred by the client at completion of the same project.

The engineering consultant project revenue controls simulation results for both sets of unique projects also suggested a 'better-before-worse' result. The short-term impact of all the considered engineering consultant project revenue controls was positive, supporting the intended effect of a reduction in the engineering consultant project revenue shortfall; whereas their long-term impact (when all their unintended effects were considered) was counterintuitive, counteractive and unintended: instead of the engineering consultant project revenue shortfall decreasing, it increased. Thus, the simulation results for both sets of projects supported a related dynamic hypothesis formulated in Section 4.9.3 as discussed in Section 6.6.5.

The next sub-section compares and discusses the impact of the competition (i.e. competing client project cost controls and their unintended effects, and engineering consultant project revenue controls and their unintended effects) on the engineering consultant's project business performance for the two sets of projects considered.

Analysis of the Impact of Competition on the Engineering Consultant's Business Performance

The reviewed literature showed that: there are many measures of engineering consultant project business performance (Section 3.3.2); current project dynamics models are limited to project performance (mainly time duration) control actions of mainly the engineering consultant or construction contractor; and control actions taken by the client to protect project performance, and control actions taken by the engineering consultant and construction contractor to protect their individual business performance targets during project execution are sparingly covered (Section 3.11). Also, in the reviewed literature, no appropriate system dynamics project model could be identified that considered: competition among project participants, with their different and competing performance measures and targets during project execution; and how such competition influences the engineering consultant's project business performance (Section 3.11).

As discussed in Chapters 4 and 5, the system dynamics simulation model of competition between two key project participants (the client and the engineering consultant) formulated in this research study included two measures (project time schedule duration and engineering consultant project revenue) of the engineering consultant's project business performance. It also captured the competition in the form of two sets of competing project controls (aimed at win-lose results), namely client project cost controls and their associated unintended effects, and engineering consultant project revenue controls and their associated unintended effects. This sub-section analyses how such competition influences the said two measures of the engineering consultant's project business performance. This novel contribution, made by this research study, expands the existing project dynamics models, deepening our understanding of project dynamics, and assists towards addressing the above-mentioned gaps identified in the reviewed literature.

In this research study, the impact of the competition between the two key project participants (client and engineering consultant) during project execution on the engineering consultant's project business performance was assessed through the determination of two impact ratios, as discussed in Sections 6.7.1 and 6.7.3:

- *impact ratio* on *project time schedule performance* (determined as the ratio of the project schedule performance index without competition to the project schedule performance index with competition); and
- *impact ratio on engineering consultant project revenue performance* (determined as the ratio of the project revenue performance index without competition to the project revenue performance index with competition).

An *impact ratio on project time schedule performance* (a measure of the impact of the competition on the engineering consultant's project business performance, in terms of project time schedule duration) of: less than 1 indicates that the competition positively influences (improves) the engineering consultant's project business performance; 1 indicates that the competition has no impact the engineering consultant's project business performance; and greater than 1 indicates that the competition negatively influences (worsens) the engineering consultant's project business performance.

In contrast, an *impact ratio on the engineering consultant project revenue performance* (a measure of the impact of the competition on the engineering consultant project business performance, in terms of project revenue) of: less than 1 indicates that the competition negatively influences (worsens) the engineering consultant project business performance; 1 indicates that the competition has no impact on the engineering consultant project business performance; and greater than 1 indicates that the competition positively influences (improves) the engineering consultant project business performance.

Table 6.29 (in Section 6.6.5) and Table 6.42 (refer to Tables 6.35 and 6.40 for more details) show the number of projects that were negatively, positively and not influenced (in terms of project time schedule performance and engineering consultant project revenue performance, respectively) by the competition for the two sets of unique raw water infrastructure projects (10 asset management planning and support-related, and 8 asset renewal-related) considered. This assessment of the impact of the competition between two key project participants (with their different and competing performance measures and targets during project execution) on the engineering consultant's project business performance (as measured by project time schedule duration and project revenue) is another novel contribution made by this research study. It assists towards addressing a related gap identified in the reviewed literature, namely no appropriate study could be identified that specifically investigated the influence of such competition on the engineering consultant's project business performance, as discussed in Chapters 1, 3, and 4.

The competition negatively influenced (impact ratio greater than 1) the project time schedule performance of: most (9/10) of the asset management planning and support-related projects; and all the 8 asset renewal-related projects considered, as shown in Table 6.29.

The competition positively influenced (impact ratio greater than 1) the project revenue performance of: most (8/10) of the asset management planning and support-related projects; and half (4/8) of the asset renewal-related projects considered, as shown in Table 6.42. However, it negatively influenced (impact ratio less than 1) the project revenue performance of: 2 asset management planning and support-related projects; and 3 asset renewal-related projects.

Table 6.42: Impact of competition on engineering consultant project revenue performance per project set

Impact of competition	Number of projects influenced		
	Asset management planning and support-related projects	Asset renewal-related projects	Total
Positive (impact ratio > 1)	8	4	**12**
Negative (impact ratio < 1)	2	3	**5**
None (impact ratio = 1)	-	1	**1**
Total	**10**	**8**	**18**

Table 6.43 (refer to Tables 6.36 and 6.41 for more details) shows the descriptive statistics for the impact ratios of the competition on project time schedule performance and on the engineering consultant's project revenue performance for the two sets of projects considered. For both sets of projects, the mean values for the impact ratios on both the project time schedule performance and on the engineering consultant's project revenue performance were greater than 1. This means that, on average, the competition: negatively influenced the project time schedule performance; and positively influenced the engineering consultant's project revenue performance, for both sets of projects considered.

The mean impact ratio on project time schedule performance was much higher than that on the engineering consultant's project revenue performance, as shown in Table 6.43. This means that, on average, the competition much more negatively influenced project time schedule performance than it positively influenced the engineering consultant's project revenue performance, for both sets of projects considered. For instance, on average, the competition led to a 28% project time schedule delay (impact ratio of 1.28) and a much lower 7% (impact ratio of 1.07) increase in the engineering consultant's project revenue for the asset management planning and support-related projects. A similar pattern is evident for the asset renewal-related projects, as shown in Table 6.43.

Even though, on average, the engineering consultant project revenue at project completion increased (was higher than that initially planned), the average net increase in the project revenue was much lower than (and not commensurate with) the average net increase in the project time schedule (since only time-based contracts were considered), and, thus the engineering consultant actually lost out. Hence, in the final analysis, on average the competition between the two key project participants (the client and engineering consultant) negatively influenced the engineering consultant's project business performance.

Table 6.43: Descriptive statistics for competition impact ratios on the engineering consultant's project business performance per project set

Statistic	Impact ratio on project time schedule performance		Impact ratio on project revenue performance	
	Asset management planning and support-related projects	Asset renewal-related projects	Asset management planning and support-related projects	Asset renewal-related projects
Median	1.29	1.17	1.10	1.01
Mean	1.28	1.22	1.07	1.03
Standard Deviation	0.15	0.23	0.08	0.12
Minimum	0.99	1.01	0.97	0.93
Maximum	1.50	1.73	1.18	1.29

Multivariate Monte Carlo behaviour mode sensitivity analyses were then conducted, to assess the sensitivity of the impact of the competition on the engineering consultant's project business performance (as measured by project time schedule performance and project revenue performance) to uncertainty in 10 key calibrated model parameters for each of the two sets of unique projects (10 asset management planning and support-related, and 8 asset renewal-related) considered. The results of the sensitivity analyses showed that both the *schedule performance index* and the project *revenue performance index* exhibited no behaviour mode sensitivity (though there were effects in absolute values, i.e., exhibited numerical sensitivity): both the base case (based on calibrated parameter values) and the random cases (based on 200 sets of randomly selected parameter values) exhibited an *S-shaped growth with overshoot and collapse* behaviour mode for all the 18 projects considered.

The above-discussed research results suggested no difference, in terms of the polarity (which was negative) and behaviour mode insensitivity of the impact of the competition on the engineering consultant's project business performance, between the two sets of unique projects considered. They supported the following dynamic hypothesis formulated in Section 4.9.3:

> *The client project cost controls and the engineering consultant project revenue controls tend to oppose (compete with) each other, generating some unintended and counteractive consequences (unintended effects) that negatively influence the engineering consultant's project business performance (increasing both 'project time schedule delay' and 'project revenue shortfall').*

Accordingly, a provisional answer for research question number 4 (posed in Section 1.6) is as follows:

Research Question:

4. *How does the competition between the two key project participants (client and engineering consultant) influence the engineering consultant's project business performance?*

Provisional Answer:

The competition between the two key project participants (client and engineering consultant) during project execution negatively influences the engineering consultant's project business performance (it results in project time schedule delays and project revenue increases that are not commensurate with the increases in the project time schedule duration, and thus, it negatively influences both the project time schedule performance and the engineering consultant's project revenue performance, both of which are the key measures of the engineering consultant's project business performance considered in the current research study).

Some previous researchers and scholars, such as Lyneis and Ford (2007), Mohammed et al. (2009), and Sutterfield et al. (2007) highlighted that the use of competition (aimed at win-lose results), as a conflict-handling style, is quite common among project participants during project execution. Yet, no appropriate study could be identified in the reviewed existing literature, as discussed in Chapter 3, that specifically investigated how such competition influences the engineering consultant's project business performance. Thus, the analysis of the impact/ influence of competition between two key project participants (the client and the engineering consultant, with their different and competing performance measures and targets during project execution) on the engineering consultant's project business performance (as measured by project time schedule duration and project revenue), as conducted in this Section 6.7, is another novel contribution made by this research study. The above-stated research findings, particularly support for the stated dynamic hypothesis from two different sets of unique raw water infrastructure projects, and the stated provisional answer for research question number 4 (posed in Section 1.6) help towards addressing the above-mentioned gap identified in the reviewed literature, and deepens our understanding of project dynamics.

The Competition Leads to 'Lose-Lose' Long-term Results

The preceding simulation and impact analysis results, coupled with those presented in Section 6.6.5, suggested the competition between the client and the engineering consultant yields lose-lose long-term results for the two key project participants: the competing client project cost controls and engineering consultant project revenue controls generate some unintended and counteractive consequences (unintended effects) that negatively influence both the project performance (increasing both 'project time schedule delay' and 'project cost overrun') (Section 6.6.5) and the engineering consultant's project business performance (increasing both 'project time schedule delay' and 'project revenue shortfall') (Section 6.7.5).

This key result is counterintuitive considering that by using competition (aimed at win-lose results), as a conflict-handling style, one project participant expects to win [and the other party to lose, though often not intentional but just as a result of intended/local rationality (Sterman, 2000)]. The client project cost controls were aimed at eliminating the 'project cost overrun' by reducing the 'estimated project cost at completion' (a 'win-lose' control in favour of the client); whilst the engineering consultant project revenue controls were aimed at eliminating the 'project revenue shortfall' by increasing the 'estimated project cost at completion' (a 'win-lose' control in favour of the engineering consultant).

Whereas the short-term impact of the individual project participants' controls supported the intended effect, their long-term impacts (after considering their unintended effects and feedbacks from the other participant) were counterintuitive. All this highlight the dynamic complexity of the competition between the two key project participants, which was illuminated through the use of system dynamics in this research study.

Indeed, system dynamics is a multi-disciplinary approach whose goal is to assist managers improve their understanding of systems characterised by dynamic complexity, and to use such understanding to design and develop more effective, high-leverage policies and structures that solve real-world problems and improve the performance of the systems (Martinez-Moyano and Richardson, 2013; Sterman, 2000). Accordingly, the next section investigates how to improve the competition (minimise its negative impacts on both the project performance and the engineering consultant's project business performance) so as to yield 'win-win' long-term results for the two key project participants.

6.8. Competition Improvement (Policy Optimisation)

This section seeks to answer the following research question (posed in Section 1.6):

5. *How can the competition be improved so as to enhance both the project performance and the business performance of the engineering consultant during project execution, yielding 'win-win' results for the two key project participants?*

One of the key findings of this research study, as discussed in the preceding section, was that the competition between the client and the engineering consultant during project execution yielded lose-lose long-term results for the two key project participants. This section focusses on formulating appropriate intervention strategies that help improve the competition (policy optimisation), i.e., minimising its negative impacts on both the project performance (client's interest) and the engineering consultant's project business performance, yielding win-win long-term results for the two key project participants.

The policy optimisation aimed at improving the competition between the two key project participants was conducted in three stages. In the *first stage* (Sections 6.8.2 and 6.8.3), data gathered for the first set of unique raw water infrastructure projects (10 asset management planning and support-related) and the associated calibrated system dynamics simulation model discussed in Section 6.4 were used to conduct a policy optimisation experiment, yielding optimised performance targets and an associated model simulation run (*With improved competition*). Subsequently, the impacts of the improved competition on both the project performance and the engineering consultant's project business performance were assessed. Comparisons were made between the impact of the original competition (determined in Sections 6.6 and 6.7) and that of the improved competition, per project and on average, with appropriate conclusions drawn as to whether or not the improved competition did minimise the negative impacts on both the project performance and the engineering consultant's project business performance.

In the *second stage* (also Sections 6.8.2 and 6.8.3), the policy optimisation experiment and impact analyses conducted in the preceding stage were repeated, but using data gathered for the second set of unique raw water infrastructure projects (8 asset renewal-related) and the associated calibrated system dynamics simulation model discussed in Section 6.5.

In the *third stage* (Section 6.8.4), a comparison of the key results (impacts of the improved competition on both project performance and the engineering consultant's project business performance, for the two sets of unique projects considered) from the preceding two stages is made, and an appropriate provisional answer to research question number 5 (posed in Section 1.6) is provided. The provisional answer includes appropriate intervention strategies that help improve the competition, thereby enhancing both the project performance and the engineering consultant's business performance, and yielding win-win long-term results for the two key project participants. It also helps to address the call made by Lyneis and Ford (2007) for research towards improvement of such competition.

The above-summarised three-stage policy optimisation (competition improvement), where the policy optimisation experiment and associated impact analyses were conducted separately for each of the two sets of unique raw water infrastructure projects considered, with subsequent comparison of results from the two sets, assisted in enhancing the validity of the associated overall key research result (presented in Section 6.8.4), namely the provisional answer for research question number 5 (posed in Section 1.6). It is a novel contribution towards the enhancement of the existing system dynamics simulation model validation, in particular policy optimisation and impact analyses, processes and procedures, and is, thus expected to benefit future system dynamics research studies.

The next sub-section discusses, in more detail, the policy optimisation process followed in the current research study.

6.8.1 Policy Optimisation Overview

As discussed in Sections 6.6 and 6.7, to assess the impacts of the competition between the two key project participants (the client and the engineering consultant) on both the project performance and the engineering consultant's project business performance, two model simulation runs were considered, namely:

- TC_WI+UE (*Without competition)*: where only the engineering consultant project time schedule control (work intensity) and its associated unintended effect were activated. No client project cost controls and their associated unintended effects were activated, and no engineering consultant project revenue controls and their associated unintended effects were activated; and
- TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE (*With competition*): where the engineering consultant project time schedule control (work intensity) and its associated unintended effect, all the client project cost controls and their associated unintended effects, and all the engineering consultant project revenue controls and their associated unintended effects were all activated.

The findings summarised in Sections 6.6.5 and 6.7.5 indicated that the competition negatively influenced both the project performance (client's interest) and the engineering consultant's business performance, yielding lose-lose long-term results for the two key project participants. That is, the simulated performance outputs were better without competition (simulation run TC_WI+UE) than with competition (simulation run TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE). Hence, improving the competition is about minimising both: the client project cost controls and their associated unintended effects (CC_RMIap+UE); and the engineering consultant project revenue controls and their associated unintended effects (RC_EASVM+UE).

It is, thus important to analyse further the system dynamics conceptual model of the competing client project cost controls and engineering consultant project revenue controls formulated in Chapter 4. As shown in Figures 4.29 to 4.31, and Table 4.11, the intensities of the client project cost control negative feedback loop and the engineering consultant project revenue control negative feedback loop are dependent upon the magnitudes of their respective performance gaps. The performance gap that the client project cost control negative feedback loop aims at closing/minimising is the 'estimated project cost overrun at completion (X)'; whereas that of the engineering consultant project revenue control negative feedback loop is the 'estimated engineering consultant project revenue shortfall at completion (T)'.

In a negative feedback loop, the performance gap triggers the corrective controls (Sterman, 2000). Thus, the client project cost controls (and their associated unintended effects) are eliminated by making X = 0; and the engineering consultant project revenue controls (and their associated unintended effects) are eliminated by making T = 0.

As shown in Table 4.11, the formulae for X and T are:

$X = W - U$; $T = V - W$

where:

U is the *client project cost at completion target*;
V is the *engineering consultant project revenue at completion target*; and
W is the *estimated project cost at completion.*

The corrective controls are activated when performance gaps are greater than zero:

X > 0 => client project cost controls; T > 0 => engineering consultant project revenue controls;

The corrective controls are deactivated when performance gaps are equal to zero:

X = 0 => no client project cost controls; T = 0 => no engineering consultant project revenue controls;

Now,

$X = 0 \Rightarrow U = W$; $T = 0 \Rightarrow V = W$

$X = 0$ AND $T = 0 \Rightarrow U = V = W$

As shown in Table 4.11, the formulae for U and V are:

$U = (100 - a)Z$; $V = bZ$

where:

a is the *client project cost variance % at completion target*;
b is the *engineering consultant project contract ceiling price % target*; and
Z is the *project contract ceiling price.*

Thus,

$$
\begin{aligned}
U = V \quad &\Rightarrow \quad (100 - a)Z = bZ \\
&\Rightarrow \quad (100 - a)Z - bZ = 0 \\
&\Rightarrow \quad 100Z - aZ - bZ = 0 \\
&\Rightarrow \quad 100 - a - b = 0 \\
&\Rightarrow \quad a + b = 100 \qquad (6.6)
\end{aligned}
$$

Thus, satisfying Equation 6.6 ($a + b = 100$) implies that: the performance targets of the two key project participants are fully aligned [i.e., *client project cost at completion* *target (U) = engineering consultant project revenue at completion target (V)*]; there are no performance gaps (i.e. both X and T are equal to zero); and, thus, no client project cost controls (and their associated unintended effects) and no engineering consultant project revenue controls (and their associated unintended effects), and effectively no competition between the two key project participants.

As discussed in Chapters 4 and 5, in this research study: only time-based contracts with a ceiling price (Turner, 2004) between the client and the engineering consultant were considered; and only the time-based costs for the engineering consultant services were considered for project cost. Hence, in this study, the project revenue realised by the engineering consultant at project completion was assumed to be equal to the project cost incurred by the client at completion of the same project.

Equation 6.6 also suggests that a key cause of the competition is 'competing performance measures and targets', and that the competition can be improved (yielding win-win long-term results) by aligning the key project participants' performance targets, which is achieved by making sure that:

> *engineering consultant project contract ceiling price % target (b) = 100 –* client *project cost variance % at completion target (a)*

That is,

> *client project cost at completion target (U) = engineering consultant project revenue at completion target (V)*

where

> *client project cost at completion target (U) = project contract ceiling price (Z) x [100 – client project cost variance % at completion target (a)]*

and

> *engineering consultant project revenue at completion target (V) = project contract ceiling price (Z) x engineering consultant project contract ceiling price % target (b).*

Policy Optimisation Objective Function (Payoff)

In this research study, policy optimisation was aimed at improving the competition between the client and the engineering consultant. Improving the competition entailed minimising the negative impact of the competition on both the project performance (as measured by project time schedule duration and project cost) and the engineering consultant's project business performance (as measured by project time schedule duration and project revenue) so as to yield win-win long-term results. The policy optimisation was, thus, conducted by minimising a payoff function that is a linear combination of three sources of error (project time schedule performance index, project cost performance index and the engineering consultant's project revenue performance index) between the model simulation outputs of two model simulation runs, namely: *Without competition* (TC_WI+UE); and *With improved competition* (TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE*).

Equation 6.7 shows the project optimisation payoff function that was used for the individual project policy optimisation. Effectively, the pay-off function maximises both the project performance (client's interest) and the engineering consultant's project business performance by simultaneously minimising the 'project time schedule delay', 'project cost overrun' and 'project revenue shortfall'.

$$\text{Project Optimisation Payoff}_i = W_{spi}\left(\frac{SPI_{ic,i} - SPI_{nc,i}}{|SPI_{ic,i}| + |SPI_{nc,i}|}\right)^2 + W_{cpi}\left(\frac{CPI_{ic,i} - CPI_{nc,i}}{|CPI_{ic,i}| + |CPI_{nc,i}|}\right)^2 + W_{rpi}\left(\frac{RPI_{ic,i} - RPI_{nc,i}}{|RPI_{ic,i}| + |RPI_{nc,i}|}\right)^2 \quad (6.7)$$

where:

W_{spi} = weight for the project time schedule performance index component;
$SPI_{ic,i}$ = simulated project time schedule performance index (*With improved competition*) for project *i*;
$SPI_{nc,i}$ = simulated project time schedule performance index (*Without competition*) for project *i*;
W_{cpi} = weight for the project cost performance index component;
$CPI_{ic,i}$ = simulated project cost performance index (*With improved competition*) for project *i*;
$CPI_{nc,i}$ = simulated project cost performance index (*Without competition*) for project *i*;
W_{rpi} = weight for the project revenue performance index component;
$RPI_{ic,i}$ = simulated project revenue performance index (*With improved competition*) for project *i*;
$RPI_{nc,i}$ = simulated project revenue performance index (*Without competition*) for project *i*.

Figure 6.17 shows a graphical representation of the systems dynamics simulation model policy optimisation payoff that was generated using Vensim DSS software. For the full list of associated equations, refer to Appendix E.

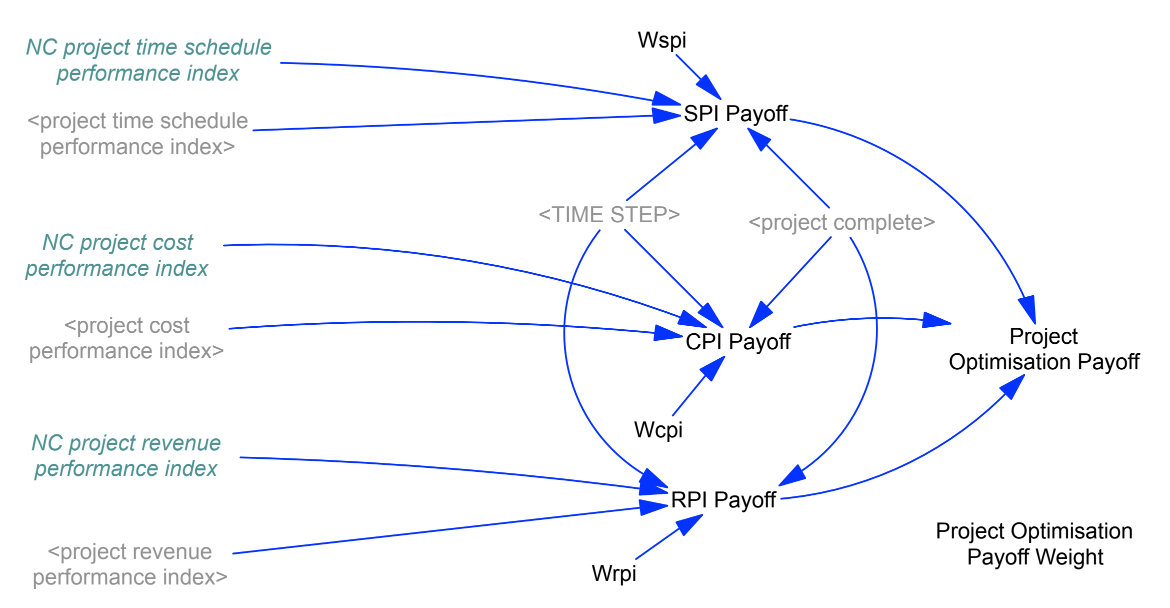


Figure 6.17: Graphical representation of the policy optimisation payoff

The Policy Optimisation Experiment

As highlighted in the preceding discussion, satisfying Equation 6.6 (*a + b = 100*) ensures that the performance targets of the two key project participants are fully aligned (i.e., the *client project cost at completion target* equals the *engineering consultant project revenue at completion target*). This is the case considering that, in this research study, the project revenue realised by the engineering consultant at project completion was assumed to be equal to the project cost incurred by the client at completion of the same project, as highlighted in Chapters 4 and 5, and in the preceding discussion. Turner (2004) also made the point that contracts need to be designed to promote cooperation between the parties involved, by essentially aligning the objectives of the consultant/contractor with those of the client. Equation 6.6 was, thus, used in the policy optimisation conducted in this research study.

The policy optimisation aimed at improving the competition between the two key project participants (the client and the engineering consultant) was conducted in three stages. In the *first stage* (Sections 6.8.2 and 6.8.3), data gathered for the first set of unique raw water infrastructure projects (10 asset management planning and support-related) and the associated calibrated system dynamics simulation model discussed in Section 6.4 were used to conduct a policy optimisation experiment and two impact analyses.

Firstly, in the system dynamics simulation model, the project-specific parameter *b* (*engineering consultant project contract ceiling price % target*) was changed to an auxiliary variable with an equation (*b = 100 – a*) adapted from Equation 6.6 so as to ensure that the performance targets of the two key project participants were fully aligned (i.e., the *client project cost at completion target* equals the *engineering consultant project revenue at completion target*).

Secondly, Vensim software's built-in optimisation module (which makes use of the Powell conjugate search algorithm) was used to automatically estimate the project-specific parameter *a (project cost variance % at completion target)* that minimised the *Project Optimisation Pay-off* (Equation 6.7) for each project. Appendix I shows the simulation model Vensim optimisation configuration details text of the: payoff (objective function) definition *.vpd* file; and the optimisation control *.voc* file, which also indicates the parameter search space (lower and upper limits of the associated model parameter feasible ranges). At the end of the policy optimisation, a simulation (TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE*, *With improved competition*) was automatically run for each project, making use of the optimised values for the *project cost variance % at completion target (a), engineering consultant project contract ceiling price % target (b), client project cost at completion target (U)* and *engineering consultant project revenue at completion targets V).*

Thirdly, the impact of the improved competition on project performance was assessed, in Section 6.8.2, through the determination of two impact ratios (interpreted the same way as described in Section 6.6), namely:

- *impact ratio* on *project time schedule performance,* determined as the ratio of the project schedule performance index without competition (model simulation run TC_WI+UE) to the project schedule performance index with improved competition (model simulation run TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE*); and
- *impact ratio on project cost performance,* determined as the ratio of the project cost performance index without competition (model simulation run TC_WI+UE) to the project cost performance index with improved competition (model simulation run TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE*).

Comparisons were made between the impact of the original competition (determined in Section 6.6) and that of the improved competition on project performance, per project and on average, with appropriate conclusions drawn as to whether or not the improved competition (resulting from the optimised performance targets of the two key project participants) did minimise the negative impact on project performance.

Lastly, the impact of the improved competition on the engineering consultant's project business performance was assessed, in Section 6.8.3, through the determination of two impact ratios (interpreted the same way as described in Section 6.7), namely:

- *impact ratio* on *project time schedule performance,* determined as described earlier in this sub-section; and
- *impact ratio on engineering consultant project revenue performance,* determined as the ratio of the project revenue performance index without competition (model simulation run TC_WI+UE) to the project revenue performance index with improved competition (model simulation run TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE*).

Comparisons were made between the impact of the original competition (determined in Section 6.7) and that of the improved competition on the engineering consultant's project business performance, per project and on average, with appropriate conclusions drawn as to whether or not the improved competition (resulting from the optimised performance targets of the two key project participants) did minimise the negative impact on the engineering consultant's project business performance.

In the *second stage* (also Sections 6.8.2 and 6.8.3), the policy optimisation experiment and impact analyses conducted in the preceding stage were repeated, but using data gathered for the second set of unique raw water infrastructure projects (8 asset renewal-related) and the associated calibrated system dynamics simulation model discussed in Section 6.5.

In the *third stage* (Section 6.8.4), a comparison of the key results (impacts of the improved competition on both project performance and the engineering consultant's project business performance, for the two sets of unique projects considered) from the preceding two stages is made, and an appropriate provisional answer to research question number 5 (posed in Section 1.6) is provided.

The next sub-section presents the key results of the policy optimisation (competition improvement) with regards to the minimisation of the competition's negative impact on project performance.

6.8.2 Minimisation of the Negative Impact of Competition on Project Performance

Infrastructure Asset Management Planning and Support-Related Projects

Table 6.15 (Section 6.6.1) shows the original client project cost at completion targets and engineering consultant project revenue at completion targets for the first set of unique raw water infrastructure projects (10 asset management planning and support-related) used in Sections 6.6 and 6.7. Table 6.44 shows the optimised client project cost at completion targets (calculated from the optimised *client project cost* *variance % at completion target (a)* values) and engineering consultant project revenue at completion targets (calculated from the optimised *engineering consultant project contract ceiling price % target* (*b*) values) for the same set of projects.

As discussed in Chapters 4 and 5, in this research study: only time-based contracts with a ceiling price (Turner, 2004) between the client and the engineering consultant were considered; and only the time-based costs for the engineering consultant services were considered for project cost. Hence, in this study, the project revenue realised by the engineering consultant at project completion was assumed to be equal to the project cost incurred by the client at completion of the same project.

Evident in Table 6.44 is that, for each project, satisfying Equation 6.6 ($a + b = 100$) implied that the performance targets of the two key project participants were fully aligned [i.e., *client project cost at completion target (U) = engineering consultant project revenue at completion target (V)*]. Also, for most of the projects, the optimised values for the *client project cost variance % at completion target* (*a*) parameter were equal (or close) to zero, while those for the *engineering consultant project contract ceiling price % target* (*b*) variable were equal (or close) to 100. This made the two key project participants' performance targets [*client project cost at completion target (U) and engineering consultant project revenue at completion target (V)]* also equal (or close) to the initially planned project contract ceiling price.

Table 6.44: Optimised project participants performance targets per project (asset management planning and support-related)

Project number	Initially planned		Client project cost performance target		Engineering consultant project revenue performance target	
	Project time schedule duration (months)	Project contract ceiling price (Z) (R million)	Client project cost variance % at completion target (a) (%)	Client project cost at completion target (U) (R million)	Engineering consultant project contract ceiling price % target (b) (%)	Engineering consultant project revenue at completion target (V) (R million)
P0	12	13.473	0.0	13.473	100.0	13.473
P1	12	15.022	0.0	15.022	100.0	15.022
P2	24	42.937	0.0	42.937	100.0	42.937
P3	9	5.752	0.0	5.752	100.0	5.752
P4	6	3.840	2.8	3.734	97.2	3.734
P5	9	5.992	0.1	5.989	99.9	5.989
P6	26	21.278	2.8	20.676	97.2	20.676
P7	7	3.817	0.0	3.817	100.0	3.817
P8	12	12.170	0.0	12.170	100.0	12.170
P9	12	10.590	0.0	10.590	100.0	10.590

Table 6.45 shows the initially planned project time schedule duration and project cost, as well as the corresponding simulated outputs for the two model simulation runs '*Without competition*' and '*With improved competition*' for the 10 asset management planning and support-related projects. There is a visible general improvement in the project performance (in terms of both project time schedule duration and project cost) from the '*With competition*' simulation (refer to Table 6.20 in Section 6.6.1) to the *'With improved competition'* simulation for all the 10 projects (except for Project P3 where there is only a very slight increase in the project cost).

Table 6.45: Planned project time duration and cost, and corresponding simulated outputs without and with improved competition (asset management planning and support-related projects)

Project number	Planned		Without competition (simulation run: TC_WI+UE)		With improved competition (simulation run: TC_WI+UE+CC_RMIap+UE +RC_EASVM+UE*)	
	Project time schedule duration (months)	Project cost (R million)	Project time schedule duration (months)	Project cost (R million)	Project time schedule duration (months)	Project cost (R million)
P0	12	13.473	12.50	14.400	11.59	13.100
P1	12	15.022	12.09	15.140	12.09	15.140
P2	24	42.937	25.09	44.890	25.03	44.780
P3	9	5.752	9.78	6.251	9.72	6.097
P4	6	3.840	6.22	3.980	6.41	3.673
P5	9	5.992	8.84	5.888	10.34	6.208
P6	26	21.278	27.34	22.380	27.22	22.130
P7	7	3.817	5.88	3.203	7.16	3.496
P8	12	12.170	12.12	12.300	11.66	11.540
P9	12	10.590	12.09	10.670	11.78	10.310

Table 6.46 shows, for each of the 10 asset management planning and support-related projects, the SPI and CPI ('*Without competition*' and '*With improved competition*') and the resulting impact ratios (of the improved competition between the client and the engineering consultant during project execution) on project time schedule performance and on project cost performance. There is a marked improvement in the impact ratios on both project time schedule performance and project cost performance from those based on the '*With competition*' simulation (Table 6.21 in Section 6.6.1) to those based on the *'With improved competition'* simulation. For instance, for Project P0: the impact ratio on project time schedule performance improved from 1.29 (or 29% time schedule delay) to 0.93 (or 7% ahead of time schedule); whilst the impact ratio on project cost performance improved from 1.10 (or 10% project cost overrun) to 0.91 (or 9% project cost saving).

Such improvement was made possible by making sure that in the *'With improved competition'* simulation (during the policy optimisation) Equation 6.6 was satisfied, which implied that the performance targets of the two key project participants were fully aligned [i.e., *client project cost at completion target (U) = engineering consultant project revenue at completion target (V)*], and also by the optimised values of the *client project cost variance % at completion target* (*a*) and the *engineering consultant project contract ceiling price % target* (*b*).

Table 6.46: SPI and CPI (without and with improved competition), and competition impact ratios per project (asset management planning and support-related)

Project number	Project time schedule performance			Project cost performance		
	Schedule performance index (SPI)		Impact ratio	Cost performance index (CPI)		Impact ratio
	Without competition (simulation run: TC_WI+UE)	With improved competition (simulation run: TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE*)		Without competition (simulation run: TC_WI+UE)	With improved competition (simulation run: TC_WI+UE+CC_RMlap+UE+RC_EASVM+UE*)	
P0	0.96	1.04	0.93	0.94	1.03	0.91
P1	0.99	0.99	1.00	0.99	0.99	1.00
P2	0.96	0.96	1.00	0.96	0.96	1.00
P3	0.92	0.93	0.99	0.92	0.94	0.98
P4	0.96	0.94	1.03	0.96	1.05	0.92
P5	1.02	0.87	1.17	1.02	0.97	1.05
P6	0.95	0.96	1.00	0.95	0.96	0.99
P7	1.19	0.98	1.22	1.19	1.09	1.09
P8	0.99	1.03	0.96	0.99	1.05	0.94
P9	0.99	1.02	0.97	0.99	1.03	0.97

Table 6.47 shows the overall descriptive statistics for the SPI and CPI ('*Without competition'* and '*With improved competition'*) and the associated impact ratios (of the improved competition between the client and the engineering consultant during project execution) on both project time schedule performance and project cost performance for the 10 asset management planning and support-related projects. There is a marked improvement from the values based on the '*With competition'* simulation (Table 6.22 in Section 6.6.1) to those based on the *'With improved competition'* simulation (Table 6.47). For instance, the mean impact ratio on project time schedule performance improved from 1.28 (or 28% time schedule delay) to 1.03 (or 3% time schedule delay); whilst the mean impact ratio on project cost performance improved from 1.07 (or 7% project cost overrun) to 0.98 (or 2% project cost saving). Thus, on average, the improved competition between the client and engineering consultant did minimise the negative impact on project performance.

Table 6.47: Descriptive statistics for SPI and CPI (without and with improved competition), and competition impact ratios (asset management planning and support-related projects)

Statistic	Project time schedule performance			Project cost performance		
	Schedule performance index (SPI)		Impact ratio	Cost performance index (CPI)		Impact ratio
	Without competition (simulation run: TC_WI+UE)	With improved competition (simulation run: TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE*)		Without competition (simulation run: TC_WI+UE)	With improved competition (simulation run: TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE*)	
Median	0.98	0.97	1.00	0.98	1.01	0.98
Mean	0.99	0.97	1.03	0.99	1.01	0.98
Standard Deviation	0.07	0.05	0.09	0.08	0.05	0.06
Minimum	0.92	0.87	0.93	0.92	0.94	0.91
Maximum	1.19	1.04	1.22	1.19	1.09	1.09

The next sub-section presents the key results of the policy optimisation (competition improvement) with regards to the minimisation of the competition's negative impact on project performance, using data gathered for the second set of unique raw water infrastructure projects (8 asset renewal-related) and the associated calibrated system dynamics simulation model discussed in Section 6.5. As indicated at the beginning of this Section 6.8, comparison of the results from the two sets of unique raw water infrastructure projects considered in this research study was aimed at enhancing the validity of the associated overall key research result (Section 6.8.4), i.e., the provisional answer for research question number 5 (posed in Section 1.6).

Infrastructure Asset Renewal-Related Projects

Table 6.23 (Section 6.6.3) shows the original client project cost at completion targets and engineering consultant project revenue at completion targets for the second set of unique raw water infrastructure projects (asset renewal-related, made up of 8 projects) used in Sections 6.6 and 6.7. Table 6.48 shows the optimised client project cost at completion targets (calculated from the optimised *client project cost variance % at completion target* (*a*) values) and engineering consultant project revenue at completion targets (calculated from the optimised *engineering consultant project contract ceiling price % target* (*b*) values) for the same set of projects.

As discussed in Chapters 4 and 5, in this research study: only time-based contracts with a ceiling price (Turner, 2004) between the client and the engineering consultant were considered; and only the time-based costs for the engineering consultant services were considered for project cost. Hence, in this study, the project revenue realised by the engineering consultant at project completion was assumed to be equal to the project cost incurred by the client at completion of the same project.

Evident in Table 6.48 is that, for each project, satisfying Equation 6.6 ($a + b = 100$) implied that the performance targets of the two key project participants were fully aligned [i.e., *client project cost at completion target (U) = engineering consultant project revenue at completion target (V)*]. Also, for most of the projects, the optimised values for the *client project cost variance % at completion target (a)* parameter were equal (or close) to zero, whilst those for the *engineering consultant project contract ceiling price % target* (*b*) variable were equal (or close) to 100. This made the two key project participants' performance targets [*client project cost at completion target (U) and engineering consultant project revenue at completion target (V)]* also equal (or close) to the initially planned project contract ceiling price.

Table 6.48: Optimised project participants performance targets per project (asset renewal-related)

Project number	Initially planned		Client project cost performance target		Engineering consultant project revenue performance target	
	Project time schedule duration (months)	Project contract ceiling price (Z) (R million)	Client project cost variance % at completion target (a) (%)	Client project cost at completion target (U) (R million)	Engineering consultant project contract ceiling price % target (b) (%)	Engineering consultant project revenue at completion target (V) (R million)
P10	10.00	6.521	2.1	6.382	97.9	6.382
P11	5.00	2.857	0.0	2.857	100.0	2.857
P12	4.00	2.535	0.0	2.535	100.0	2.535
P13	6.00	4.327	0.1	4.324	99.9	4.324
P14	10.00	7.592	0.0	7.591	100.0	7.591
P15	6.00	3.312	0.0	3.311	100.0	3.311
P16	8.00	6.670	0.0	6.670	100.0	6.670
P17	5.00	2.632	0.0	2.632	100.0	2.632

Table 6.49 shows the initially planned project time schedule duration and project cost, as well as the corresponding simulated outputs for the two model simulation runs '*Without competition'* and '*With improved competition'* for the 8 asset renewal-related projects. There is a visible general improvement in the project performance (particularly in terms of project time schedule duration) from the '*With competition'* simulation (Table 6.26 in Section 6.6.3) to the *'With improved competition'* simulation shown in Table 6.49 for all the 8 projects considered.

Table 6.49: Planned project time duration and cost, and corresponding simulated outputs without and with improved competition (asset renewal-related projects)

Project number	Planned		Without competition (simulation run: TC_WI+UE)		With improved competition (simulation run: TC_WI+UE+CC_RMIap+UE +RC_EASVM+UE*)	
	Project time schedule duration (months)	Project cost (R million)	Project time schedule duration (months)	Project cost (R million)	Project time schedule duration (months)	Project cost (R million)
P10	10.00	6.521	10.53	6.867	10.41	6.572
P11	5.00	2.857	5.41	3.089	5.28	2.946
P12	4.00	2.535	4.72	2.991	4.53	2.821
P13	6.00	4.327	6.59	4.755	6.50	4.500
P14	10.00	7.592	10.69	8.113	10.66	7.884
P15	6.00	3.312	6.63	3.657	6.59	3.475
P16	8.00	6.670	7.53	6.279	7.53	6.120
P17	5.00	2.632	5.28	2.780	5.19	2.629

Table 6.50 shows, for each of the 8 asset renewal-related projects, the SPI and CPI ('*Without competition'* and '*With improved competition'*) and the resulting impact ratios (of the improved competition between the client and the engineering consultant during project execution) on project time schedule performance and on project cost performance. There is a marked improvement in the impact ratios on both project time schedule performance and project cost performance from those based on the '*With competition'* simulation (Table 6.27 in Section 6.6.3) to those based on the *'With improved competition'* simulation. For instance, for Project P10: the impact ratio on project time schedule performance improved from 1.35 (or 35% time schedule delay) to 0.99 (or 1% ahead of time schedule); whilst the impact ratio on project cost performance improved from 1.07 (or 7% project cost overrun) to 0.96 (or 4% project cost saving).

Such improvement was made possible by making sure that in the *'With improved competition'* simulation (during policy optimisation) Equation 6.6 was satisfied, which implied that the performance targets of the two key project participants were fully aligned [i.e., *client project cost at completion target (U) = engineering consultant project revenue at completion target (V)*], and also by the optimised *client project cost variance % at completion target (a)* and *engineering consultant project contract ceiling price % target (b)*.

Table 6.50: SPI and CPI (without and with improved competition), and competition impact ratios per project (asset renewal-related)

Project number	Project time schedule performance			Project cost performance		
	Schedule performance index (SPI)		Impact ratio	Cost performance index (CPI)		Impact ratio
	Without competition (simulation run: TC_WI+UE)	With improved competition (simulation run: TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE*)		Without competition (simulation run: TC_WI+UE)	With improved competition (simulation run: TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE*)	
P10	0.95	0.96	0.99	0.95	0.99	0.96
P11	0.92	0.95	0.98	0.92	0.97	0.95
P12	0.85	0.88	0.96	0.85	0.90	0.94
P13	0.91	0.92	0.99	0.91	0.96	0.95
P14	0.94	0.94	1.00	0.94	0.96	0.97
P15	0.91	0.91	1.00	0.91	0.95	0.95
P16	1.06	1.06	1.00	1.06	1.09	0.97
P17	0.95	0.96	0.98	0.95	1.00	0.95

Table 6.51 shows the overall descriptive statistics for the SPI and CPI ('*Without competition*' and '*With improved competition*') and the associated impact ratios (of the improved competition between the client and the engineering consultant during project execution) on both project time schedule performance and project cost performance for the 8 asset renewal-related projects. There is a marked improvement from the values based on the '*With competition*' simulation (Table 6.28 in Section 6.6.3) to those based on the *'With improved competition'* simulation. For instance, the mean impact ratio on project time schedule performance improved from 1.22 (or 22% time schedule delay) to 0.99 (or 1% ahead of time schedule); whilst the mean impact ratio on project cost performance improved from 1.03 (or 3% project cost overrun) to 0.96 (or 4% project cost saving). Thus, on average, the improved competition between the client and engineering consultant did minimise the negative impact on project performance.

Table 6.51: Descriptive statistics for SPI and CPI (without and with improved competition), and competition impact ratios (asset renewal-related projects)

Statistic	Project time schedule performance			Project cost performance		
	Schedule performance index (SPI)		Impact ratio	Cost performance index (CPI)		Impact ratio
	Without competition (simulation run: TC_WI+UE)	With improved competition (simulation run: TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE*)		Without competition (simulation run: TC_WI+UE)	With improved competition (simulation run: TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE*)	
Median	0.93	0.94	0.99	0.93	0.97	0.95
Mean	0.94	0.95	0.99	0.94	0.98	0.96
Standard Deviation	0.06	0.05	0.01	0.06	0.05	0.01
Minimum	0.85	0.88	0.96	0.85	0.90	0.94
Maximum	1.06	1.06	1.00	1.06	1.09	0.97

The next sub-section presents the key results of the policy optimisation (competition improvement) with regards to the minimisation of the competition's negative impact on the engineering consultant's project business performance.

6.8.3 Minimisation of the Negative Impact of Competition on the Engineering Consultant's Business Performance

Infrastructure Asset Management Planning and Support-Related Projects

Table 6.15 (Section 6.6.1) shows the original engineering consultant project revenue at completion targets for the first set of unique raw water infrastructure projects (10 asset management planning and support-related projects) as used in Sections 6.6 and 6.7. Table 6.44 (Section 6.8.2) shows the optimised engineering consultant project revenue at completion targets for the same set of projects.

As discussed in Chapters 4 and 5, in this research study: only time-based contracts with a ceiling price (Turner, 2004) between the client and the engineering consultant were considered; and only the time-based costs for the engineering consultant services were considered for project cost. Hence, in this study, the project revenue realised by the engineering consultant at project completion was assumed to be equal to the project cost incurred by the client at completion of the same project.

Table 6.52 shows the initially planned project time schedule duration and engineering consultant project revenue, as well as the corresponding simulated outputs for the two model simulation runs '*Without competition'* and '*With improved competition'* for the 10 asset management planning and support-related projects. There is a visible general decrease in both the project time schedule duration (improvement) and the engineering consultant project revenue (worsening) from the

'*With competition'* simulation (Table 6.34 in Section 6.7.1) to the *'With improved competition'* simulation shown in Table 6.52 for all the considered 10 projects.

Table 6.52: Planned project time duration and engineering consultant's project revenue, and corresponding simulated outputs without and with improved competition (asset management planning and support-related projects)

Project number	Planned		Without competition (simulation run: TC_WI+UE)		With improved competition (simulation run: TC_WI+UE+CC_RMIap+UE +RC_EASVM+UE*)	
	Project time schedule duration (months)	Engineering consultant project revenue (R million)	Project time schedule duration (months)	Engineering consultant project revenue (R million)	Project time schedule duration (months)	Engineering consultant project revenue (R million)
P0	12	13.473	12.50	14.400	11.59	13.100
P1	12	15.022	12.09	15.140	12.09	15.140
P2	24	42.937	25.09	44.890	25.03	44.780
P3	9	5.752	9.78	6.251	9.72	6.097
P4	6	3.840	6.22	3.980	6.41	3.673
P5	9	5.992	8.84	5.888	10.34	6.208
P6	26	21.278	27.34	22.380	27.22	22.130
P7	7	3.817	5.88	3.203	7.16	3.496
P8	12	12.170	12.12	12.300	11.66	11.540
P9	12	10.590	12.09	10.670	11.78	10.310

Table 6.53 shows, for each of the 10 asset management planning and support-related projects, the SPI (same as that in Section 6.8.2) and RPI ('*Without competition'* and '*With improved competition'*) and the resulting impact ratios (of the improved competition between the client and the engineering consultant during project execution) on the engineering consultant's project time schedule performance and project revenue performance. There was a marked improvement in the impact ratios on project time schedule performance from those based on the '*With competition'* simulation (Table 6.35 in Section 6.7.1) to those based on the *'With improved competition'* simulation shown in Table 6.53. For instance, for Project P0, the impact ratio on project time schedule performance improved from 1.29 (or 29% time schedule delay) to 0.93 (or 7% ahead of time schedule).

There was, however, a general worsening of the impact ratios on the engineering consultant project revenue performance from those based on the '*With competition'* simulation (Table 6.35 in Section 6.7.1) to those based on the *'With improved competition'* simulation shown in Table 6.53. For instance, for Project P0, the impact ratio on the engineering consultant project revenue performance worsened from 1.10 (or 10% project revenue increase) to 0.91 (or 9% project revenue shortfall).

Table 6.53: SPI and RPI (without and with improved competition), and competition impact ratios per project (asset management planning and support-related)

Project number	Engineering consultant project time schedule performance			Engineering consultant project revenue performance		
	Schedule performance index (SPI)		Impact ratio	Revenue performance index (RPI)		Impact ratio
	Without competition (simulation run: TC_WI+UE)	With improved competition (simulation run: TC_WI+UE+CC_RMlap+UE+RC_EASVM+UE*)		Without competition (simulation run: TC_WI+UE)	With improved competition (simulation run: TC_WI+UE+CC_RMlap+UE+RC_EASVM+UE*)	
P0	0.96	1.04	0.93	0.94	1.03	0.91
P1	0.99	0.99	1.00	0.99	0.99	1.00
P2	0.96	0.96	1.00	0.96	0.96	1.00
P3	0.92	0.93	0.99	0.92	0.94	0.98
P4	0.96	0.94	1.03	0.96	1.05	0.92
P5	1.02	0.87	1.17	1.02	0.97	1.05
P6	0.95	0.96	1.00	0.95	0.96	0.99
P7	1.19	0.98	1.22	1.19	1.09	1.09
P8	0.99	1.03	0.96	0.99	1.05	0.94
P9	0.99	1.02	0.97	0.99	1.03	0.97

Table 6.54 shows the overall descriptive statistics for the SPI and RPI (‘*Without competition*’ and ‘*With improved competition*’) and the associated impact ratios (of the improved competition between the client and the engineering consultant during project execution) on engineering consultant’s project time schedule performance and project revenue performance for the 10 asset management planning and support-related projects. There was a marked improvement in the impact ratios on the project time schedule performance from the ‘*With competition’* simulation (Table 6.36 in Section 6.7.1) to the *‘With improved competition’* simulation. For instance, the mean impact ratio on project time schedule performance improved from 1.28 (or 28% time schedule delay) to 1.03 (or 3% time schedule delay).

There was, however, a worsening of the impact ratios on the engineering consultant project revenue performance from those based on the ‘*With competition’* simulation to those based on the *‘With improved competition’*. For instance, the mean impact ratio on the engineering consultant project revenue performance worsened from 1.07 (or 7% project revenue increase) to 0.98 (or 2% project revenue shortfall). Nonetheless, the 9% average decrease in the engineering consultant project revenue was much lower than the 25% average decrease in the project time schedule duration. As such, since only time-based contracts were considered, the engineering consultant actually gained. Hence, on average, the improved competition between the client and the engineering consultant did minimise the negative impact on the engineering consultant’s project business performance.

Such improvement was made possible by making sure that in the *'With improved competition'* simulation (during the policy optimisation) Equation 6.6 was satisfied, which implied that the performance targets of the two key project participants were fully aligned [i.e., *client project cost at completion target (U) = engineering consultant project revenue at completion target (V)*], and also by the optimised values of the *client project cost variance % at completion target (a)* and the *engineering consultant project contract ceiling price % target* (*b*).

Table 6.54: Descriptive statistics for SPI and RPI (without and with improved competition) and competition impact ratios (asset management planning and support-related projects)

Statistic	Engineering consultant project time schedule performance			Engineering consultant project revenue performance		
	Schedule performance index (SPI)		Impact ratio	Revenue performance index (RPI)		Impact ratio
	Without competition (simulation run: TC_WI+UE)	With improved competition (simulation run: TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE*)		Without competition (simulation run: TC_WI+UE)	With improved competition (simulation run: TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE*)	
Median	0.98	0.97	1.00	0.98	1.01	0.98
Mean	0.99	0.97	1.03	0.99	1.01	0.98
Standard Deviation	0.07	0.05	0.09	0.08	0.05	0.06
Minimum	0.92	0.87	0.93	0.92	0.94	0.91
Maximum	1.19	1.04	1.22	1.19	1.09	1.09

The next sub-section presents the key results of the policy optimisation (competition improvement) with regards to the minimisation of the competition's negative impact on the engineering consultant's project business performance, using data gathered for the second set of unique raw water infrastructure projects and the associated calibrated system dynamics simulation model discussed in Section 6.5. As indicated at the beginning of this Section 6.8, comparison of the results from the two sets of unique raw water infrastructure projects considered in this study was aimed at enhancing the validity of the associated overall key research result (Section 6.8.4), i.e., the provisional answer for research question number 5 (posed in Section 1.6).

Infrastructure Asset Renewal-Related Projects

Table 6.23 (Section 6.6.3) shows the original engineering consultant project revenue at completion targets for the second set of raw water infrastructure projects (8 asset renewal-related projects) used in Sections 6.6 and 6.7. Table 6.48 (Section 6.8.2) shows the optimised engineering consultant project revenue at completion targets (calculated from the optimised *engineering consultant project contract ceiling price % target* (*b*) values) for the same set of projects.

Table 6.55 shows the initially planned project time schedule duration and engineering consultant project revenue, as well as the corresponding simulated outputs for the two model simulation runs '*Without competition'* and '*With improved competition'* for the 8 asset renewal-related projects. There is a visible general decrease in both the project time schedule duration (improvement) and the engineering consultant project revenue (worsening) from the '*With competition'* simulation (Table 6.39 in Section 6.7.3) to the *'With improved competition'* simulation shown in Table 6.55 for all the 8 projects considered.

Table 6.55: Planned project time duration and engineering consultant's project revenue, and corresponding simulated outputs without and with improved competition (asset renewal-related projects)

Project number	Planned		Without competition (simulation run: TC_WI+UE)		With improved competition (simulation run: TC_WI+UE+CC_RMIap+UE +RC_EASVM+UE*)	
	Project time schedule duration (months)	Engineering consultant project revenue (R million)	Project time schedule duration (months)	Engineering consultant project revenue (R million)	Project time schedule duration (months)	Engineering consultant project revenue (R million)
P10	10.00	6.521	10.53	6.867	10.41	6.572
P11	5.00	2.857	5.41	3.089	5.28	2.946
P12	4.00	2.535	4.72	2.991	4.53	2.821
P13	6.00	4.327	6.59	4.755	6.50	4.500
P14	10.00	7.592	10.69	8.113	10.66	7.884
P15	6.00	3.312	6.63	3.657	6.59	3.475
P16	8.00	6.670	7.53	6.279	7.53	6.120
P17	5.00	2.632	5.28	2.780	5.19	2.629

Table 6.56 shows, for each of the 8 asset renewal-related projects, the SPI (same as that in Section 6.8.2) and RPI ('*Without competition'* and '*With improved competition'*) and the resulting impact ratios (of the improved competition between the client and the engineering consultant during project execution) on the engineering consultant's project time schedule performance and project revenue performance. There was a marked improvement in the impact ratios on project time schedule performance from those based on the '*With competition'* simulation (Table 6.40 in Section 6.7.3) to those based on the *'With improved competition'* simulation. For instance, for Project P10, the impact ratio on project time schedule performance improved from 1.35 (35% time schedule delay) to 0.99 (1% ahead of time schedule).

There was, however, a general worsening of the impact ratios on the engineering consultant project revenue performance from those based on the '*With competition'* simulation to those based on the *'With improved competition'* simulation. For instance, for Project P10, the impact ratio on the engineering consultant project revenue performance worsened from 1.07 (or 7% project revenue increase) to 0.96 (or 4% project revenue shortfall).

Table 6.56: SPI and RPI (without and with improved competition) and competition impact ratios per project (asset renewal-related)

Project number	Engineering consultant project time schedule performance			Engineering consultant project revenue performance		
	Schedule performance index (SPI)		Impact ratio	Revenue performance index (RPI)		Impact ratio
	Without competition (simulation run: TC_WI+UE)	With improved competition (simulation run: TC_WI+UE+CC_RMlap+UE+RC_EASVM+UE*)		Without competition (simulation run: TC_WI+UE)	With improved competition (simulation run: TC_WI+UE+CC_RMlap+UE+RC_EASVM+UE*)	
P10	0.95	0.96	0.99	0.95	0.99	0.96
P11	0.92	0.95	0.98	0.92	0.97	0.95
P12	0.85	0.88	0.96	0.85	0.90	0.94
P13	0.91	0.92	0.99	0.91	0.96	0.95
P14	0.94	0.94	1.00	0.94	0.96	0.97
P15	0.91	0.91	1.00	0.91	0.95	0.95
P16	1.06	1.06	1.00	1.06	1.09	0.97
P17	0.95	0.96	0.98	0.95	1.00	0.95

Table 6.57 shows the overall descriptive statistics for the SPI and RPI ('*Without competition'* and '*With improved competition'*) and the associated impact ratios (of the improved competition between the client and the engineering consultant during project execution) on engineering consultant's project time schedule performance and project revenue performance for the 8 asset renewal-related projects. There was a marked improvement in the impact ratios on the project time schedule performance from the '*With competition'* simulation (Table 6.41 in Section 6.7.3) to those based on the *'With improved competition'* simulation. For instance, the mean impact ratio on project time schedule performance improved from 1.22 (or 22% time schedule delay) to 0.99 (or 1% ahead of time schedule).

There was, however, a worsening of the impact ratios on the engineering consultant project revenue performance from those based on the '*With competition'* simulation to those based on the *'With improved competition'* simulation. For instance, the mean impact ratio on the engineering consultant project revenue performance worsened from 1.03 (or 3% project revenue increase) to 0.96 (or 4% project revenue shortfall). Nonetheless, the 7% average decrease in the engineering consultant project revenue was much lower than the 23% average decrease in the project time schedule duration. As such, since only time-based contracts were considered, the engineering consultant actually gained. Hence, on average, the improved competition between the client and the engineering consultant did minimise the negative impact on the engineering consultant's project business performance.

Such improvement was made possible by making sure that in the *'With improved competition'* simulation (during the policy optimisation) Equation 6.6 was satisfied, which implied that the performance targets of the two key project participants were fully aligned [i.e., *client project cost at completion target (U) = engineering consultant project revenue at completion target (V)*], and also by the optimised values of the *client project cost variance % at completion target* (*a*) and the *engineering consultant project contract ceiling price % target* (*b*).

Table 6.57: Descriptive statistics for SPI and RPI (without and with improved competition), and competition impact ratios (asset renewal-related projects)

Statistic	Engineering consultant project time schedule performance			Engineering consultant project revenue performance		
	Schedule performance index (SPI)		Impact ratio	Revenue performance index (RPI)		Impact ratio
	Without competition (simulation run: TC_WI+UE)	With improved competition (simulation run: TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE*)		Without competition (simulation run: TC_WI+UE)	With improved competition (simulation run: TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE*)	
Median	0.93	0.94	0.99	0.93	0.97	0.95
Mean	0.94	0.95	0.99	0.94	0.98	0.96
Standard Deviation	0.06	0.05	0.01	0.06	0.05	0.01
Minimum	0.85	0.88	0.96	0.85	0.90	0.94
Maximum	1.06	1.06	1.00	1.06	1.09	0.97

The next sub-section is the third stage of the policy optimisation (competition improvement), i.e., comparison of the key results from the preceding two stages (Sections 6.8.2 and 6.8.3), providing a provisional answer to research question number 5 (posed in Section 1.6).

6.8.4 Comparisons and Discussions

Sections 6.6 and 6.7 analysed the impacts of the competition (i.e. combined impact of the competing client project cost controls and their unintended effects, and engineering consultant project revenue controls and their unintended effects) on the project performance and on the engineering consultant's project business performance, respectively. The analyses made use of data gathered for two sets of unique raw water infrastructure projects (10 asset management planning and support-related projects, and 8 asset renewal-related) and the calibrated system dynamics simulation models discussed in Sections 6.4 and 6.5.

One of the key findings from the impact analyses conducted in Sections 6.6 and 6.7 was that, in the long-term, the competition between the two key project participants (the client and engineering consultant) negatively influenced both the project performance (increased both 'project time schedule delay' and 'project cost overrun'), which is of client's interest, and the engineering consultant's project business performance (increasing both 'project time schedule delay' and 'project revenue shortfall'). Put differently, the competition yielded lose-lose long-term results for the two key project participants.

The purpose of Section 6.8 was, thus to formulate appropriate intervention strategies that help improve the competition (policy optimisation), i.e., minimise its negative impacts on both the project performance (as measured by project time schedule duration and project cost) and engineering consultant's business performance (as measured by project time schedule duration and project revenue), yielding win-win long-term results for the two key project participants.

The policy optimisation aimed at improving the competition between the two key project participants was conducted in three stages, as described in Section 6.8.1. In the *first stage* (Sections 6.8.2 and 6.8.3), data gathered for the first set of unique raw water infrastructure projects (10 asset management planning and support-related) and the associated calibrated system dynamics simulation model discussed in Section 6.4 were used to conduct a policy optimisation experiment, yielding optimised performance targets and an associated model simulation run (*With improved competition*). Subsequently, the impacts of the improved competition on both the project performance and the engineering consultant's project business performance were assessed. Comparisons were made between the impact of the original competition (determined in Sections 6.6 and 6.7) and that of the improved competition, per project and on average, with appropriate conclusions drawn as to whether or not the improved competition did minimise the negative impacts on both project performance and engineering consultant's project business performance.

In the *second stage* (also Sections 6.8.2 and 6.8.3), the policy optimisation experiment and impact analyses conducted in the preceding stage were repeated, but using data gathered for the second set of unique raw water infrastructure projects (8 asset renewal-related) and the associated calibrated system dynamics simulation model discussed in Section 6.5.

In the *third stage* (this Section 6.8.4), a comparison of the key results (impacts of the improved competition on both project performance and the engineering consultant's project business performance for the two sets of unique projects considered) from the preceding two stages is made, and an appropriate provisional answer to research question number 5 (posed in Section 1.6) is provided.

The above-summarised three-stage policy optimisation (competition improvement), where the policy optimisation experiment and associated impact analyses were conducted separately for each of the two sets of unique raw water infrastructure projects considered, with subsequent comparison of results from the two sets, assisted in enhancing the validity of the associated overall key research result (presented later in this Section 6.8.4), namely the provisional answer for research question number 5 (posed in Section 1.6). It is a novel contribution towards the enhancement of the existing system dynamics simulation model validation, in particular policy optimisation and impact analyses, processes and procedures, and is, thus expected to benefit future system dynamics research studies.

The next sub-section compares the optimised performance targets for the two key project participants (the client and the engineering consultant) for the two sets of projects presented in Sections 6.8.2.

Optimised Performance Targets

Table 6.15 (Section 6.6.1) and Table 6.23 (Section 6.6.3) show the original client project cost at completion targets and engineering consultant project revenue at completion targets for the two sets of unique raw water infrastructure projects (10 asset management planning and support-related projects, and 8 asset renewal-related projects, respectively) used in Sections 6.6 and 6.7. Tables 6.44 and 6.48 (Section 6.8.2) show the respective optimised client project cost at completion targets (calculated from the optimised *client project cost variance % at completion target (a)* values) and engineering consultant project revenue at completion targets (calculated from the optimised *engineering consultant project contract ceiling price % target* (*b*) values) for the same two sets of projects.

As discussed in Chapters 4 and 5, in this research study: only time-based contracts with a ceiling price (Turner, 2004) between the client and the engineering consultant were considered; and only the time-based costs for the engineering consultant services were considered for project cost. Hence, in this study, the project revenue realised by the engineering consultant at project completion was assumed to be equal to the project cost incurred by the client at completion of the same project.

Evident in Tables 6.44 and 6.48 is that, for each project, the optimised performance targets of the two key project participants were fully aligned [i.e., the optimised *client project cost at completion target (U)* was equal to the optimised *engineering consultant project revenue at completion target (V)*] as a result of satisfying Equation 6.6 (*a* + *b* = *100*). Also, for most of the projects (8 asset management planning and support-related, and 7 asset renewal-related), optimised values for the *client project cost variance % at completion target (a*) parameter were equal (or close) to zero, whilst those for the *engineering consultant project contract ceiling price % target* (*b*) variable were equal (or close) to 100. As a result, the two key project participants' optimised performance targets [optimised *client project cost at completion target (U)* and optimised *engineering consultant project revenue at completion target (V)]* were equal (or close) to the initially planned project contract ceiling price.

In the current research study, only time-based contracts with a ceiling price (Turner, 2004) between the client and the engineering consultant were considered. The preceding key research findings suggest that more optimal performance (to the benefit of both key project participants) is achieved when the contract price is fixed, rather than having a ceiling price, and when the performance targets [*client project cost at completion target (U)* and optimised *engineering consultant project revenue at completion target (V)*] are equal to the fixed contract price. This sounds reasonable considering that one of the challenges with time-based contracts with a ceiling price is determining the appropriate ceiling price. As a result, the individual parties to the contract (the two key project participants considered) may have different views regarding the accuracy of the ceiling price, leading them to setting up their own individual performance targets (*a* and *b*) that may not satisfy Equation 6.6. The resulting misaligned performance targets would then lead to competition between the client and the engineering consultant, which competition negatively influences both the project performance and the engineering consultant's business performance, as found in Sections 6.6 and 6.7. Thus, the values of *a* and *b* are essentially influenced by the ceiling price because if the contract price was fixed, then *a* would be equal to zero and *b* equal to 100, as the preceding finding suggests.

The next sub-section compares the impacts of the improved competition on project performance (Section 6.8.2) between the two sets of unique projects considered.

Minimising the Impact of the Competition on Project Performance

Tables 6.29 and 6.30 (Section 6.6.5) show the number of projects that were negatively, positively and not influenced (in terms of project time schedule performance and project cost performance, respectively) by the original competition (based on the '*With competition'* simulation run) between the client and the engineering consultant for the two sets of unique raw water infrastructure projects

(10 asset management planning and support-related projects, and 8 asset renewal-related projects) considered. Tables 6.58 and 6.59 (refer to Tables 6.46 and 6.50 in Section 6.8.2 for more details) show the number of projects that were negatively, positively and not influenced (in terms of project time schedule performance and project cost performance, respectively) by the improved competition (based on the *'With improved competition'* simulation run) for the same two sets of projects.

The improved competition negatively influenced (impact ratio greater than 1) the project time schedule performance of: only 3 (out of 10) of the asset management planning and support-related projects; and none of the 8 asset renewal-related projects considered, as shown in Table 6.58. This was a marked improvement from the case before the policy optimisation, where the original competition negatively influenced the project time schedule performance of: most (9/10) of the asset management planning and support-related projects; and all of the 8 asset renewal-related projects considered in this research study, as shown in Table 6.29.

The improved competition negatively influenced (impact ratio greater than 1) the project cost performance of: only 2 (out of 10) of the asset management planning and support-related projects; and none of the 8 asset renewal-related projects considered, as shown in Table 6.59. This is also a marked improvement from the case before the policy optimisation, where the original competition negatively influenced the project cost performance of: most (8/10) of the asset management planning and support-related projects; and half (4/8) of the asset renewal-related projects considered, as shown in Table 6.30.

Table 6.58: Impact of improved competition on project time schedule performance per project set

Impact of competition	Number of projects influenced		
	Asset management planning and support-related projects	Asset renewal-related projects	Total
Negative (impact ratio > 1)	3	-	**3**
Positive (impact ratio < 1)	4	5	**9**
None (impact ratio = 1)	3	3	**6**
Total	**10**	**8**	**18**

Table 6.59: Impact of improved competition on project cost performance per project set

Impact of competition	Number of projects influenced		
	Asset management planning and support-related projects	Asset renewal-related projects	Total
Negative (impact ratio > 1)	2	-	**2**
Positive (impact ratio < 1)	6	8	**14**
None (impact ratio = 1)	2	-	**2**
Total	**10**	**8**	**18**

Table 6.31 (Section 6.6.5) shows the descriptive statistics for the impact ratios on project time schedule performance and on project cost performance of the original competition (based on the '*With competition'* simulation run) for the two sets of unique projects. Table 6.60 (refer to Tables 6.47 and 6.51 in Section 6.8.2 for more details) shows the descriptive statistics for the impact ratios on project time schedule performance and on project cost performance of the improved competition (based on the *'With improved competition'* simulation run) for the same two sets of projects.

There was a marked improvement in descriptive statistics for the impact ratios on both project time schedule performance and on project cost performance from those due to the original competition (Table 6.31) to those due to the improved competition (Table 6.60) for both sets of projects. For instance, for asset management planning and support-related projects: the mean impact ratio on project time schedule performance improved from 1.28 (28% time schedule delay) to 1.03 (3% time schedule delay); whilst the mean impact ratio on project cost performance improved from 1.07 (7% project cost overrun) to 0.98 (2% project cost saving).

In the improved/optimised competition case, the mean impact ratios on both the project time schedule performance and on the project cost performance were close to 1 for both project sets considered, as shown in Table 6.60. This means that, on average, the improved/optimised competition (compared to the original competition case in Section 6.6.5) minimised the negative impact on project performance for both sets of projects considered. Such improvement was made possible by making sure that in the improved/optimised competition: Equation 6.6 was satisfied, which implied that the performance targets of the two key project participants were fully aligned [i.e., *client project cost at completion target (U)* = *engineering consultant project revenue at completion target (V)*]; and that the values of the *client project cost variance % at completion target (a)* and the *engineering consultant project contract ceiling price % target* (*b*) were optimised for all the projects considered.

Table 6.60: Descriptive statistics for improved competition impact ratios on project performance per project set

Statistic	Impact ratio on project time schedule performance		Impact ratio on project cost performance	
	Asset management planning and support-related projects	Asset renewal-related projects	Asset management planning and support-related projects	Asset renewal-related projects
Median	1.00	0.99	0.98	0.95
Mean	1.03	0.99	0.98	0.96
Standard Deviation	0.09	0.01	0.06	0.01
Minimum	0.93	0.96	0.91	0.94
Maximum	1.22	1.00	1.09	0.97

The next sub-section compares the impacts of the improved competition (Section 6.8.3) on the engineering consultant's project business performance between the two sets of unique projects considered.

Minimising the Impact of Competition on the Engineering Consultant's Business Performance

Table 6.29 (Section 6.6.5) and Table 6.42 (Section 6.7.5) show the number of projects that were negatively, positively and not influenced (in terms of project time schedule performance and engineering consultant project revenue performance, respectively) by the original competition (based on the '*With competition'* simulation run) between the client and the engineering consultant for the two sets of unique raw water infrastructure projects (10 asset management planning and support-related projects, and 8 asset renewal-related projects) considered. Table 6.58 and Table 6.61 (refer to Tables 6.53 and 6.56 in Section 6.8.3 for more details) show the number of projects that were negatively, positively and not influenced (also in terms of project time schedule performance and engineering consultant project revenue performance, respectively) by the improved competition (based on the *'With improved competition'* simulation run) for the same two sets of projects.

The improved competition positively influenced (impact ratio greater than 1) the project revenue performance of: only 2 (out of 10) of the asset management planning and support-related projects; and none of the 8 asset renewal-related projects considered, as shown in Table 6.61. This is a marked deterioration from the case before the policy optimisation, where the original competition positively influenced the project revenue performance of: most (8/10) of the asset management planning and support-related projects; and half (4/8) of the asset renewal-related projects considered, as shown in Table 6.42 (Section 6.7.5).

Table 6.61: Impact of improved competition on engineering consultant project revenue performance per project set

Impact of competition	Number of projects influenced		
	Asset management planning and support-related projects	Asset renewal-related projects	Total
Positive (impact ratio > 1)	2	-	**2**
Negative (impact ratio < 1)	6	8	**14**
None (impact ratio = 1)	2	-	**2**
Total	**10**	**8**	**18**

Table 6.43 (Section 6.7.5) shows the descriptive statistics for the impact ratios on project time schedule performance and on the engineering consultant's project revenue performance of the original competition (based on the '*With competition'*

simulation run) for the two sets of unique projects. Table 6.62 (refer to Tables 6.54 and 6.57 in Section 6.8.3 for more details) shows the descriptive statistics for the impact ratios on project time schedule performance and on the engineering consultant's project revenue performance of the improved competition (based on the *'With improved competition'* simulation run) for the same two sets of projects.

There was a marked improvement in the descriptive statistics for the impact ratios on project time schedule performance from those due to the original competition (Table 6.43) to those due to the improved competition (Table 6.62). For instance, for the asset management planning and support-related projects, the mean impact ratio on project time schedule performance improved from 1.28 (or 28% time schedule delay) to 1.03 (or 3% time schedule delay).

There was, however, a deterioration in the descriptive statistics for the impact ratios on the engineering consultant's project revenue performance from those based on the original competition (Table 6.43) to those based on the improved competition (Table 6.62). For instance, for the asset management planning and support-related projects, the mean impact ratio on the engineering consultant's project revenue performance deteriorated from 1.07 (or 7% project revenue increase) to 0.98 (or 2% project revenue shortfall). Nonetheless, the 9% average decrease in the engineering consultant's project revenue was much lower than the 25% average decrease in the project time schedule duration. As such, since only time-based contracts were considered, the engineering consultant actually gained. Hence, on average, the improved competition between the client and the engineering consultant did minimise the negative impact on the engineering consultant's project business performance.

In the improved/optimised competition case, the mean values for the impact ratios on both the project time schedule performance and on the engineering consultant's project revenue performance were close to 1 for both sets of projects considered, as shown in Table 6.62. This means that, on average, the improved/optimised competition (compared to the original competition case in Section 6.7.5) minimised the negative impact on the engineering consultant's project business performance for both sets of projects considered. Such improvement was made possible by making sure that in the improved/optimised competition: Equation 6.6 was satisfied, which implied that the performance targets of the two key project participants were fully aligned [i.e., *client project cost at completion target (U) = engineering consultant project revenue at completion target (V)*]; and that the values of the *client project cost variance % at completion target* (*a*) and the *engineering consultant project contract ceiling price % target* (*b*) were optimised for all the projects considered.

Table 6.62: Descriptive statistics for improved competition impact ratios on engineering consultant's project business performance per project set

Statistic	Impact ratio on project time schedule performance		Impact ratio on project revenue performance	
	Asset management planning and support-related projects	Asset renewal-related projects	Asset management planning and support-related projects	Asset renewal-related projects
Median	1.00	0.99	0.98	0.95
Mean	1.03	0.99	0.98	0.96
Standard Deviation	0.09	0.01	0.06	0.01
Minimum	0.93	0.96	0.91	0.94
Maximum	1.22	1.00	1.09	0.97

The next sub-section discusses the key research results presented so far in this Section 6.8.4, and formulates an appropriate provisional answer to research question number 5 (posed in Section 1.6), i.e., appropriate intervention strategies that help improve the competition, yielding win-win long-term results for the two key project participants.

Competition Improvement to Yield 'Win-Win' Long-term Results (Recommended Intervention Strategies)

The findings summarised in Sections 6.6.5 and 6.7.5 indicated that the competition between the client and the engineering consultant during project execution negatively influenced both the project performance (client's interest) and the engineering consultant's business performance, yielding lose-lose long-term results. That is, the simulated performance outputs were better without competition than with competition. Hence, the competition improvement (policy optimisation) discussed in this Section 6.8 focussed on minimising its negative impacts on both the project performance (as measured by project time schedule duration and project cost) and engineering consultant's business performance (as measured by project time schedule duration and project revenue), in the particular case of time-based contracts with a ceiling price (Turner, 2004) between the client and the engineering consultant. It entailed minimising both: the client project cost controls and their associated unintended effects); and the engineering consultant project revenue controls and their associated unintended effects.

Results presented so far in this Section 6.8 suggested that, it is indeed possible to improve the competition, yielding win-win long-term results for the two key project participants. Firstly, an analysis of the system dynamics conceptual model of the competing client project cost controls and engineering consultant project revenue controls formulated in Chapter 4 (Figure 4.31 and Table 4.11), conducted in Section

6.8.1, indicated that to eliminate both the client project cost controls (and their associated unintended effects) and the engineering consultant project revenue controls (and their associated unintended effects) requires first satisfying Equation 6.6 [$a + b = 100$, where a is the *project cost variance % at completion target* and b is the *engineering consultant project contract ceiling price % target*], which results in the performance targets of the two key project participants being fully aligned (i.e., the *client project cost at completion target* being equal to the *engineering consultant project revenue at completion target*). This finding is in line with Turner (2004) who made the point that contracts need to be designed to promote cooperation between the parties involved, by essentially aligning the objectives of the engineering consultant with those of the client.

Secondly, for both sets of unique projects considered, the optimised values for the *client project cost variance % at completion target (a)* parameter were equal (or close) to zero, whilst those for the *engineering consultant project contract ceiling price % target* (b) variable were equal (or close) to 100, satisfying Equation 6.6 ($a + b = 100$). As a result, the two key project participants' optimised performance targets [optimised *client project cost at completion target (U)* and optimised *engineering consultant project revenue at completion target (V)]* were equal (or close) to the initially planned project contract ceiling price. This suggested that more optimal performance (to the benefit of both key project participants) is achieved when the contract price is fixed than with a ceiling price, and when the performance targets [*client project cost at completion target (U)* and *engineering consultant project revenue at completion target (V)*] are equal to the fixed contract price.

Indeed, one of the challenges encountered with time-based contracts with a ceiling price is determining the appropriate ceiling price. As a result, the individual parties to the contract (the two key project participants considered) may have different views regarding the accuracy of the ceiling price, leading them to setting up their own individual performance targets (a and b) that may not satisfy Equation 6.6. The resulting misaligned (conflicting) performance targets would then lead to competition between the client and the engineering consultant, which competition negatively influences both the project performance and the engineering consultant's business performance, as found in Sections 6.6 and 6.7. Thus, the values of a and b are essentially influenced by the contract ceiling price because if the contract price was fixed, then a would be equal to zero and b equal to 100, as the above-mentioned research finding suggests.

Changing the total project contract price from a ceiling price to a fixed price is effectively changing the type of the contract from a time-based contract to a fixed-price contract. This is not just a simple exercise considering that the two types of contract are usually appropriate for different circumstances. A time-based contract is more appropriate for more complex projects where the total project scope and associated total project cost are not fully known at contract award, whereas a fixed-price contract is more appropriate for less complex projects where the total project scope and total associated project cost are fully known at contract award (Project Management Institute, 2017; Steyn et al., 2012; Turner, 2004).

Steyn et al. (2012) recommended progressive elaboration of a project plan (rolling wave planning) for complex projects that entails: splitting the project into phases; developing a detailed plan (with accurately defined scope, time duration and cost) for the first phase, and high-level plans (with mostly roughly defined scope, time duration and cost) for the subsequent phases and for the overall project; as the first phase progresses and more information becomes available, developing a detailed plan for the second phase and revised high-level plans for the subsequent phases and for the overall project; and the process continues until the project is completed. Similarly and arguably, rather than changing the total project contract price from a ceiling price to a fixed price (considering that the total project scope and associated total project cost are not fully known at contract award), the project contract price may be set to fixed price for the first stage and be progressively elaborated.

Thirdly, for both sets of unique projects considered, the optimised performance targets led to the improved/optimised competition which, on average, minimised the negative impact on both the project performance (as measured by project time schedule duration and project cost) and the engineering consultant's project business performance (as measured by project time schedule duration and project revenue), a win-win long-term result for the two key project participants. This was in sharp contrast to the original competition which had a significant negative impact on both the project performance and the engineering consultant's project business performance, a lose-lose long-term result (as discussed in Sections 6.6 and 6.7).

The implication of these findings is that the two project participants need to employ systems thinking and recognise the project as a system (Daniel and Daniel, 2018; Pourdehnad, 2007). They need to recognise (and appropriately extend their mental models) that, although they are individual systems as individual organisations in isolation of each other, during project execution: as key project participants, they are actually subsystems of a bigger system (the project) and thus cannot afford to operate in 'silos'; they continuously interact with each other; they are highly interrelated and rely upon each other, not only in terms of project tasks and activities, but more importantly in terms of performance achievements; and the bigger system (the project) has emergent properties [such as project performance (Pourdehnad, 2007) and the engineering consultant's project business performance, as neither participant can individually achieve his/her performance targets] that are greater than the sum of the individual subsystems (holism). As such, their performance measures and targets cannot be separated: any attempt to do so will result in lose-lose long-term results (as the findings in Sections 6.6 and 6.7 suggested). Hence, they need to fully align their performance targets.

Accordingly, a provisional answer for the research question number 5 (posed in Section 1.6) is as follows:

<u>Research Question:</u>

5. *How can the competition be improved so as to enhance both the project performance and the business performance of the engineering consultant during project execution, yielding 'win-win' long-term results for the two key project participants?*

<u>Provisional Answer (Proposed Interventions):</u>

The competition between two the key project participants (the client and the engineering consultant) during project execution can be improved through some key interventions that improve both the project performance and the engineering consultant's project business performance, yielding win-win long-term results for the two key project participants.

Firstly, the two key project participants need to embrace the systems thinking perspective and recognise (and appropriately extend their mental models) that, during project execution: as key project participants, they are actually subsystems of a bigger system (the project) and thus cannot afford to operate in 'silos', taking project controls aimed at win-lose results; they are highly interrelated and rely upon each other, not only in terms of project tasks and activities, but more importantly in terms of long-term performance results; and the bigger system (the project) has emergent properties (in particular, project performance (client's interest) and the engineering consultant's project business performance, as neither participant can individually achieve his/her performance targets) that are greater than the sum of the individual subsystems (holism).

Secondly, the two key project participants need to fully align their individual performance targets. This research study considered only time-based contracts with a ceiling price, where: only the time-based costs for the engineering consultant services were considered for project cost; and the project revenue realised by the engineering consultant at project completion was assumed to be equal to the project cost incurred by the client at completion of the same project.

In such a particular case, fully aligning the individual performance targets of the two key project participants means ensuring that the 'client project cost at completion target' is equal to the 'engineering consultant project revenue at completion target'; which is achieved by satisfying the equation a + b = 100, where a is the 'project cost variance % at completion target', and b is the 'engineering consultant project contract ceiling price % target'. This essentially eliminates/minimises the performance gaps (project cost overrun and project revenue shortfall) of the client project cost control and engineering consultant project revenue control negative feedback loops, respectively. This, in turn, minimises the competing client project cost controls and their associated unintended effects, and the engineering consultant project revenue controls and their associated unintended effects.

Thirdly, they may also consider fixing the contract price, instead of having a ceiling price [which means setting the 'client project cost variance % at completion target' (a) to zero, and the 'engineering consultant project contract ceiling price % target' (b) to 100. This also ensures that the performance targets of the two key project participants are fully aligned and also that the two key project participants' performance targets are equal to the fixed contract price.

Rather than changing the total project contract price from a ceiling price to a fixed price (considering that the total project scope and associated total project cost may not be fully known at contract award), the project contract price may be progressively elaborated in a rolling wave planning manner. This may be done as follows: splitting the project into phases; starting the project with a fixed-price contract for the first phase which has accurately defined scope, time duration and cost; increasing the contract price (including associated scope and time duration) progressively for the subsequent phases until the project is completed. This ensures that, at any given project stage, the contract price is fixed (rather than having a ceiling price). The client may still use the ceiling price amount for internal overall project budgeting purposes, but not for inclusion in the contract with the engineering consultant.

Some previous researchers and scholars, such as Lyneis and Ford (2007), Mohammed et al. (2009), and Sutterfield et al. (2007) highlighted that the use of competition (aimed at win-lose results), as a conflict-handling style, is quite common among project participants during project execution. Yet, no appropriate study could be identified in the reviewed existing literature, as discussed in Chapter 3, that specifically investigated how such competition: influences both project performance and the engineering consultant's project business performance; or may be improved to yield win-win long-term results for the two key project participants.

This research study found that the competition (i.e. combined impact of the competing client project cost controls and their unintended effects, and engineering consultant project revenue controls and their unintended effects) negatively influenced both the project performance and the engineering consultant's project business performance, as discussed in Sections 6.6 and 6.7, respectively. Put differently, the competition (aimed at win-lose results) yielded lose-lose long-term results for the two key project participants. This highlighted the dynamic complexity of the competition between the two key project participants, which was illuminated through the use of system dynamics in this research study.

Indeed, system dynamics is a multi-disciplinary approach whose goal is to assist managers improve their understanding of systems characterised by dynamic complexity, and to use such understanding to design and develop more effective, high-leverage policies and structures that solve real-world problems and improve the performance of the systems (Martinez-Moyano and Richardson, 2013; Sterman, 2000). Accordingly, this Section 6.8 investigated how to improve the competition (minimise its negative impacts on both the project performance and the engineering consultant's project business performance) so as to yield 'win-win' long-term results.

A three-stage policy optimisation (competition improvement), where the policy optimisation experiment and associated impact analyses were conducted separately for each of the two sets of unique raw water infrastructure projects (10 asset management planning and support-related projects, and 8 asset renewal-related) considered, with subsequent comparison of results from the two sets, as conducted in this Section 6.8, assisted in enhancing the validity of the above-stated provisional answer for research question number 5 (posed in Section 1.6). It is a novel contribution towards the enhancement of the existing system dynamics simulation model validation, in particular policy optimisation and impact analyses, processes and procedures, and is, thus expected to benefit future system dynamics research studies.

As already discussed in this Section 6.8.4, key research findings from the policy optimisation experiments and associated impact analyses, supported by both sets of unique projects considered, indicated that the competition can be improved (minimising the negative impacts on both the project performance and the engineering consultant's project business performance, yielding 'win-win' long-term results for the two key project participants) by fully aligning the individual performance targets of the two key project participants. They also indicated that, just like project performance, the engineering consultant's project business performance is a key emergent property of the project system. It is thus inappropriate, within the systems thinking perspective, for project management guides and standards such as Project Management Institute (2017), and

International Organization for Standardisation (2012) to only focus on project performance; they also need to adequately address and emphasise the project business performance of the other key project participants (e.g., engineering consultant and construction contractor).

The above-stated key research findings, particularly the provisional answer for research question number 5, help towards addressing the above-mentioned related gap identified in the reviewed literature and the call by Lyneis and Ford (2007) for research towards improvement of competition among project participants. They also help deepen our understanding of project dynamics, and illuminate appropriate interventions that enhance both the project performance and the engineering consultant's business performance, yielding win-win long-term results for the two key project participants. The proposed interventions also help to ensure that:

- there is full cooperation, unity of purpose and shared project vision between the client and the engineering consultant, as a result of the fully-aligned project participants' performance targets. This results in the project being completed faster, and the engineering consultant invoicing commensurately and getting paid on time (time value of money);
- there is transparency between the two key project participants with regards to their individual performance targets, with mutual agreement thereon;
- the frequency and format (indicating the required detail) of project progress reports, and the frequency, agenda and duration of progress meetings are agreed upon at project inception and maintained as far as possible throughout project execution. This enables the engineering consultant to develop an appropriate project plan that allocates adequate time for progress reports and meetings. No productive time is, thus unnecessarily wasted by the engineering consultant on too many progress reports and meetings;
- the engineering consultant is largely self-motivated to work faster, with no unnecessary pressure (work intensity) applied on him/her by the client to work faster, thereby reducing work errors (enhancing project deliverables quality), reducing the rework cycle and speeding up project work completion;
- the normal invoice approval and payment delay is agreed upon at project inception and adhered to as far as possible throughout project execution. This enables the engineering consultant to have adequate project cash flow, and thus resource the project fully, speeding up project completion; and
- superior performance (exceeding the client's targets) by the engineering consultant is appropriately incentivised (Project Management Institute, 2017; Steyn et al., 2012; Turner, 2004).

The win-win long-term results for the client and the engineering consultant as a result of improving the competition help build mutual trust between the two key project participants, which trust enhances: the chances of future repeated business for the engineering consultant and/or performance referrals by the client; and the quality of the project deliverables and/or price discounts received by the client, as highlighted by Goetsch and Davis (2012).

6.9. Conclusion

This chapter focussed on the model testing and evaluation, as well as policy analysis and design stages of the system dynamics modelling process recommended in existing literature (Martinez-Moyano and Richardson, 2013; Sterman, 2000). It applied best practices in system dynamics model validation, testing, simulation and optimisation.

Model Calibration

Model calibration, which is part of system dynamics model testing and validation, entails estimation of values for model parameters (model constants, which form part of model structure) to minimise the error between the simulated behaviour (simulation model outputs) and the corresponding observed behaviour (gathered real-world data) (Oliva, 2003; Parvan et al., 2015; Rahmandad and Sterman, 2012).

Real-world data gathered for two sets of unique raw water infrastructure projects (10 asset management planning and support-related projects, and 8 asset renewal-related projects) were used to conduct two separate model calibrations (discussed in Sections 6.4 and 6.5, respectively) on the system dynamics simulation model of the competition between the client and the engineering consultant during project execution formulated in Chapter 5. The resultant two calibrated system dynamics simulation models were then used to separately conduct similar simulation and optimisation experiments, with subsequent comparison of results from the two sets aimed at enhancing the validity of the resulting provisional answers for research questions number 3 to 5 (posed in Section 1.6), as discussed in Sections 6.6 to 6.8.

The calibration of the system dynamics simulation model using two sets of unique projects belonging to two types of raw water infrastructure projects, as conducted in this research study, offers a novel extension to the existing system dynamics simulation model testing and validation body of knowledge, considering that model calibration in the reviewed literature was limited to either only one project (Oliva, 2003) or multiple projects of the same project type (Parvan, 2012; Parvan et al., 2015). It is, thus expected to benefit future system dynamics research studies.

In this research study, model calibration was expressed as a single optimization problem in line with Oliva (2003) and Parvan et al. (2015). Two calibration payoffs were defined and used (for minimisation during the optimisation process), namely:

Project Pay-off (used for individual project optimisation); and *All Projects Pay-off* (sum of the individual *Project Pay-offs* used for simultaneous optimisation of all the projects in each set of projects considered).

Parvan et al. (2015) calibrated their system dynamics simulation model of inter-phase feedbacks in design-bid-build educational building construction projects by minimising a pre-defined payoff function formed by a linear combination of three sources of error between the model simulation outputs and their corresponding real-world project data, namely project time duration, project cost, and project cost curve (based on the invoicing schedule). This research study adapted the payoff function used by Parvan et al. (2015): to new data gathered for the two sets of unique raw water infrastructure projects considered; and extending it to include the engineering consultant project cash inflow (invoice payment) curve as a fourth source of error.

Thus, the *Project Pay-off* was formulated as a linear combination of four sources of error between key model simulation outputs and their associated real-world project data, namely project time duration, project cost, project cost curve (assumed to be based on the project invoices submitted by the engineering consultant to the client), and project invoice payment curve (indicative of the engineering consultant project cash inflow curve). This new payoff function, as used in this study, helps to produce more accurate calibrated model parameters and thus, better model reproduction of observed real-world behaviour for the right reasons, owing to the additional source of error. It extends existing project model calibration payoffs, and is also expected to benefit future system dynamics research studies.

Analysis of the Impact of Competition on Project Performance

The reviewed literature showed that: there are many measures of project performance (Section 3.3.1), yet current project dynamics models are limited to project performance (mainly time schedule duration) control actions of mainly the engineering consultant or construction contractor; and control actions taken by the client to protect project performance, and control actions taken by the engineering consultant and construction contractor to protect their individual business performance targets during project execution are sparingly covered (Section 3.11). Also, in the reviewed literature, no appropriate system dynamics project model could be identified that considered: competition among project participants, with their different and competing performance measures and targets during project execution; and how such competition influences project performance (Section 3.11).

In this research study, two measures of project performance (project time schedule duration and project cost) were used as simulation model outputs, similar to the models of De Marco (2006), Ford et al. (2007), and Parvan et al. (2015)). However, unlike in any of the said previous models, the system dynamics simulation model formulated in this research study (as discussed in Chapters 4 and 5) also captured the competition between two key project participants (the client and the engineering consultant) in the form of two sets of competing project controls (aimed at win-lose results), namely client project cost controls and their associated unintended effects, and engineering consultant project revenue controls and their associated unintended effects. This research study analysed how such competition influences the said two measures of project performance. Such a novel contribution, made by this research study, expands the existing project dynamics models, helps to deepen our understanding of project dynamics, and assists towards addressing the above-mentioned gaps identified in the reviewed literature.

Thus, subsequent to the model calibrations, discussed earlier in this Section 6.9, an analysis of the impact of the competition on project performance was conducted in three stages. In the *first stage* (Sections 6.6.1 and 6.6.2), three sets of simulation experiments were conducted using the data gathered for the first set of unique raw water infrastructure projects (10 asset management planning and support-related projects) and the associated calibrated system dynamics simulation model discussed in Section 6.4. In each case, the model simulation outputs were analysed to determine whether or not they supported a related dynamic hypothesis formulated in Section 4.9.3. Firstly, 36 different simulations were run, for each project, by varying combinations of active client project cost controls and their unintended effects. Secondly, a further 46 different model simulations were run, for each project, by varying combinations of active engineering consultant project revenue controls and their unintended effects. Thirdly, two simulations were run for each project: one without competition (only the engineering consultant project time schedule control (work intensity) and its associated unintended effect were activated; no client project cost controls and their associated unintended effects were activated; and no engineering consultant project revenue controls and their associated unintended effects were activated); the other with competition (all the said controls and their unintended effects were activated).

The impact of the competition on the project performance of each project and on average (Section 6.6.1) was then assessed through the determination of two impact ratios, namely: *impact ratio* on *project time schedule performance* (determined as the ratio of the project schedule performance index without competition to the project schedule performance index with competition); and *impact ratio on project cost performance* (determined as the ratio of the project cost performance index without competition to the project cost performance index with competition). Subsequently, a multivariate Monte Carlo behaviour mode sensitivity analysis was conducted to assess, for each project, the sensitivity of the impact to uncertainty in selected key calibrated model parameters (Section 6.6.2).

In the *second stage* (Sections 6.6.3 and 6.6.4), all the three sets of model simulation experiments, impact analysis and sensitivity analysis conducted in the preceding stage were repeated, but using data gathered for the second set of unique raw water infrastructure projects (asset renewal-related, made up of 8 projects) and the associated calibrated system dynamics simulation model discussed in Section 6.5. The second set of unique projects was included in the model simulation experiments and impact analysis for the purposes of comparison (in the next stage) of the research results from the two sets so as to enhance the validity of the associated overall key research results.

In the *third stage* (Section 6.6.5), a comparison of the key results (client project cost controls' counteractive and unintended effects, engineering consultant project revenue controls' counteractive and unintended effects, as well as polarity and behaviour mode sensitivity of the impact of the competition on project performance) from the preceding two stages was made, with appropriate conclusions drawn as to whether or not the associated dynamic hypotheses had been supported by the two sets of projects considered, and an appropriate provisional answer to research question number 3 (posed in Section 1.6) was provided.

The above-summarised three-stage analysis of the impact of competition on project performance, where the impact analysis and associated sensitivity analysis were conducted separately for each of the two sets of unique raw water infrastructure projects considered (using the associated calibrated system dynamics simulation model), with subsequent comparison of results from the two sets, assisted in enhancing the validity of the associated overall key research results, namely support for the related dynamic hypotheses and a provisional answer for research question number 3 (posed in Section 1.6) which helps to address one gap identified in the reviewed literature (i.e. how the competition influences project performance) as discussed in Chapters 1, 3 and 4. It is a novel contribution towards the enhancement of the existing system dynamics simulation model validation, in particular impact and sensitivity analyses, processes and procedures, and is, thus expected to benefit future system dynamics research studies.

The client project cost controls simulation results for both sets of unique projects considered suggested a 'better-before-worse' result that is characteristic of dynamic complexity (Sterman, 2000). The short-term impact of all the client project cost controls considered supported the intended effect of a reduction in project cost overrun. However, when all the unintended effects of the client project cost controls (i.e., decrease in productivity due to 'less time spent on real work' and 'engineering consultant project revenue controls', increase in work errors due to 'haste makes waste', and decrease in project workforce due to 'insufficient operating cash flow for engineering consultant' – all of which result in a decrease in project work completion rate) were considered, the long-term impact of the client project cost controls was counterintuitive, counteractive and unintended: instead of the project cost overrun decreasing, it increased. This supported a related dynamic hypothesis formulated in Chapter 4.

As discussed in Chapters 4 and 5, in this research study: only time-based contracts with a ceiling price (Turner, 2004) between the client and the engineering consultant were considered; and only the time-based costs for the engineering consultant services were considered for project cost. Hence, in this study, the project revenue realised by the engineering consultant at project completion was assumed to be equal to the project cost incurred by the client at completion of the same project.

The engineering consultant project revenue controls simulation results for both sets of unique projects considered also suggested a 'better-before-worse' result. The short-term impact of all engineering consultant project revenue controls considered supported the intended effect of an increase in the engineering consultant project revenue and a decrease in engineering consultant project revenue shortfall. But, when all the unintended effects of the engineering consultant project revenue controls (i.e., client project cost controls, which result in an increase in project work completion rate) were considered, the long-term impact of engineering consultant project revenue controls was counterintuitive, counteractive and unintended: instead of the engineering consultant project revenue shortfall decreasing, it increased. This supported a related dynamic hypothesis formulated in Chapter 4.

The simulation and impact analysis results for both sets of unique projects considered suggested that the competition between the two key project participants (client and engineering consultant) during project execution negatively influenced project performance (it resulted in project time schedule delay and project cost overrun and thus, it negatively influenced both project time schedule duration and project cost, which are the two key measures of project performance considered in this research study). This was also supported by a multivariate Monte Carlo behaviour mode sensitivity analysis that was conducted to assess the sensitivity of the impact to uncertainty in some key calibrated model parameters. This finding supported a related dynamic hypothesis formulated in Chapter 4, and provided a provisional answer for research question number 3 (posed in Section 1.6), which helps to address one gap identified in the reviewed literature (i.e. how the competition influences project performance) as discussed in Chapters 1, 3 and 4.

Analysis of the Impact of Competition on the Engineering Consultant's Business Performance

In addition to the literature gaps mentioned in the preceding sub-section, no appropriate study could be identified in the reviewed literature that investigated how the competition influences the engineering consultant's project business performance (Section 3.11). The reviewed literature also showed that there are many measures of engineering consultant project business performance (Section 3.3.2). As discussed in Chapters 4 and 5, the system dynamics simulation model of competition between two key project participants (the client and the engineering consultant) formulated in this research study included two measures (project time schedule duration and engineering consultant project revenue) of the engineering consultant's project business performance. This research study analysed how such competition influences the said two measures of the engineering consultant's project business performance. Such a novel contribution, made by this research study, also expands the existing project dynamics models, helps to deepen our understanding of project dynamics, and assists towards addressing the above-mentioned gap identified in the reviewed literature.

The analysis of the impact of the competition on the engineering consultant's project business performance was conducted in three stages (Section 6.7), similar to those described for the analysis of the impact of the competition on project performance in the preceding sub-section. The impact of the competition on the engineering consultant's project business performance was assessed through the determination of two impact ratios, namely: *impact ratio* on *project time schedule performance* (determined as the ratio of the project schedule performance index without competition to the project schedule performance index with competition); and *impact ratio on engineering consultant project revenue performance* (determined as the ratio of the project revenue performance index without competition to the project revenue performance index with competition).

The simulation and impact analysis results for both sets of unique projects considered suggested that the competition negatively influenced the engineering consultant's project business performance: on average, it resulted in project time schedule delays and project revenue increases that were much lower than (and not commensurate with) the increases in the project time schedule durations (as only time-based contracts were considered), and thus, it negatively influenced both the project time schedule duration and the engineering consultant's project revenue, which are the two key measures of the engineering consultant's project business performance considered in the current research study. This was also supported by a multivariate Monte Carlo behaviour mode sensitivity analysis that was conducted to assess the sensitivity of the impact to uncertainty in some key calibrated model parameters. This finding supported a related dynamic hypothesis formulated in Chapter 4, and provided a provisional answer for research question number 4 (posed in Section 1.6), which helps to address one gap identified in the reviewed literature (i.e. how the competition influences the engineering consultant's project business performance) as discussed in Chapters 1, 3 and 4.

The Competition Leads to 'Lose-Lose' Long-term Results

The results from the preceding two simulation and impact analyses suggested that the competition between the client and the engineering consultant yields lose-lose long-term results for the two key project participants: the competing client project cost controls and engineering consultant project revenue controls generate some unintended and counteractive consequences (unintended effects) that negatively influence both the project performance (increasing both 'project time schedule delay' and 'project cost overrun') and the engineering consultant's project business performance (increasing both 'project time schedule delay' and 'project revenue shortfall'). This finding is counterintuitive considering that by using competition (aimed at win-lose results), as a conflict-handling style, each project participant expected to win [while the other loses, though often not intentional but just as a result of intended/local rationality (Sterman, 2000)]. The client project cost controls were aimed at reducing/eliminating the 'project cost overrun' by reducing the 'estimated project cost at completion' (a 'win-lose' control in favour of the client); whilst engineering consultant project revenue controls were aimed at reducing/ eliminating the 'project revenue shortfall' by increasing the 'estimated project cost at completion' (a 'win-lose' control in favour of the engineering consultant).

Whereas the short-term impact of the individual project participants' controls supported their intended effect, their long-term impacts (after considering their unintended effects) were counterintuitive and unintended. All this highlighted the dynamic complexity of the competition between the two key project participants, which was illuminated through the use of system dynamics. Indeed, system dynamics is a multi-disciplinary approach whose goal is to assist managers improve their understanding of systems characterised by dynamic complexity, and to use such understanding to design and develop more effective, high-leverage policies and structures that solve real-world problems and improve the performance of the systems (Martinez-Moyano and Richardson, 2013; Sterman, 2000).

Competition Improvement (Policy Optimisation)

The next step in this research study was, thus to investigate how to improve the competition (policy optimisation), yielding win-win long term results for the two key project participants (Section 6.8). Essentially, improving the competition focussed on minimising the negative impact of the competition on both the project performance (as measured by project time schedule duration and project cost) and the engineering consultant's business performance (as measured by project time schedule duration and project revenue). It entailed minimising both: the client project cost controls and their associated unintended effects); and the engineering consultant project revenue controls and their associated unintended effects.

An analysis of the system dynamics conceptual model of the competing client project cost controls and engineering consultant project revenue controls formulated in Chapter 4 (Figure 4.31 and Table 4.11) indicated that to eliminate both the client project cost controls (and their associated unintended effects) and the engineering consultant project revenue controls (and their associated unintended effects) requires first satisfying Equation 6.6 [$a + b = 100$, where a is the *project cost variance % at completion target* and b is the *engineering consultant project contract ceiling price % target*], which results in the performance targets of the two key project participants being fully aligned (i.e., the *client project cost at completion target* being equal to the *engineering consultant project revenue at completion target*). This finding is in line with Turner (2004) who highlighted that contracts need to be designed to promote cooperation between the parties involved, by essentially aligning the objectives of the engineering consultant with those of the client.

As discussed in Chapters 4 and 5, in this research study: only time-based contracts with a ceiling price (Turner, 2004) between the client and the engineering consultant were considered; and only the time-based costs for the engineering consultant services were considered for project cost. Hence, in this study, the project revenue realised by the engineering consultant at project completion was assumed to be equal to the project cost incurred by the client at completion of the same project.

The policy optimisation aimed at improving the competition between the two key project participants was conducted in three stages. In the *first stage* (Sections 6.8.2 and 6.8.3), data gathered for the first set of unique raw water infrastructure projects (10 asset management planning and support-related) and the associated calibrated system dynamics simulation model discussed in Section 6.4 were used to conduct a policy optimisation experiment, to yield optimised performance targets for the two key project participants. The policy optimisation experiment was conducted by minimising a payoff function (Equation 6.7) that is a linear combination of three sources of error (project time schedule performance index, project cost performance index and the engineering consultant's project revenue performance index) between the model simulation outputs of two model simulation runs: one without competition; and the other with improved competition. Effectively, this maximised both the project performance (client's interest) and the engineering consultant's project business performance by simultaneously minimising the 'project time schedule delay', 'project cost overrun' and 'project revenue shortfall'.

Vensim software's built-in optimisation module (which makes use of the Powell conjugate search algorithm) was used to automatically estimate the project-specific parameter *a (project cost variance % at completion target)* that minimised the *Project Optimisation Pay-off* (Equation 6.7) for each project. The other project-specific parameter *b* (*engineering consultant project contract ceiling price % target*) was changed to an auxiliary variable with an equation (*b = 100 – a*) adapted from Equation 6.6 (*a + b = 100*) so as to ensure that the performance targets of the two key project participants were fully aligned (i.e., the *client project cost at completion target* equals the *engineering consultant project revenue at completion target*). At the end of the policy optimisation, a simulation (*With Improved Competition*) was automatically run for each project, making use of the optimised values for the *project cost variance % at completion target (a), engineering consultant project contract ceiling price % target (b), client project cost at completion target (U)* and *engineering consultant project revenue at completion targets V).*

Subsequently, the impact of the improved competition on project performance was assessed through the determination of two impact ratios, namely: *impact ratio* on *project time schedule performance* (the ratio of the project schedule performance index without competition to the project schedule performance index with improved competition); and *impact ratio on project cost performance* (the ratio of the project cost performance index without competition to the project cost performance index with improved competition. Then, the impact of the improved competition on the engineering consultant's project business performance was assessed through the determination of two impact ratios, namely: *impact ratio* on *project time schedule performance* (the ratio of the project schedule performance index without competition to the project schedule performance index with improved competition); and *impact ratio on engineering consultant project revenue performance* (the ratio of the project revenue performance index without competition to the project revenue performance index with improved competition).

Comparisons were made between the impact of the original competition (determined in Sections 6.6 and 6.7) and that of the improved competition, per project and on average, with appropriate conclusions drawn as to whether or not the improved competition did minimise the negative impacts on both project performance and engineering consultant's project business performance.

In the *second stage* (also Sections 6.8.2 and 6.8.3), the policy optimisation experiment and impact analyses conducted in the preceding stage were repeated, but using data gathered for the second set of unique raw water infrastructure projects (8 asset renewal-related) and the associated calibrated system dynamics simulation model discussed in Section 6.5. The second set of unique projects was included in this policy optimisation for the purposes of comparison (in the next stage) of the research results from the two sets so as to enhance the validity of the associated overall key research results.

In the *third stage* (Section 6.8.4), a comparison of the key results (impacts of the improved competition on both project performance and the engineering consultant's project business performance for the two sets of unique projects considered) from the preceding two stages was made, and an appropriate provisional answer to research question number 5 (posed in Section 1.6) provided.

The above-summarised three-stage policy optimisation (competition improvement), where the policy optimisation experiment and associated impact analyses were conducted separately for each of the two sets of unique raw water infrastructure projects considered, with subsequent comparison of results (optimised performance targets, and the impact of the improved competition on both project performance and on the engineering consultant's project business performance, with that of the original competition) from the two sets, assisted in enhancing the validity of the associated overall key research result, namely the provisional answer for research question number 5 (posed in Section 1.6). It is also a novel contribution towards the enhancement of the existing system dynamics simulation model validation, in particular policy optimisation and impact analyses, processes and procedures, and is, thus expected to benefit future system dynamics research studies.

One of the key results was that, for both sets of unique projects considered, on average the improved/optimised competition minimised the negative impact on both the project performance (as measured by project time schedule duration and project cost) and the engineering consultant's project business performance (as measured by project time schedule duration and project revenue), a win-win long-term result for the two key project participants. This was in sharp contrast to the original competition which had a significant negative impact on both the project performance and the engineering consultant's project business performance, a lose-lose long-term result (as discussed in Sections 6.6 and 6.7).

Such improvement was made possible by making sure that in the improved/optimised competition: Equation 6.6 was satisfied, which implied that the performance targets of the two key project participants were fully aligned [i.e., *client project cost at completion target (U) = engineering consultant project revenue at completion target (V)*]; and that the values of the *client project cost variance % at completion target (a*) and the *engineering consultant project contract ceiling price % target* (*b*) were optimised for all the projects considered.

The implication of these findings is that the two project participants need to employ systems thinking and recognise the project as a system (Daniel and Daniel, 2018; Pourdehnad, 2007). In view of this and the above-highlighted findings, a provisional answer for research question number 5 (posed in Section 1.6) was provided (in Section 6.8.4), with some recommended interventions that can improve the competition between the client and the engineering consultant during project execution, in the particular case of time-based contracts with a ceiling price, yielding win-win long-term results for the two key participants. They included, among others:

Firstly, the two key projects participants need to embrace the systems thinking perspective and recognise (and appropriately extend their mental models) that, during project execution: as key project participants, they are actually subsystems of a bigger system (the project) and thus cannot afford to operate in 'silos', taking project controls aimed at win-lose results; they are highly interrelated and rely upon each other, not only in terms of project tasks and activities, but more importantly in terms of long-term performance results; and the bigger system (the project) has emergent properties (in particular project performance (client's interest) and the engineering consultant's project business performance, as neither participant can individually achieve his/her performance targets) that are greater than the sum of the individual subsystems (holism).

Secondly, the two key project participants need to fully align their individual performance targets. This research study considered only time-based contracts with a ceiling price, where: only the time-based costs for the engineering consultant services were considered for project cost; and the project revenue realised by the engineering consultant at project completion was assumed to be equal to the project cost incurred by the client at completion of the same project.

In such a particular case, fully aligning the individual performance targets of the two key project participants means ensuring that the 'client project cost at completion target' is equal to the 'engineering consultant project revenue at completion target'; which is achieved by satisfying the equation $a + b = 100$, where a is the 'project cost variance % at completion target', and b is the 'engineering consultant project contract ceiling price % target'. This essentially eliminates/minimises the performance gaps (project cost overrun and project revenue shortfall) of the client project cost control and engineering consultant project revenue control negative feedback loops, respectively. This, in turn, minimises the competing client project cost controls and their associated unintended effects, and the engineering consultant project revenue controls and their associated unintended effects; thereby enhancing both project performance and the engineering consultant's project business performance. The next chapter concludes this research study, providing some recommendations for project management practice and for future research.

7. Conclusions and Recommendations

The objectives of this research study were to investigate, using a combination of existing literature, empirical study and system dynamics: how competition develops between two key project participants (the client and the engineering consultant) during project execution; how the competition influences project performance; how the competition influences the business performance of the engineering consultant; and how the competition can be improved so as to enhance both the project performance and the business performance of the engineering consultant, yielding win-win long-term results for the two key project participants.

The research methodology appropriately selected and followed to achieve the stated research objectives was mixed methods research (MMR) (Cameron et al., 2015; Morse and Niehaus, 2009), incorporating the system dynamics approach (Martinez-Moyano and Richardson, 2013; Sterman, 2000). The particular type of MMR design chosen was the qualitatively-driven one with sequential quantitative and qualitative supplementary components, conducted simultaneously, i.e. QUAL → quan+qual. This was, effectively, a two-stage research design.

The first stage was qualitative, embedded multiple-case study (Yin, 2014). It, effectively, covered the problem identification and definition, and system conceptualisation stages of the system dynamics modelling process (Martinez-Moyano and Richardson, 2013; Sterman, 2000). The second stage was causal explanatory research: simultaneous quantitative and qualitative (quan+qual) MMR (Cameron et al., 2015; Morse and Niehaus, 2009), with multiple cases (projects). It, effectively, covered the simulation model formulation, model testing and evaluation, as well as policy analysis and design stages of the system dynamics modelling process recommended in existing literature (Martinez-Moyano and Richardson, 2013; Sterman, 2000). The next section highlights the key research results.

7.1. Research Results

7.1.1 Results Summary

Five research questions were formulated in line with the stated research objectives to guide the investigation. The first two research questions were related to the first research objective, while the third to the fifth research questions were related to the second to the fourth research objectives, respectively. The research questions were answered through the above-mentioned two-stage research design.

In the first stage of the current research study (qualitative, embedded multiple-case study), appropriate dynamic hypotheses and a system dynamics conceptual model (qualitative modelling) of the competition between two key project participants (the client and the engineering consultant) during project execution were formulated from a combination of: existing literature; key findings from an embedded multiple-case study (Yin, 2014) that captured relevant mental models of the two key project participants (contemporary client and engineering consultant project managers) (Martinez-Moyano and Richardson, 2013; Sterman, 2000); and use of causal loop diagrams (systems thinking tool) (Monat and Gannon, 2015; Sterman, 2000).

The formulated system dynamics conceptual model consisted of three groups of project controls (negative feedback loops) [namely, engineering consultant project time schedule control (work intensity), client project cost controls, and engineering consultant project revenue controls] and their unintended effects (positive feedback loops). It suggested that, in the particular case of time-based contracts with a ceiling price, the competition arises from the use of conflicting performance measures and targets by the two key project participants, resulting in client project cost controls and engineering consultant project revenue controls that oppose/conflict each other. The client project cost controls aim at reducing/eliminating the 'project cost overrun' by reducing 'estimated project cost at completion' (a 'win-lose' control in favour of the client); whilst the engineering consultant project revenue controls aim at reducing/eliminating the 'project revenue shortfall' by increasing 'estimated project cost at completion' (a 'win-lose' control in favour of the engineering consultant).

Though the project controls of one project participant are often intendedly rational, their mutually-exclusive and 'win-lose' solution orientation, coupled with the reactive project controls of the other project participant that are also mutually-exclusive and 'win-lose' solution orientated, effectively mean the use of competition (aimed at 'win-lose' end-results) as a conflict-handling style. Unintended effects of both the client project cost controls and the engineering consultant project revenue controls aggravate the competition. Thus, the formulated system dynamics conceptual model provided a provisional answer for research question number 1 (*How can competition between two key project participants (client and engineering consultant) during project execution be conceptually modelled using systems thinking?*).

In the second stage of the research study (causal explanatory, involving multiple cases/projects), the conceptual model formulated in the preceding stage was converted to an appropriate system dynamics simulation model (quantitative modelling) of the competition using Vensim DSS software (Ventana Systems, 2018) by: developing appropriate model graphical representations (stocks and flows, and feedback loops); specifying mathematical equations for the relationships among the model variables and parameters, ensuring dimensional consistency in all equations; and specifying initial conditions, where applicable, in line with Martinez-Moyano and Richardson (2013), Rahmandad and Sterman (2012), and Sterman (2000).

The formulated system dynamics simulation model consisted of six subsystems, namely: ‘project work flow and remaining work estimation’, ‘engineering consultant project time schedule control (work intensity) and its unintended effect’, ‘client project cost controls and their unintended effects’, ‘engineering consultant project revenue controls and their unintended effects’, ‘model calibration’, and ‘policy optimisation’. The first four subsystems captured the competition between the two key project participants, with appropriate graphical representations (stock and flow diagrams, and causal loop diagrams), model equations, and initial conditions, where applicable. This provided a provisional answer for research question number 2 (*How can the competition between the two key project participants (client and engineering consultant) during project execution be quantitatively modelled (simulation model) using system dynamics?).* The last two subsystems captured the objective functions used in model calibration and policy optimisation, respectively.

Project-specific data gathered for 18 unique raw water infrastructure-related projects were used to calibrate the model as well as for the subsequent simulations, impact analyses and optimisation experiments.

The client project cost controls simulation results suggested a ‘better-before-worse’ result, characteristic of dynamic complexity (Sterman, 2000). The short-term impact of all the client project cost controls considered supported the intended effect of a reduction in project cost overrun. However, when all the unintended effects of the client project cost controls (i.e., decrease in productivity due to ‘less time spent on real work’ and ‘engineering consultant project revenue controls’, increase in work errors due to ‘haste makes waste’, and decrease in project workforce due to ‘insufficient operating cash flow for engineering consultant’) were considered, the long-term impact of client project cost controls was counterintuitive, counteractive and unintended: instead of the project cost overrun decreasing, it increased.

The engineering consultant project revenue controls simulation results also suggested a ‘better-before-worse’ result. The short-term impact of all the engineering consultant project revenue controls considered supported the intended effect of a reduction in project revenue shortfall. However, when all the unintended effects of the engineering consultant project revenue controls (i.e., all the three client project cost controls considered, namely, increasing the frequency of both progress meetings and reports, and delaying approval and payment of the engineering consultant’s invoices) were considered, the long-term impact of the engineering consultant project revenue controls was counterintuitive, counteractive and unintended: instead of the project revenue shortfall decreasing, it increased.

The simulation and impact analyses results suggested that the competition negatively influenced project performance. The competition resulted in project time schedule delay and project cost overrun. Thus, it negatively influenced both project time schedule duration and project cost, which are the two key measures of project performance considered in this research study. This finding was also supported by a multivariate Monte Carlo behaviour mode sensitivity that was conducted to assess the sensitivity of the impact to uncertainty in some key calibrated model parameters. It supported a related dynamic hypothesis formulated in the first stage of the research study, and provided a provisional answer for research question number 3 (*How does the competition between the two key project participants (client and engineering consultant) influence project performance?).*

The simulation and impact analyses results also suggested that the competition negatively influenced the engineering consultant's project business performance. The competition resulted in project time schedule delays, and project revenue increases that were much lower than (and not commensurate with) the increases in the project time schedule durations. Thus, it negatively influenced both the project time schedule duration and the engineering consultant's project revenue, which are the two key measures of the engineering consultant's project business performance considered in this research study. This finding was also supported by a multivariate Monte Carlo behaviour mode sensitivity that was conducted to assess the sensitivity of the impact to uncertainty in some key calibrated model parameters. It supported a related dynamic hypothesis formulated in the first stage of the study, and provided a provisional answer for research question number 4 (*How does the competition between the two key project participants (client and engineering consultant) influence the engineering consultant's project business performance?).*

The preceding two research results suggested that the competition between the client and the engineering consultant yields lose-lose long-term results for the two key project participants. The competing client project cost controls and engineering consultant project revenue controls generate some unintended and counteractive consequences (unintended effects) that negatively influence both the project performance (increasing both project time schedule delay and project cost overrun) and the engineering consultant's project business performance (increasing both project time schedule delay and project revenue shortfall). This finding is counterintuitive considering that by using competition (aimed at win-lose results), as a conflict-handling style, each project participant expected to win [while the other loses, though often not intentional but just as a result of intended/local rationality (Sterman, 2000)]. The client project cost controls were aimed at reducing/ eliminating the 'project cost overrun' by reducing the 'estimated project cost at completion' (a 'win-lose' control in favour of the client); whilst the engineering consultant project revenue controls were aimed at reducing/ eliminating the 'project revenue shortfall' by increasing the 'estimated project cost at completion' (a 'win-lose' control in favour of the engineering consultant).

Whereas the short-term impacts of the project participants' controls supported their intended effects, their long-term impacts (after considering their unintended effects) were counterintuitive and unintended. This highlighted the dynamic complexity of the competition, which was illuminated through the use of system dynamics. Indeed, system dynamics is a multi-disciplinary approach whose goal is to assist managers improve their understanding of systems characterised by dynamic complexity, and to use such understanding to design and develop more effective, high-leverage policies and structures that solve real-world problems and improve the performance of the systems (Martinez-Moyano and Richardson, 2013; Sterman, 2000).

Accordingly, the next step was to investigate appropriate interventions (policy optimisation) that improve the competition (minimising its negative impacts on both project performance and engineering consultant's project business performance). The policy optimisation results suggested some interventions that can improve the competition between the two the key project participants, thereby enhancing both the project performance and the engineering consultant's project business performance, yielding win-win long-term results for the two key project participants.

Firstly, the two key project participants need to employ systems thinking and recognise (and appropriately extend their mental models) that during project execution: as key project participants, they are subsystems of a bigger system (the project), and thus, cannot afford to operate in 'silos', taking project controls aimed at win-lose results; they are highly interrelated and interdependent, not only in terms of project tasks/activities, but more importantly in terms of long-term performance results; and the bigger system (the project) has emergent properties (in particular, project performance (client's interest) and engineering consultant's project business performance, as neither participant can individually achieve his/her performance targets) that are greater than the sum of the individual subsystems (holism).

Secondly, the two key project participants need to fully align their individual performance targets. This research study considered only time-based contracts with a ceiling price, where: only the time-based costs for the engineering consultant services were considered for project cost; and the project revenue realised by the engineering consultant at project completion was assumed to be equal to the project cost incurred by the client at completion of the same project. In such a particular case, fully aligning the individual performance targets of the two key project participants means ensuring that the 'client project cost at completion target' is equal to the 'engineering consultant project revenue at completion target'. This essentially eliminates/minimises the performance gaps (project cost overrun and project revenue shortfall) of the client project cost control and engineering consultant project revenue control negative feedback loops, respectively. This, in turn, minimises the competing project controls (client project cost controls and engineering consultant project revenue controls) and their unintended effects.

The above-mentioned key interventions, among others (Chapter 6), provided a provisional answer for research question number 5 (*How can the competition be improved so as to enhance both the project performance and the business performance of the engineering consultant during project execution, yielding 'win-win' long-term results for the two key project participants?)*.

7.1.2 Closing of the Research Gap

The current research study managed to address a number of gaps identified in the reviewed literature (Chapter 3) and also made some novel contributions to the project management and system dynamics bodies of knowledge. Firstly, some previous researchers (Lyneis and Ford, 2007; Mohammed et al., 2009; Sutterfield et al., 2007) highlighted the prevalence of competition (aimed at win-lose results), as a conflict-handling style, among project participants as one of the key challenges encountered during project execution. Yet, in the reviewed literature, no appropriate, or at least adequate, system dynamics model could be identified that considered such competition among project participants, with their different and competing performance measures and targets during project execution. Also, no appropriate study could be identified, in the reviewed literature, that specifically investigated how such competition influences both project performance and the engineering consultant's (or construction contractor's) project business performance, and how it can be improved so as to yield win-win long-term results for the project participants.

As discussed in the preceding subsection, the current research study formulated an appropriate system dynamics simulation model of the competition between two key project participants (client and engineering consultant) during project execution, and used it to conduct some simulation and policy optimisation experiments. The model simulations and impact analyses results, that counterintuitively suggested that the competition (aimed at win-lose results) negatively influence both the project performance and the engineering consultant's project business performance (i.e., lose-lose long-term results), help to understand the dynamic complexity of the competition and its impacts. The subsequent policy optimisation and impact analyses suggested some key interventions that help to improve the competition (minimising its negative impact on both the project performance and the engineering consultant's project business performance), yielding win-win long-term results for the two key project participants, as also discussed in the preceding subsection. This research study, thus heeded a call made by Lyneis and Ford (2007) for research towards the system dynamics modelling and improvement of such competition.

Secondly, current project dynamics models (Ford et al., 2007; Lyneis and Ford, 2007; Nasirzadeh and Nojedehi, 2013) in the reviewed literature are limited to project performance control actions of mainly one project participant (engineering consultant or construction contractor). Control actions taken by the client to protect project performance, and control actions taken by the engineering consultant (or construction contractor) to protect his/her project business performance during project execution are sparingly covered in the reviewed existing literature. The current research study, as discussed in this thesis, took into consideration: control actions taken by the client to protect project performance (project cost); and control actions taken by the engineering consultant to protect his/her project business performance (project revenue).

Thirdly, current project performance controls are mainly aimed at achieving project time schedule target. This research study, as discussed, took into consideration another key measure (cost) of project performance, in addition to time schedule.

7.2. Contributions of this Research Study

7.2.1 Theoretical Implications and Contributions

This research study made some novel contributions that expand knowledge in such areas as system dynamics simulation model testing and validation, application of system dynamics to project and business performance controls, conflict handling, performance risk mitigation, and application of systems thinking to project management (including project stakeholder management), as highlighted next.

System Dynamics Simulation Model Testing and Validation

As discussed in this thesis, real-world data gathered for two sets of unique raw water infrastructure projects (10 asset management planning and support-related projects, and 8 asset renewal-related projects) were used to conduct two separate model calibrations on the formulated system dynamics simulation model of the competition between the client and the engineering consultant during project execution. This resulted in two sets of calibrated system dynamics simulation models, one for each of the two sets of unique projects.

Next, to assess the impact of the competition on both the project performance and the engineering consultant's project business performance, appropriate model simulations, impact analyses and sensitivity analyses were conducted separately for each of the two sets of unique projects considered (using the associated calibrated system dynamics simulation models), with subsequent comparison of results from the two sets aimed at enhancing the validity of the resulting provisional answers for research questions number 3 and 4 (discussed in Section 7.1). Subsequently, to improve the competition, appropriate policy optimisation experiments and impact analyses were conducted separately for each of the two sets of unique projects considered (using the associated calibrated system dynamics simulation models), with subsequent comparison of results from the two sets aimed at enhancing the validity of the resulting provisional answer for research question number 5 (discussed in Section 7.1).

The above-summarised process, from model calibration to policy optimisation, followed in this research study, using two sets of unique projects belonging to two types of raw water infrastructure projects, is a novel extension to the existing system dynamics simulation model testing and validation body of knowledge. This is so considering that model calibration and the subsequent simulation and optimisation experiments in the reviewed literature are limited to either only one project (Oliva, 2003) or multiple projects of the same project type (Parvan, 2012; Parvan et al., 2015). Hence, such contribution of this research study is expected to benefit future system dynamics research studies.

Parvan et al. (2015) calibrated their system dynamics simulation model of inter-phase feedbacks in design-bid-build educational building construction projects by minimising a pre-defined payoff function formed by a linear combination of three sources of error between the model simulation outputs and their corresponding real-world project data, namely project time duration, project cost, and project cost curve (based on the invoicing schedule). This research study adapted the payoff function used by Parvan et al. (2015): to new data gathered for the two sets of unique raw water infrastructure projects considered; and extending it to include the engineering consultant project cash inflow (invoice payment) curve as a fourth source of error. The new payoff function (Equation 6.2, in Section 6.4.2), as used in this research study, helps to produce more accurate or even appropriate model parameters, and thus, better model reproduction of observed real-world behaviour for the right reasons, owing to the additional source of error. It is another contribution of this study expected to benefit future system dynamics model testing and validation.

Application of System Dynamics to Project and Business Performance Controls

In the reviewed literature, no appropriate, or at least adequate, system dynamics model could be identified that considered competition among project participants, with their different and competing performance measures and targets during project execution. The system dynamics simulation model of the competition between the client and the engineering consultant, formulated in this research study, adapted the (engineering consultant) project time schedule control (work intensity) and associated 'haste makes waste' unintended effect from the model of Ford et al.

(2007), and added two new sets of competing project controls (aimed at win-lose results), namely client project cost controls and associated unintended effects, as well as engineering consultant project revenue controls and associated unintended effects. Unlike the project models of Ford et al. (2007) and other previous researchers (Lyneis and Ford, 2007; Nasirzadeh and Nojedehi, 2013), it captures project controls and associated performance measures and targets of two (not just one) key project participants (the client and the engineering consultant) during project execution. It is a novel extension to the existing project dynamics models and helps project managers to deepen their understanding of project dynamics.

Project management has proven to be one of the most important forms of management due to its versatility, demand and widespread use in almost every discipline, field and organisation. Yet, poor project performance continues to be commonplace (Molloy and Chetty, 2015; Morris, 2008; Standish, 2014; Sterman, 1992). The results from the simulation and impact analyses, as discussed in Section 7.1, suggested that the competition (aimed at win-lose results) between the client and the engineering consultant yields lose-lose long-term results for the two key project participants: it negatively influenced both the project performance and the engineering consultant's project business performance. This finding provides an alternative explanation as to why poor project performance is quite common. As such, it is a novel contribution to the project performance body of knowledge. It also provides an alternative explanation for poor project business performance for projectised organisations, such as the engineering consultant and the construction contractor, enriching the project business performance body of knowledge.

Conflict Handling and Performance Risk Mitigation

The results from the simulation and impact analyses (Section 7.1) suggested that the competition (aimed at win-lose results), as a conflict-handling style (Barki and Hartwick, 2001; Marques et al., 2015; Project Management Institute, 2017; Rahim, 2002), between the client and the engineering consultant during project execution yields a 'better-before-worse' result, characteristic of dynamic complexity (Sterman, 2000). The short term impact of the competing client project cost controls and engineering consultant project revenue controls (both aimed at win-lose results) was the intended win-lose result. However, after considering the associated unintended effects, the competition yielded lose-lose long-term results for the two key project participants: it negatively influenced both the project performance (project time schedule delay and project cost overrun) and the engineering consultant's project business performance (project time schedule delay and project revenue shortfall). Thus, neither of the two key project participants won in the long-term.

This finding is counterintuitive considering that by using competition (aimed at win-lose results), as a conflict-handling style, each project participant expected to win [while the other loses, though often not intentional but just as a result of intended/local rationality (Sterman, 2000)]. It helps project managers (both the client and engineering consultant) improve their understanding of the dynamic complexity of the competition, and use other conflict-handling styles that yield win-win long-term results. As such, it is a novel contribution to the conflict handling body of knowledge, particularly for the project execution phase where dysfunctional conflict is inevitable as highlighted in existing literature (Barki and Hartwick, 2001; Hwang and Ng, 2013; Morris, 2013; Project Management Institute, 2017).

The policy optimisation results suggested some interventions (stated in the provisional answer for research question number 5 in Section 7.1) that improve the competition, thereby enhancing both the project performance and the engineering consultant's project business performance, yielding win-win long-term results for the two key project participants. In this regard, the suggested interventions help to enrich project performance risk mitigation and business performance risk mitigation (for a projectised organisation) body of knowledge.

Application of Systems Thinking to Project Management (Including Project Stakeholder Management)

Some previous researchers (Daniel and Daniel, 2018; Pourdehnad, 2007) acknowledge the importance of applying systems thinking to project management, recognising projects as systems. However, when it comes to recognising performance as an emergent property of the project system, there seems to be a narrow focus on only project performance (client's interest) in the reviewed literature, including the PMBoK Guide (Project Management Institute, 2017). Yet, for some key project participants such as the engineering consultant and construction contractor, as projectised organisations, project execution is basically their 'operations' (Cha et al., 2018). As such, they are particularly interested in their project business performances during project execution.

The PMBoK Guide highlights that effective project stakeholder management (i.e., correctly identifying all the project stakeholders, and planning, managing and monitoring stakeholder engagement to meet the stakeholders' needs and expectations) promotes stakeholder collaboration, and, as such, it is key to project success (Project Management Institute, 2017). However, the PMBoK Guide focusses mainly on project performance. For instance, it includes project performance data as a key input to the "Monitor Stakeholder Engagement" process, but excludes project business performance data for such key stakeholders as the engineering consultant and/or construction contractor (projectised organisations).

Yet, the discussed findings of this research study indicate that the engineering consultant's project business performance is another key emergent property of the project system (as such, it must also be a key input to the "Monitor Stakeholder Engagement" process), in addition to project performance. Indeed, the provisional answer for research question number 5 (Section 7.1) highlights that the competition, found to negatively influence both project performance and the engineering consultant's project business performance (lose-lose long-term results), can be improved (minimising its negative impacts on both project performance and the engineering consultant's project business performance, yielding win-win long-term results) by fully aligning the individual performance targets of the two key project participants. This is a novel contribution made by this research study to the application of systems thinking to project management (including project stakeholder management) body of knowledge.

It is thus, inappropriate, within the systems thinking perspective, for project management guides and standards such as Project Management Institute (2017), and International Organization for Standardisation (2012) to only focus on project performance. They need to also adequately cover and emphasise the importance of the project business performance of the other key project stakeholders (such as the engineering consultant and the construction contractor) for win-win long-term results.

7.2.2 Managerial Practice Implications and Contributions

The key interventions, suggested in the current study, that improve the competition yielding win-win long-term results for the client and the engineering consultant imply that the two key projects participants need to employ systems thinking and recognise the project as a system (Daniel and Daniel, 2018; Pourdehnad, 2007). They need to recognise (and appropriately extend their mental models) that although they are individual systems as individual organisations in isolation of each other, during project execution: as key project participants, they are actually subsystems of a bigger system (the project) and thus cannot afford to operate in 'silos', taking project controls aimed at win-lose results; they continuously interact with each other; they are highly interrelated and interdependent, not only in terms of project tasks and activities, but more importantly in terms of performance achievements; and the bigger system (the project) has emergent properties (such as project performance and the engineering consultant's project business performance, as neither party can achieve its performance targets in isolation of the other) that are greater than the sum of the individual subsystems (holism).

As such, their performance measures and targets cannot be separated: any attempt to do so will result in lose-lose long-term results, as the provisional answers to research questions number 3 and 4 (Section 7.1) suggested. They need to ensure their performance targets are fully aligned during project execution.

The system dynamics simulation model formulated in the current research study may be used practically as a project management and engineering consulting business management decision-making tool. Firstly, the model can assist in predicting/monitoring and control of both project performance and the project business performance of the engineering consultant during project execution; thereby assisting in both project risk management (client) and business risk management (engineering consultant). Secondly, during/after project execution, the model may be used for dispute resolution between the two key project participants.

7.3. Limitations of this Research Study

While this research study managed to address all of its objectives, its findings are not free of limitations. Notably, the current study: only focussed on the project execution stage, and excludes all other project life cycle stages; only considered two key project participants (the client and the engineering consultant), with all other project stakeholders excluded; only considered projects with time-based contracts with a ceiling price between the client and the engineering consultant, with only the time-based costs for the engineering consultant services considered for the project cost; and was case-study based (though multiple cases, clients and projects, were considered). These constraints limit generalizability of the research results.

7.4. Recommendations

It is recommended that both the client and the engineering consultant (and other key project participants such as the construction contractor): consider and put into practice the key interventions (in particular, employing systems thinking and ensuring alignment of performance targets during project execution) aimed at improving the competition, yielding win-win long-term results for both parties; and use the system dynamics simulation model formulated in this research study as a practical project management and engineering consulting business management decision-making and risk management tool during project execution.

Further research studies may consider: performance controls of a construction contractor, in projects involving design and construction; other key measures of project performance and business performance; other types of project contracts; and other types of projects. Such studies will not only expand knowledge, but will also help managers to further deepen their understanding of project dynamics, and to formulate high-leverage policies and structures that enhance the resulting project performance and business performance of the projectised stakeholders.

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Appendices

Appendix A: Interview Questionnaire (Stage 1)

University of Pretoria

INTERVIEW QUESTIONNAIRE
(For Stage 1 of the Research Study: Exploratory, Qualitative Research)

Competition Between Key Project Participants During Project Execution – A System Dynamics Approach

An academic research study conducted by

Alfred Mutizwa Chitongo

in partial fulfilment of the requirements for the degree of

PHILOSOPHIAE DOCTOR (Project Management)

in the

GRADUATE SCHOOL OF TECHNOLOGY MANAGEMENT, FACULTY OF ENGINEERING, BUILT ENVIRONMENT AND INFORMATION TECHNOLOGY, UNIVERSITY OF PRETORIA

Supervisor: Professor Leon Pretorius

STRICTLY CONFIDENTIAL

QUESTIONNAIRE REFERENCE NUMBER : ....

Interview Date : ....

(for researcher's use only)

Definitions of terms

In this research study, the following terms are defined as indicated:

- ***Project execution:*** covers design (detailed planning, preliminary design, detailed design, and procurement packaging) and construction (installation, commissioning and hand-over of project deliverables to the customer's end-user).
- ***Project deliverables:*** refers to the whole set of project outputs produced during project execution. They differ with different projects and stage of the project. For a typical design stage they may include specifications, design calculations, drawings, procurement packages, etc.
- ***Project participants:*** refers to those project stakeholders who are actively involved in the execution of the project. Key project participants during the design stage of project execution are the client and the engineering consultant.

Instructions for filling in the questionnaire:

- The 'Research Participant Informed Consent' form must be completed first before completing this questionnaire.
- This questionnaire must be completed by the Researcher in a semi-structured interview.
- The Researcher reads out each question to the Research Participant (clarifying further where necessary) and records the Research Participant's response.
- The Researcher reads out the recorded response for confirmation.

Research participants are requested to answer all the questions in this questionnaire based on their usual experiences on managing projects <u>in general</u>, and <u>not</u> based on particular projects.

Section A: Biographical Details

<u>Please indicate the answer with a tick.</u>

a1). Research Participant's category?

(1) Client (2) Engineering Consultant

a2). Research Participant's typical role on the projects?

(1) Project Manager (2) Project Director

Section B: Key Performance Measures During Project Execution

<u>Question b1 must be answered *only* by the Engineering Consultant; and question b2 *only* by the Client.</u>

b1). As an Engineering Consultant Project Manager or Project Director, indicate which of the following are the <u>key indicators</u> typically used by your <u>line manager</u> to <u>measure</u> your <u>performance</u> during the design stage of project execution:

(1) Project Net Profit (2) Project Cash Flow (3) Project Revenue

(4) Project Return on Investment

(5) Other. Please specify……………………………………………………………

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b2). As a Client Project Manager or Project Director, indicate which of the following are the <u>key performance indicators</u> typically used by your <u>line manager</u> to <u>measure</u> your <u>performance</u> during the design stage of project execution:

(1) Project Time Duration (2) Project Cost (3) Quality of Deliverables

(4) Safety (5) Disputes (6) Environmental Impact

(7) Other. Please specify……………………………………………………………

……………………………………………………………………………………………

Section C: Performance Review Frequency

c1). How often is your performance reviewed by your line manager?

(1) Monthly (2) Quarterly (3) Every 6 months (4) Annually

(5) In line with project baseline schedule (6) Other. Please specify:…

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c2). Why does your line manager review your performance that often?

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Section D: Conflict Handling

<u>In this section, wherever there is 'Client / Engineering Consultant' cancel 'Engineering Consultant' when interviewing the Engineering Consultant; otherwise cancel 'Client' when interviewing the Client.</u>

d1). The conflicts you have with the Client / Engineering Consultant project manager, during the design stage of project execution, are usually concerning what?

(1) Project time schedule (2) Project cost (3) Project deliverables' quality

(4) Engineering Consultant's project profit

(5) Engineering Consultant's project cash flow

(6) Engineering Consultant's project revenue

(7) Engineering Consultant's Project Return on Investment

(8) Other. Please specify: ………………………………..…………………………

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d2). How do you usually handle/resolve such conflicts?

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d3). Why do you usually handle them that way?

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<u>In the following 4 questions, the meanings of the 5 numbers are (from left to right): (1) Never, (2) Rarely, (3) Sometimes, (4) Often, (5) Always. Indicate your answer by ticking the appropriate number.</u>

d4). In conflict situations where you disagree with the Client / Engineering Consultant, do you insist that your position be accepted?

Never (1) (2) (3) (4) (5) Always

d5). In conflict situations where you disagree with the Client / Engineering Consultant, do you stand firm in expressing your viewpoints?

Never (1) (2) (3) (4) (5) Always

d6). In conflict situations where the Client / Engineering Consultant disagrees with you, does he/she insist that his/her position be accepted?

Never (1) (2) (3) (4) (5) Always

d7). In conflict situations where the Client / Engineering Consultant disagrees with you, does he/she stand firm in expressing his/her viewpoints?

Never (1) (2) (3) (4) (5) Always

Section E: Management Controls by Engineering Consultant

<u>The questions in this section must only be answered by the Engineering Consultant.</u>

Project Time Schedule Performance:

e1. What control actions do you usually take to bring a project that is (or is forecasted to be) behind time schedule back on track?

(1) Add more workforce (2) Make workforce work overtime

(3) Make workforce work faster by applying pressure on them

(4) Other. Please specify…………………………………………………………………

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e2). Do you usually succeed in bringing the project back on schedule when you take such controls? Please explain.

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e3). How does your project workforce react when you take such control actions?

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e4). How does the client react when you take such control actions?

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Project Cost Performance:

e5). What control actions do you usually take to bring a project that is (or is forecasted to be) above cost budget back within budget?

(1) Reduce workforce (2) Reduce overtime

(3) Make workforce work faster by applying pressure on them

(4) Other. Please specify……………………………………………………………

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e6). Do you usually succeed in bringing the project back within budget when you take such controls? Please explain.

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e7). How does your project workforce react when you take such control actions?

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e8). How does the client react when you take such control actions?

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Profit / Revenue Performance:

e9). What control actions do you usually take when you forecast a shortfall in your project profit or revenue?

(1) Reduce workforce (2) Reduce overtime

(3) Make workforce work faster by applying pressure on them

(4) Other. Please specify……………………………………………………………

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e10). Do you usually succeed in achieving your project profit/revenue target when you take such controls? Please explain.

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e11). How does your project workforce react when you take such control actions?

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e12). How does the client react when you take such control actions?

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Cash Flow Performance:

e13). What control actions do you usually take when you forecast a cash flow shortfall?

(1) Reduce workforce (2) Reduce overtime (3) Reduce time spent on the project (4) Make workforce work faster by applying pressure on them

(5) Other. Please specify……………………………………………………………

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…………………………………………………………………………………………

e14). Do you usually succeed in achieving your cash flow target when you take such controls? Please explain.

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e15). How does your project workforce react when you take such control actions?

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e16). How does the client react when you take such control actions?

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Section F: Management Controls by the Client

<u>The questions in this section must only be answered by the Client.</u>

Project Time Schedule Performance:

f1). How is your trust in Engineering Consultant usually affected when a project is (or forecasted to be) behind time schedule?

…………………………………………………………………………………………
…………………………………………………………………………………………
…………………………………………………………………………………………
…………………………………………………………………………………………

f2. What control actions do you usually take to bring a project that is (or forecasted to be) behind time schedule back on track?

(1) Demand more progress reports (2) Hold more progress meetings
(3) Delay invoice payments (4) Invoke contractual penalties
(5) Other. Please specify…………………………………………………………
…………………………………………………………………………………………
…………………………………………………………………………………………

f3). Do you usually succeed in bringing the project back on schedule when you take such controls? Please explain.

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f4). How does the Engineering Consultant react when you take such control actions?

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Project Cost Performance:

f6. How is your trust in the Engineering Consultant usually affected when a project is (or forecasted to be) above cost budget?

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f7. What control actions do you take to bring a project that is (or forecasted to be) above cost budget back within budget?

(1) Demand more progress reports (2) Hold more progress meetings

(3) Delay invoice payments (4) Invoke contractual penalties

(5) Other. Please specify………………………………………………………………

……………………………………………………………………………………………

……………………………………………………………………………………………

f8). Do you typically succeed in bringing the project back within budget when you take such controls? Please Explain.

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f9). How does the Engineering Consultant react when you take such control actions?

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General Comments and Feedback:

Do you have any feedback or comments regarding this research study in general, or this questionnaire in particular?

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THANK YOU VERY MUCH FOR PARTICIPATING IN THIS INTERVIEW!

Appendix B: Interview Questionnaire (Stage 2)

University of Pretoria

INTERVIEW QUESTIONNAIRE
(For Stage 2 of the Research Study)

Competition Between Key Project Participants During Project Execution – A System Dynamics Approach

An academic research study conducted by

Alfred Mutizwa Chitongo

in partial fulfilment of the requirements for the degree of

PHILOSOPHIAE DOCTOR (Project Management)

in the

**GRADUATE SCHOOL OF TECHNOLOGY MANAGEMENT,
FACULTY OF ENGINEERING, BUILT ENVIRONMENT AND INFORMATION TECHNOLOGY,
UNIVERSITY OF PRETORIA**

Supervisor: Professor Leon Pretorius

STRICTLY CONFIDENTIAL

QUESTIONNAIRE REFERENCE NUMBER : ....

Interview Date : ....

(for researcher's use only)

Definitions of terms

In this research study, the following terms are defined as indicated:

- ***Project execution:*** covers design (detailed planning, preliminary design, detailed design, and procurement packaging) and construction (installation, commissioning and hand-over of project deliverables to the customer's end-user).
- ***Project participants:*** refers to those project stakeholders who are actively involved in the execution of the project. Key project participants during the design stage of project execution are the client and the engineering consultant.
- ***Project deliverables:*** refers to the whole set of project outputs produced during project execution. They differ from project to project, and from stage to stage of the project. For a typical design stage they may include specifications, design calculations, drawings, procurement packages, etc.
- ***Tasks:*** are project deliverables, major parts thereof. They include: design criteria; technical specifications; design calculation sheets; drawings; technical reports; etc. They differ from project to project, and from stage to stage of the project.

Instructions for filling in the questionnaire:

- The 'Research Participant Informed Consent' form must be completed first before completing this questionnaire.
- This questionnaire must be completed by the Researcher in a semi-structured interview.
- The Researcher reads out each question to the Research Participant (clarifying further where necessary) and records the Research Participant's response.
- The Researcher reads out the recorded response for confirmation.

Research participants are requested to answer the questions in this questionnaire based on only the project execution stage of only one specific project in which he/she was/is the project manager.

Section A: Demographics

Please indicate your answer with a tick.

a1). Research Participant's category?

(1) Client (2) Engineering Consultant

a2). Research Participant's role on the project?

(1) Project Manager (2) Project Director

Section B: Project Performance

Originally Planned Project Scope, Time and Cost:

b1). a) What was the nature of the project tasks to be done, as part of project scope?

(1) design criteria (2) technical specifications (3) design calculation sheets

(4) drawings (5) technical reports (6) Other. Please specify:……....…............

………………………………………………………………………………………

b2) What was the original project scope (total number of tasks)?

Tasks..……………

b3). What was the originally planned project time schedule duration?

Months…………………………………………………

b4). What was the original project contract ceiling price (only labour-related component)?

ZAR……………………….……………………………

b5). Please provide details of the originally planned workforce schedule, showing the role and number of persons per month throughout the original time schedule duration.

Document……………………………………………………………………………

Scope Variations:

b6). Were there any project scope variations?

(1) Yes (2) No

If Yes, provide details of the project scope variations, showing, for each variation: the number of tasks added/removed; price; time duration; time (month from inception) the variation was introduced; and originator (Client or Engineering Consultant).

Document……………………………………………………………………………

Actual Project Scope, Time and Cost:

b7). What was the actual overall project scope?

Tasks..……………………………………………………

b8). What was the actual overall project time schedule duration?

Months…………………………………………………

b9). What was the actual total project cost (based on actual invoice payments)?

ZAR……………………….……………………………

Client Internal Target for Project Cost:

Question b10 must only be answered by the Client.

b10). What was the project cost variance percentage target?

%…………

Section C: Engineering Consultant Business Performance

Questions in this section must only be answered by the Engineering Consultant.

c1). What was the targeted revenue as a % of the project contract ceiling price?

%…………

c2). What was the targeted workforce cost as a % of the targeted revenue?

%…………

c3). What was the contractual normal invoices approval and payment delay?

Months…………………………………………………

c4). What was the contractual maximum invoices approval and payment delay?

Months…………………………………………………

c5). Please provide details of the originally planned project invoicing schedule showing, for each invoice: month to be submitted; associated deliverable; and amount.

Document………………………………………………………………………………

c6). Please provide details of your actual project invoices register showing, for each invoice: date submitted; associated deliverable; amount; and date paid.

Document………………………………………………………………………………

Section D: Conflict Handling

In this section, wherever there is ‘Client / Engineering Consultant’ cancel ‘Engineering Consultant’ when interviewing the Engineering Consultant; otherwise cancel ‘Client’ when interviewing the Client.

d1). What kind of conflicts did you mostly have with the Client/Engineering Consultant?

(1) Project performance related (2) Engineering consultant's business performance related (3) Other. Please specify:…………………………………… ………………………………………………………………………………………

In the following 4 questions, the meanings of the seven numbers are (from left to right): (1) Strongly disagree, (2) Disagree, (3) Disagree to some extent, (4) Neither agree nor disagree, (5) Agree to some extent, (6) Agree, and (7) Strongly agree. Indicate your answer by underlying the appropriate number.

d2). In conflict situations where you disagreed with the Client / Engineering Consultant, did you insist that your position be accepted?

Strongly disagree (1) (2) (3) (4) (5) (6) (7) Strongly agree

d3). In conflict situations where you disagreed with the Client / Engineering Consultant, did you stand firm in expressing your viewpoints?

Strongly disagree (1) (2) (3) (4) (5) (6) (7) Strongly agree

d4). In conflict situations where the Client / Engineering Consultant disagreed with you, did he/she insist that his/her position be accepted?

Strongly disagree (1) (2) (3) (4) (5) (6) (7) Strongly agree

d5). In conflict situations where the Client / Engineering Consultant disagreed with you, did he/she stand firm in expressing his/her viewpoints?

Strongly disagree (1) (2) (3) (4) (5) (6) (7) Strongly agree

Section E: Engineering Consultant Project Time Schedule Controls

The questions in this section must only be answered by the Engineering Consultant.

Project Workflow

e1). What was the normal workforce productivity?

Tasks/month/person………………………………………………………………

e2). What was the average number of revisions performed on a single task?

Number……………………………………………………………..

Overtime:

e3). What was the standard work-month (total number of normal working hours per month per person)?

Hours/month/person………………………………………………………………

e4). What was the maximum work-month (maximum number of permissible working hours per month per person)?

Hours/month/person……………………………………………………………

Work intensity:

e5). What was the average delay before applying pressure on the workforce to work faster so as to meet a deadline?

Days……………………………………………………………………………

Section F: Client Project Cost Controls

The questions in this section must only be answered by the Client.

Progress Reports, Meetings and Inspections:

f1). What was the original frequency of progress meetings agreed at project inception?

Number of Meetings/month ……………

f2). Please provide a details of your actual progress meetings schedule (showing actual number of progress meetings per month).

Document………………………………………………………………………

f3). What was the original frequency of progress reports agreed at project inception?

Number of Progress Reports/month…………………..………………………

f4). Please provide details of your actual progress reports schedule (showing actual number of progress reports per month).

Document………………………………………………………………………

f5). What was the original frequency of progress inspections by Client agreed at project inception?

Number of Progress Inspections /month……………..…………………………

f6). Please provide details of your actual progress inspections schedule (showing actual number of progress inspections by Client per month).

Document………………………………………………………………………

Invoices approval and payment delay:

<see Section C>

Penalties:

f7). Please provide details of any penalties invoked against the Engineering Consultant.

…………………………………………………………………………………………………

…………………………………………………………………………………………………

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Section G: Engineering Consultant Project Revenue Controls

The questions in this section must only be answered by the Engineering Consultant.

Effort Adjustment:

<see Sections B, C and E>

Project Scope Variations:

<see Section B>

General Comments and Feedback:

Do you have any feedback or comments regarding this research study in general, or this questionnaire in particular?

………………………………………………………………………………………………

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THANK YOU VERY MUCH FOR PARTICIPATING IN THIS INTERVIEW!

Appendix C: Ethics Approval Letter

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Engineering,
Built Environment and Information Technology

1956 – 2016
60
years of
Engineering Education

Reference number: EBIT/16/2016 30 May 2016

Mr AM Chitongo
Department GSTM
University of Pretoria
Pretoria
0028

Dear Mr Chitongo,

FACULTY COMMITTEE FOR RESEARCH ETHICS AND INTEGRITY

Your recent application to the EBIT Research Ethics Committee refers.

Approval is granted for the application with reference number that appears above.

1. This means that the research project entitled "Competition between key projects participants during project execution – A system dynamics approach" has been approved as submitted. It is important to note what approval implies. This is expanded on in the points that follow.

2. This approval does not imply that the researcher, student or lecturer is relieved of any accountability in terms of the Code of Ethics for Scholarly Activities of the University of Pretoria, or the Policy and Procedures for Responsible Research of the University of Pretoria. These documents are available on the website of the EBIT Research Ethics Committee.

3. If action is taken beyond the approved application, approval is withdrawn automatically.

4. According to the regulations, any relevant problem arising from the study or research methodology as well as any amendments or changes, must be brought to the attention of the EBIT Research Ethics Office.

5. The Committee must be notified on completion of the project.

The Committee wishes you every success with the research project.

Prof JJ Hanekom
Chair: Faculty Committee for Research Ethics and Integrity
FACULTY OF ENGINEERING, BUILT ENVIRONMENT AND INFORMATION TECHNOLOGY

EBIT Research Ethics Committee
Room 15-6, Level 15, Engineering Building 1
University of Pretoria, Private Bag X20
Hatfield 0028, South Africa
Tel +27 (0)12 420 3736
Email mari.ferreira@up.ac.za

Fakulteit Ingenieurswese, Bou-omgewing en Inligtingtegnologie
Lefapha la Boetšenere, Tikologo ya Kago le Theknolotši ya Tshedimošo

Appendix D: Research Participant Informed Consent Form

Research Participant Informed Consent Form

(Must be signed by each research participant, and kept on record by the researcher)

Research Study Background:

1 Title of the PhD research study: *Competition Between Key Project Participants During Project Execution – A System Dynamics Approach.*

2 Key objectives of the research study are to investigate:

- the factors that influence competition among key project participants, with different performance measures during project execution;
- the influence of the competition on project and business performance;
- how the competition may be improved so as to enhance project and business performance.

3 The information provided by the research participant will be strictly confidential and anonymous, and will be used only for this PhD study.

4 The research participant is requested to voluntarily participate in this research study, and to provide honest input and information.

Research Participant's Informed Consent:

1 I ………………………………………………………..… hereby voluntarily grant my permission for participation in the above-mentioned academic research study as explained to me by Alfred Mutizwa Chitongo.

2 The nature, objective, possible safety and health implications have been explained to me and I understand them.

3 I understand my right to choose whether to participate in the research project and that the information furnished will be handled confidentially. I am aware that the results of the investigation may be used for the purposes of academic publication.

4 Upon signature of this form, you will be provided with a copy.

Signed: ___________________________ Date: ________________

Witness: ___________________________ Date: ________________

Researcher: ___________________________ Date: ________________

Appendix E: System Dynamics Simulation Model Equations

Design Development Stage 1st Progress Claim Invoice[project]= DELAY INFORMATION (
design development stage 1st progress claim invoice amount[project], progress reporting delay[project], 0)
~ R

Inception Stage Progress Claim Invoice[project]= DELAY INFORMATION (
inception stage progress claim invoice amount[project], progress reporting delay[project], 0)
~ R

Design Development Stage 2nd Progress Claim Invoice[project]= DELAY INFORMATION (
design development stage 2nd progress claim invoice amount[project], progress reporting delay[project], 0)
~ R

Design Development Stage Final Invoice[project]= DELAY INFORMATION (
design development stage final invoice amount[project], progress reporting delay[project], 0)
~ R

Closeout Stage Invoice[project]= DELAY INFORMATION (
closeout stage invoice amount[project], progress reporting delay[project], 0)
~ R

Concept And Viability Stage Final Invoice[project]= DELAY INFORMATION (
concept and viability stage final invoice amount[project], progress reporting delay[project], 0)
~ R

Concept And Viability Stage Progress Claim Invoice[project]= DELAY INFORMATION (
concept and viability stage progress claim invoice amount[project], progress reporting delay[project], 0)
~ R

Inception Stage Final Invoice[project]= DELAY INFORMATION (
inception stage final invoice amount[project], progress reporting delay[project], 0)
~ R

original work resource rate[project]=
Original Work Workforce Fraction[project]*total resource rate[project]*(1-project complete[project])
~ Tasks/Month

effective workforce required to complete[project]=
MIN(XIDZ(effort required to complete estimated work remaining[project], time remaining[project], ZIDZ(
effort required to complete estimated work remaining[project], estimated time to complete estimated work remaining[project])),
(Workforce[project]*maximum work intensity[project]))*(1-project complete[project])
~ person

rework resource rate[project]=
Rework Workforce Fraction[project]*total resource rate[project]*(1-project complete[project])
~ Tasks/Month

quality assurance resource rate[project]=
Quality Assurance Workforce Fraction[project]*total resource rate[project]*(1-project complete[project])
~ Tasks/Month

Total Project Scope[project]= INTEG (project scope increase[project],initial project scope[project])
~ Tasks

workforce fraction adjustment delay=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input','C44')
~ Month

change rework workforce fraction[project]=
(target rework workforce fraction[project]-Rework Workforce Fraction[project])/workforce fraction adjustment delay
~ 1/Month

work intensity adjustment delay=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input','C43')
~ Month

change engineering consultant effort adjustment[project]=
(engineering consultant effort adjustment target[project]-Engineering Consultant Effort Adjustment[project])/
engineering consultant effort adjustment delay
~ Month*person/Month

project scope variation demand adjustment delay=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input','C50')
~ Month

change workforce size[project]=(target workforce size[project]-Workforce[project])/workforce adjustment delay
~ person/Month

change work intensity[project]=(target work intensity[project]-Work Intensity[project])/work intensity adjustment delay
~ 1/Month

change original work workforce fraction[project]=

(target original work workforce fraction[project]-Original Work Workforce Fraction[project])/workforce fraction adjustment delay
~ 1/Month

engineering consultant effort adjustment delay=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input','C49')
~ Month

change quality assurance workforce fraction[project]=
(target quality assurance workforce fraction[project]-Quality Assurance Workforce Fraction[project])/
workforce fraction adjustment delay
~ 1/Month

change engineering consultant project scope variation motivations[project]=
(engineering consultant project scope variation motivations target[project]-
Engineering Consultant Project Scope Variation Motivations[project])/project scope variation demand adjustment delay
~ R/Month

workforce adjustment delay=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input','C42')
~ Month

Engineering Consultant Project Revenue[project]= DELAY FIXED (
(Inception Stage Progress Claim Invoice[project]+Inception Stage Final Invoice[project]+
Concept And Viability Stage Progress Claim Invoice[project]+Concept And Viability Stage Final Invoice[project]+
Design Development Stage 1st Progress Claim Invoice[project]+Design Development Stage 2nd Progress Claim Invoice[project]+
Design Development Stage Final Invoice[project]+Closeout Stage Invoice[project]), 0, 0)
~ R

time design development stage 2nd progress claim was completed[project]=SAMPLE IF TRUE(
("project % complete"[project]>=(concept and viability stage complete definition[project]+
(design development stage 2nd progress claim fraction[project]*(design development stage complete definition[project]-
concept and viability stage complete definition[project])))):AND:(
time design development stage 2nd progress claim was completed[project]=0):AND:(
design development stage 2nd progress claim fraction[project]>0),Time, 0)
~ Month

time design development stage 1st progress claim was completed[project]=SAMPLE IF TRUE(
("project % complete"[project]>=(concept and viability stage complete definition[project]+
(design development stage 1st progress claim fraction[project]*(design development stage complete definition[project]-
concept and viability stage complete definition[project])))):AND:(
time design development stage 1st progress claim was completed[project]=0):AND:(
design development stage 1st progress claim fraction[project]>0),Time, 0)
~ Month

time concept and viability stage progress claim was completed[project]=SAMPLE IF TRUE(
("project % complete"[project]>=(inception stage complete definition[project]+(
concept and viability stage progress claim fraction[project]*(concept and viability stage complete definition[project]-
inception stage complete definition[project])))):AND:(time concept and viability stage progress claim was completed[project]=0)
:AND:(concept and viability stage progress claim fraction[project]>0), Time, 0)
~ Month

engineering consultant trust deficit to be filled by project scope variation motivations[project]=
engineering consultant trust deficit[project]*project scope variation motivations policy[project]
~ Dmnl

project scope variation motivations policy[project]=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input',\
'C37')
~ Dmnl

progress reports demand policy[project]=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input','C23')
~ Dmnl

client trust deficit to be filled by delaying invoices approval and payments[project]=
client trust deficit[project]*invoice approval and payment delay policy[project]
~ Dmnl

client trust deficit to be filled by progress meetings demand[project]=client trust deficit[project]*progress meetings demand policy[project]
~ Dmnl

client trust deficit to be filled by progress reports demand[project]=client trust deficit[project]*progress reports demand policy[project]
~ Dmnl

invoice approval and payment delay policy[project]=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input','C32')
~ Dmnl

engineering consultant trust deficit to be filled by effort adjustment[project]=
engineering consultant trust deficit[project]*effort adjustment policy[project]
~ Dmnl

progress meetings demand policy[project]=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input','C26')

~ Dmnl

effort adjustment policy[project]=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input','C35')
~ Dmnl

total change in work intensity due to client project cost controls[project]=
(change in work intensity due to progress reports demand[project]+
change in work intensity due to progress meetings demand[project]+
change in work intensity due to invoices approval and payment delay[project])*(1-project complete[project])
~ Dmnl

total change in productivity due to client project cost controls[project]=
productivity change due to progress reports demand[project]+productivity change due to progress meetings demand[project]
~ Tasks/(Month*person)

RC No Engineering Consultant Trust very high Effort Adjustment[project]:THE CONDITION:
TI Engineering Consultant Trust to zero[project]:AND:TI large estimated engineering consultant project revenue shortfall at completion[project]:IMPLIES:Engineering Consultant Effort Adjustment[project]>=RC RAMP CHECK(3, (estimated engineering consultant project revenue shortfall at completion[project]/average workforce unit cost[project]), 0.4, TIME STEP)
~

RC No Engineering Consultant Trust very high Project Scope Variation Motivations[project]:THE CONDITION:
TI Engineering Consultant Trust to zero[project]:AND:TI large estimated engineering consultant project revenue shortfall at completion[project]:IMPLIES:Engineering Consultant Project Scope Variation Motivations[project]>=RC RAMP CHECK(3, estimated engineering consultant project revenue shortfall at completion[project], 0.4, TIME STEP)
~

TI large estimated project cost overrun at completion[project]:TEST INPUT:
estimated project cost overrun at completion[project]=RC STEP(estimated project cost overrun at completion[project]/ estimated project cost overrun at completion[project], (9*client project cost at completion target[project]), 2)
~

RC No Client Trust very high Progress Reports Demand[project]:THE CONDITION:
TI Client Trust to zero[project]:IMPLIES:Progress Reports Demand[project]>=RC RAMP CHECK(2, (Progress Reports Demand[project]/Progress Reports Demand[project]), 5, 4*TIME STEP)
~

RC Very high estimated engineering consultant project revenue shortfall at completion no Engineering Consultant Trust[project] :THE CONDITION:TI large estimated engineering consultant project revenue shortfall at completion[project]:IMPLIES: Engineering Consultant Trust In Client[project]<=RC RAMP CHECK(2, Engineering Consultant Trust In Client[project], 0.001, TIME STEP)
~

RC Very high estimated project cost overrun at completion no Client Trust[project]:THE CONDITION:
TI large estimated project cost overrun at completion[project]:IMPLIES:Client Trust In Engineering Consultant[project]<= RC RAMP CHECK(2, Client Trust In Engineering Consultant[project]/Client Trust In Engineering Consultant[project], 0.25, TIME STEP)
~

TI large estimated engineering consultant project revenue shortfall at completion[project]:TEST INPUT:
estimated engineering consultant project revenue shortfall at completion[project]=
RC STEP(estimated engineering consultant project revenue shortfall at completion[project]/
estimated engineering consultant project revenue shortfall at completion[project],
engineering consultant project revenue at completion target[project], 2)
~

productivity[project]=
MAX(0, (normal productivity[project]-total change in productivity due to client project cost controls[project]-
total change in productivity due to engineering consultant project revenue controls[project]))
~ Tasks/Month/person

change in productivity due to engineering consultant effort adjustment[project]=normal productivity[project]*
Engineering Consultant Effort Adjustment[project]/(engineering consultant project revenue at completion target[project]/
average workforce unit cost[project])
~ Tasks/(person*Month)

effective workforce deficit[project]=
MAX(0, (effective workforce required to complete[project]-effective workforce available to complete work remaining[project]))*(1-project complete[project])
~ person

RC Very high Engineering Consultant Effort Adjustment no productivity[project]:THE CONDITION:
TI maximum Effort Adjustment[project]:IMPLIES:productivity[project]<=RC RAMP CHECK(2, productivity[project], 0.125, TIME STEP)
~

total change in productivity due to engineering consultant project revenue controls[project]=
change in productivity due to engineering consultant effort adjustment[project]+
change in productivity due to project scope variation motivations[project]
~ Tasks/(person*Month)

TI large Project Scope Variation Motivations[project]:TEST INPUT:
Engineering Consultant Project Scope Variation Motivations[project]=RC STEP(

Engineering Consultant Project Scope Variation Motivations[project]/
Engineering Consultant Project Scope Variation Motivations[project],
engineering consultant project revenue at completion target[project], 2)
~

RC Too much Work Intensity too many work errors[project]:THE CONDITION:
TI large Work Intensity[project]:IMPLIES:error fraction[project]>=RC RAMP CHECK((2+(2*TIME STEP)), 0.99, 0.99, TIME STEP)
~

TI maximum Effort Adjustment[project]:TEST INPUT:
Engineering Consultant Effort Adjustment[project]=RC STEP(Engineering Consultant Effort Adjustment[project]/
Engineering Consultant Effort Adjustment[project], (engineering consultant project revenue at completion target[project]/
average workforce unit cost[project]), 2)
~

RC Too long Invoices Approval And Payment Delay no engineering consultant project cash inflow[project]:THE CONDITION:
TI large Invoices Approval And Payment Delay[project]:IMPLIES:Engineering Consultant Project Cash Inflow[project]<=
RC RAMP CHECK((2+TIME STEP), Engineering Consultant Project Cash Inflow[project], 0.001, TIME STEP)
~

engineering consultant project operating cash sufficiency ratio[project]=
XIDZ(engineering consultant project cash ratio[project], expected engineering consultant project cash ratio[project], 1)
~ Dmnl

TI engineering consultant project operating cash sufficiency ratio to zero[project]:TEST INPUT:
engineering consultant project operating cash sufficiency ratio[project]=RC STEP(
engineering consultant project operating cash sufficiency ratio[project], 0, 2)
~

change in workforce due to cash flow deficit[project]=
(1-engineering consultant project operating cash sufficiency ratio[project])*initial workforce[project]*
invoices approval and payment delay ripple effect on workforce switch
~ person

engineering consultant project cash ratio[project]=
ZIDZ(Engineering Consultant Project Cash Inflow[project], engineering consultant project cash outflow[project])
~ Dmnl

Engineering Consultant Project Cost[project]=SAMPLE IF TRUE(
Time=month, (Instantaneous Project Cost[project]*(1-engineering consultant project gross profit margin[project])), 0)
~ R

engineering consultant project gross profit[project]=Engineering Consultant Project Revenue[project]-
Engineering Consultant Project Cost[project]
~ R

engineering consultant project cash flow[project]=
Engineering Consultant Project Cash Inflow[project]-engineering consultant project cash outflow[project]
~ R

Invoice Payment Curve[project]= INTEG (
XIDZ((Engineering Consultant Project Cash Inflow[project]-
Actual Engineering Consultant Project Cash Inflow Cumulative[project])^2,((
Engineering Consultant Project Cash Inflow[project])^2+(Actual Engineering Consultant Project Cash Inflow
Cumulative[project])^2)/2,0)*IF THEN ELSE("project % complete"[project]<=0, 0, 1),0)
~ Dmnl*Month

Engineering Consultant Project Cash Inflow[project]= DELAY INFORMATION (
Engineering Consultant Project Revenue[project], Invoices Approval And Payment Delay[project], 0)
~ R

Expected Engineering Consultant Project Cash Inflow[project]= DELAY FIXED (
Engineering Consultant Project Revenue[project], normal invoices approval and payment delay[project], 0)
~ R

add to project cost[project]=(average workforce unit cost[project]*Workforce[project])*(1-project complete[project])
~ R/Month

Invoicing Curve[project]= INTEG (
XIDZ((Engineering Consultant Project Revenue[project]-Actual Engineering Consultant Project Revenue[project])^2,
((Engineering Consultant Project Revenue[project])^2+(Actual Engineering Consultant Project Revenue[project])^2)/2,0)*
IF THEN ELSE("project % complete"[project]<=0, 0, 1),0)
~ Dmnl*Month

expected engineering consultant project cash flow[project]=
Expected Engineering Consultant Project Cash Inflow[project]-engineering consultant project cash outflow[project]
~ R

expected engineering consultant project cash ratio[project]=
ZIDZ(Expected Engineering Consultant Project Cash Inflow[project], engineering consultant project cash outflow[project])
~ Dmnl

productivity change due to progress reports demand[project]=
(normal productivity[project]*((Progress Reports Demand[project]-normal progress reports demand[project])/

maximum progress reports demand[project]))*progress reports policy ripple effect on productivity switch
~ Tasks/(Month*person)

productivity change due to progress meetings demand[project]=
(normal productivity[project]*((Progress Meetings Demand[project]-normal progress meetings demand[project])/
maximum progress meetings demand[project]))*progress meetings policy ripple effect on productivity switch
~ Tasks/(Month*person)

change in work intensity due to invoices approval and payment delay[project]=
normal work intensity[project]*((Invoices Approval And Payment Delay[project]-
normal invoices approval and payment delay[project])/maximum invoices approval and payment delay[project])
~ Dmnl

RC No sufficient engineering consultant project operating cash no Workforce[project]:THE CONDITION:
TI engineering consultant project operating cash sufficiency ratio to zero[project]:IMPLIES:Workforce[project]<=
RC RAMP CHECK(4, Workforce[project], 0.01, TIME STEP)
~

RC No Client Trust very high Progress Meetings Demand[project]:THE CONDITION:
TI Client Trust to zero[project]:IMPLIES:Progress Meetings Demand[project]>=RC RAMP CHECK(2,
(Progress Meetings Demand[project]/Progress Meetings Demand[project]), 5, 4*TIME STEP)
~

project complete[project]=
IF THEN ELSE(("project % complete"[project]>=project complete definition[project]):OR:(total backlog[project]=0) , 1 , 0)
~ Dmnl

TI large Invoices Approval And Payment Delay[project]:TEST INPUT:
Invoices Approval And Payment Delay[project]=RC STEP(Invoices Approval And Payment Delay[project], 120, 2)
~

RC Too many Progress Meetings no productivity[project]:THE CONDITION:TI large Progress Meetings Demand[project]
:IMPLIES:productivity[project]<=RC RAMP CHECK(2, productivity[project], 0.125, TIME STEP)
~

RC Too many Progress Reports no productivity[project]:THE CONDITION:TI large Progress Report Demand[project]
:IMPLIES:productivity[project]<=RC RAMP CHECK(2, productivity[project], 0.125, TIME STEP)
~

TI Engineering Consultant Trust to zero[project]:TEST INPUT:
Engineering Consultant Trust In Client[project]=RC STEP(Engineering Consultant Trust In Client[project], 0, 2)
~

RC Very high Engineering Consultant Project Scope Variation Motivations no productivity[project]:THE CONDITION:
TI large Project Scope Variation Motivations[project]:IMPLIES:productivity[project]<=RC RAMP CHECK(2, productivity[project],
0.125, TIME STEP)
~

RC No Client Trust very high Invoices Approval And Payment Delay[project]:THE CONDITION:
TI Client Trust to zero[project]:IMPLIES:Invoices Approval And Payment Delay[project]>=RC RAMP CHECK(2,
(Invoices Approval And Payment Delay[project]/Invoices Approval And Payment Delay[project]), 9, 64*TIME STEP)
~

TI Client Trust to zero[project]:TEST INPUT:
Client Trust In Engineering Consultant[project]=RC STEP(Client Trust In Engineering Consultant[project], 0, 2)
~

TI large Progress Report Demand[project]:TEST INPUT:
Progress Reports Demand[project]=RC STEP(Progress Reports Demand[project], 160, 2)
~

TI large Progress Meetings Demand[project]:TEST INPUT:
Progress Meetings Demand[project]=RC STEP(Progress Meetings Demand[project], 160, 2)
~

TI productivity to zero[project]:TEST INPUT:productivity[project]=RC STEP(productivity[project], 0, 2)
~

RC No Work Intensity no project work completion[project]:THE CONDITION:
TI Work Intensity to zero[project]:IMPLIES:project work completion rate[project]<=RC RAMP CHECK((2+TIME STEP),
project work completion rate[project], 0.0001, TIME STEP)
~

RC No productivity no project work completion[project]:THE CONDITION:
TI productivity to zero[project]:IMPLIES:project work completion rate[project]<=RC RAMP CHECK(2,
project work completion rate[project], 0.0001, TIME STEP)
~

RC No Work Backlog no project work completion[project]:THE CONDITION:
TI Total Backlog to zero[project]:IMPLIES:project work completion rate[project]<=RC RAMP CHECK(2,
project work completion rate[project], 0.0001, TIME STEP)
~

TI Work Intensity to zero[project]:TEST INPUT:Work Intensity[project]=RC STEP(Work Intensity[project], 0, 2)

TI Total Backlog to zero[project]:TEST INPUT:total backlog[project]=RC STEP(total backlog[project], 0, 2)
~

TI large Work Intensity[project]:TEST INPUT:Work Intensity[project]=RC STEP(Work Intensity[project], 1000, 2)
~

TI Workforce to zero[project]:TEST INPUT:Workforce[project]=RC STEP(Workforce[project], 0, 2)
~

RC No Workforce no project work completion[project]:THE CONDITION:
TI Workforce to zero[project]:IMPLIES:project work completion rate[project]<=RC RAMP CHECK((2+TIME STEP),
roject work completion rate[project], 0.0001, TIME STEP)
~

change in work intensity due to progress meetings demand[project]=normal work intensity[project]*
((Progress Meetings Demand[project]-normal progress meetings demand[project])/maximum progress meetings demand[project])
~ Dmnl

client project cost at completion target[project]=
Project Contract Ceiling Price[project]*(1-"client project cost variance % at completion target"[project])
~ R

Client Trust In Engineering Consultant[project]= DELAY FIXED (
normal client trust[project]*lookup for effect of estimated project cost overrun at completion on client trust[project]
(((client project cost at completion target[project]+estimated project cost overrun at completion[project])/
client project cost at completion target[project])), 0, normal client trust[project])
~ Dmnl

estimated project cost overrun at completion[project]=
Estimated Project Cost At Completion[project]-client project cost at completion target[project]
~ R

estimated project cost variance at completion[project]=
earned value at completion[project]-Estimated Project Cost At Completion[project]
~ R

lookup for effect of estimated project revenue shortfall at completion on engineering consultant trust[project](
[(0,0)-(10,1)],(0,0),(1,1),(10,1))
~ Dmnl

Engineering Consultant Trust In Client[project]= DELAY FIXED (
normal engineering consultant trust[project]*lookup for effect of estimated project revenue shortfall at completion on engineering
consultant trust[project](((engineering consultant project revenue at completion target[project]-
estimated engineering consultant project revenue shortfall at completion[project])/
engineering consultant project revenue at completion target[project])), 0, normal engineering consultant trust[project])
~ Dmnl

engineering consultant trust deficit[project]=
normal engineering consultant trust[project]-Engineering Consultant Trust In Client[project]
~ Dmnl

Estimated Project Cost At Completion[project]= DELAY INFORMATION (
(estimated cost to complete[project]+Instantaneous Project Cost[project]), progress reporting delay[project],
(budget at completion[project]*(1-"client project cost variance % at completion target"[project])))
~ R

progress reporting delay[project]=
(normal progress reporting delay[project]*normal progress reports demand[project]/Progress Reports Demand[project])*
(1-project complete[project])
~ Month

estimated cost to complete[project]=
ZIDZ((estimated time to complete estimated work remaining[project]*
effective workforce available to complete work remaining[project]*average workforce unit cost[project]), Work Intensity[project])
~ R

estimated time to complete estimated work remaining[project]=
IF THEN ELSE(Project Time Schedule Duration[project]<1, (Planned Project Time Schedule Duration[project]-
Project Time Schedule Duration[project]), ZIDZ(Estimated Work Remaining[project],
project work completion rate[project])*(1-project complete[project]))
~ Month

indicated work intensity[project]=
MAX(normal work intensity[project], (Work Intensity[project]+(effective workforce deficit[project]/Workforce[project])+
total change in work intensity due to client project cost controls[project])*(1-project complete[project])*work intensity policy)
~ Dmnl

Estimated Work Remaining[project]= INTEG ((project scope increase[project]*(1+relative effort for quality assurance[project])/
(1-base error fraction[project]))-project work completion rate[project], initial project scope[project]*
(1+relative effort for quality assurance[project])/(1-base error fraction[project]))
~ Tasks

quality assurance completion rate[project]=MIN(quality assurance resource rate[project], quality assurance process rate[project])
~ Tasks/Month

quality assurance process rate[project]=quality assurance backlog[project]/minimum work duration
~ Tasks/Month

rework completion rate[project]=MIN(rework resource rate[project], rework process rate[project])
~ Tasks/Month

original work completion rate[project]=MIN(original work resource rate[project], original work process rate[project])
~ Tasks/Month

rework process rate[project]=Rework To Do[project]/minimum work duration
~ Tasks/Month

project work completion rate[project]=
MIN((original work completion rate[project]+rework completion rate[project]+quality assurance completion rate[project]),
Estimated Work Remaining[project]/minimum work duration)
~ Tasks/Month

original work process rate[project]=Original Work To Do[project]/minimum work duration
~ Tasks/Month

minimum work duration=GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input','C72')
~ Month

client trust deficit[project]=normal client trust[project]-Client Trust In Engineering Consultant[project]
~ Dmnl

change in work intensity due to progress reports demand[project]=normal work intensity[project]*
((Progress Reports Demand[project]-normal progress reports demand[project])/maximum progress reports demand[project])
~ Dmnl

budget at completion[project]=Project Contract Ceiling Price[project]
~ R

Total Work Completed[project]= INTEG (project work completion rate[project], 0)
~ Task

perceive project cost[project]= DELAY INFORMATION (add to project cost[project], progress reporting delay[project], 0)
~ R/Month

Reported Project Cost[project]= INTEG (perceive project cost[project],0)
~ R

project scope increase[project]=STEP((((Original Work To Do[project]+additional project scope[project])-Original Work To Do[project])/
TIME STEP), month)+STEP(-(((Original Work To Do[project]+additional project scope[project])-
Original Work To Do[project])/TIME STEP), month+TIME STEP)
~ Tasks/Month

cumulate invoices[project]=
STEP((((Actual Engineering Consultant Project Revenue[project]+actual engineering consultant project invoices[project])-
Actual Engineering Consultant Project Revenue[project])/TIME STEP), month)+
STEP(-(((Actual Engineering Consultant Project Revenue[project]+actual engineering consultant project invoices[project])-
Actual Engineering Consultant Project Revenue[project])/TIME STEP), month+TIME STEP)
~ R/Month

Actual Engineering Consultant Project Cash Inflow Cumulative[project]= INTEG (cumulate cash inflow[project],0)
~ R

Actual Engineering Consultant Project Revenue[project]= INTEG (cumulate invoices[project],0)
~ R

cumulate cash inflow[project]=
STEP((((Actual Engineering Consultant Project Cash Inflow Cumulative[project]+
actual engineering consultant project cash inflow[project])-Actual Engineering Consultant Project Cash Inflow
Cumulative[project])/TIME STEP), month)+STEP(-(((Actual Engineering Consultant Project Cash Inflow
Cumulative[project]+actual engineering consultant project cash inflow[project])-
Actual Engineering Consultant Project Cash Inflow Cumulative[project])/TIME STEP), month+TIME STEP)
~ R/Month

engineering consultant project revenue at completion target[project]=
"engineering consultant project contract ceiling price % target"[project]*Project Contract Ceiling Price[project]
~ R

change project contract price[project]=
STEP((((Project Contract Ceiling Price[project]+additional project contract price[project])-
Project Contract Ceiling Price[project])/TIME STEP), month)+STEP(-(((Project Contract Ceiling Price[project]+
additional project contract price[project])-Project Contract Ceiling Price[project])/TIME STEP), month+TIME STEP)
~ R/Month

extend deadline[project]=
STEP((((Planned Project Time Schedule Duration[project]+additional project time schedule duration[project])-
Planned Project Time Schedule Duration[project])/TIME STEP), month)+STEP(-(((
Planned Project Time Schedule Duration[project]+additional project time schedule duration[project])-
Planned Project Time Schedule Duration[project])/TIME STEP), month+TIME STEP)
~ Month/Month

```
estimated engineering consultant project revenue shortfall at completion[project]=
	engineering consultant project revenue at completion target[project]-
	estimated engineering consultant project revenue at completion[project]
	~	R

time design development stage was completed[project]=SAMPLE IF TRUE(
	(("project % complete"[project]>=design development stage complete definition[project]):AND:
	(time design development stage was completed[project]=0)), Time, 0)
	~	Month

Engineering Consultant Project Scope Variation Motivations[project]= INTEG (
	change engineering consultant project scope variation motivations[project],0)
	~	R

change in productivity due to project scope variation motivations[project]=
	normal productivity[project]*Engineering Consultant Project Scope Variation Motivations[project]/
	engineering consultant project revenue at completion target[project]
	~	Tasks/(Month*person)

"engineering consultant project contract ceiling price % target"[project]=
	GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input','C10')
	~	Dmnl

design development stage 2nd progress claim fraction[project]=
	GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input','C18')
	~	Dmnl

normal progress reporting delay[project]=
	GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input','C64')
	~	Month

actual engineering consultant project invoices[project]:LOOK FORWARD::=
	GET XLS DATA('Project Participants Competition Model Parameters.xlsx', 'Input', '82', 'D166')
	~	R

Project Payoff Weight=-1
	~	Dmnl

Invoicing Curve Payoff[project]=
	IF THEN ELSE(Time = FINAL TIME-2*TIME STEP, Invoicing Curve[project]/IF THEN ELSE(
	Project Time Schedule Duration[project]=0, FINAL TIME, Project Time Schedule Duration[project])*Wic, 0)/TIME STEP
	~	Dmnl/Month

Invoice Payment Curve Payoff[project]=
	IF THEN ELSE(Time = FINAL TIME-2*TIME STEP, Invoice Payment Curve[project]/IF THEN ELSE(
	Project Time Schedule Duration[project]=0, FINAL TIME, Project Time Schedule Duration[project])*Wipc, 0)/TIME STEP
	~	Dmnl/Month

Wt=1/3
	~	Dmnl

Wc=1/3
	~	Dmnl

Wic=1/6
	~	Dmnl

Time Payoff[project]=
	IF THEN ELSE(project complete[project]=0, 0, (Project Time Schedule Duration[project]-
	Actual Project Time Schedule Duration[project])^2/(((Project Time Schedule Duration[project])^2+
	(Actual Project Time Schedule Duration[project])^2)/2)/TIME STEP)*Wt
	~	Dmnl/Month

All Projects Payoff=SUM(Project Payoff[project!])
	~	Dmnl/Month

Project Payoff[project]=Time Payoff[project]+Cost Payoff[project]+Invoicing Curve Payoff[project]+Invoice Payment Curve Payoff[project]
	~	Dmnl/Month

actual engineering consultant project cash inflow[project]:LOOK FORWARD::=
	GET XLS DATA('Project Participants Competition Model Parameters.xlsx', 'Input', '82', 'D193')
	~	R

Actual Project Time Schedule Duration[project]=
	GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input','C76')
	~	Month

Actual Project Cost[project]=GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input','C77')
	~	R

Cost Payoff[project]=
	IF THEN ELSE(project complete[project]=0, 0, XIDZ((Instantaneous Project Cost[project]-Actual Project Cost[project])^2,
	((Instantaneous Project Cost[project])^2+(Actual Project Cost[project])^2)/2,0)/TIME STEP)*Wc
	~	Dmnl/Month
```

Wipc=1/6
~ Dmnl

month:LOOK FORWARD::=
GET XLS DATA('Project Participants Competition Model Parameters.xlsx', 'Input', '82', 'D82')
~ Month

time concept and viability stage was completed[project]=SAMPLE IF TRUE(
(("project % complete"[project]>=concept and viability stage complete definition[project]):AND:
(time concept and viability stage was completed[project]=0)), Time, 0)
~ Month

time inception stage progress claim was completed[project]=SAMPLE IF TRUE(
("project % complete"[project]>=(inception stage progress claim fraction[project]*
inception stage complete definition[project])):AND:(time inception stage progress claim was completed[project]=0):AND:
(Time>0):AND:(inception stage progress claim fraction[project]>0), Time, 0)
~ Month

concept and viability stage progress claim fraction[project]=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input','C15')
~ Dmnl

additional project time schedule duration[project]:LOOK FORWARD::=
GET XLS DATA('Project Participants Competition Model Parameters.xlsx', 'Input', '82', 'D111')
~ Month

additional project contract price[project]:LOOK FORWARD::=
GET XLS DATA('Project Participants Competition Model Parameters.xlsx', 'Input', '82', 'D138')
~ R

inception stage progress claim fraction[project]=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input','C13')
~ Dmnl

design development stage 1st progress claim fraction[project]=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input','C17')
~ Dmnl

Original Work To Do[project]= INTEG (
project scope increase[project]-original correct[project]-original incorrect[project], initial project scope[project])
~ Tasks

maximum invoices approval and payment delay[project]=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C69')
~ Month

maximum progress meetings demand[project]=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C65')
~ meetings/Month

maximum progress reports demand[project]=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C62')
~ reports/Month

maximum work intensity[project]=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C58')
~ Dmnl

time closeout stage was completed[project]=SAMPLE IF TRUE(
((project complete[project]=1):AND:(time closeout stage was completed[project]=0)), Time, 0)
~ Month

engineering consultant project cash outflow[project]= ACTIVE INITIAL (Engineering Consultant Project Cost[project], 0)
~ R

Original Work Workforce Fraction[project]= INTEG (
change original work workforce fraction[project], target original work workforce fraction[project])
~ Dmnl

Instantaneous Project Cost[project]= INTEG (add to project cost[project], 0)
~ R

Project Time Schedule Duration[project]= INTEG (add to duration[project], 0)
~ Month

Quality Assurance Workforce Fraction[project]= INTEG (
change quality assurance workforce fraction[project], target quality assurance workforce fraction[project])
~ Dmnl

Rework Workforce Fraction[project]= INTEG (change rework workforce fraction[project], target rework workforce fraction[project])
~ Dmnl

add to duration[project]=1-project complete[project]
~ Dmnl

additional project scope[project]:LOOK FORWARD::=
GET XLS DATA('Project Participants Competition Model Parameters.xlsx', 'Input', '82', 'D84')
~ Tasks

original correct[project]=original work completion rate[project]*(1-error fraction[project])
~ Tasks/Month

average workforce unit cost[project]=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C8')
~ R/person/Month

base error fraction[project]=GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input','C40')
~ Dmnl

change invoices approval and payment delay[project]=
(target invoices approval and payment delay[project]-Invoices Approval And Payment Delay[project])/
invoices approval and payment delay adjustment delay[project]
~ Dmnl

change progress meetings demand[project]=
(target progress meetings demand[project]-Progress Meetings Demand[project])/
progress meetings demand adjustment delay[project]
~ meetings/(Month*Month)

change progress reports demand[project]=
(target progress reports demand[project]-Progress Reports Demand[project])/progress reports demand adjustment delay[project]
~ reports/(Month*Month)

progress meetings demand adjustment delay[project]=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C46')
~ Month

concept and viability stage complete definition[project]=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input','C14')
~ Dmnl

correctly approve[project]=
quality assurance completion rate[project]*ZIDZ(Work Done Correctly[project], quality assurance backlog[project])
~ Tasks/Month

design development stage complete definition[project]=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C16')
~ Dmnl

earned value[project]=budget at completion[project]*"project % complete"[project]
~ R

earned value at completion[project]=Project Contract Ceiling Price[project]
~ R

effective workforce available to complete work remaining[project]=Workforce[project]*Work Intensity[project]
~ person

effort required to complete estimated work remaining[project]=Estimated Work Remaining[project]/normal productivity[project]
~ person*Month

Engineering Consultant Effort Adjustment[project]= INTEG (change engineering consultant effort adjustment[project], 0)
~ Month*person

engineering consultant effort adjustment target[project]=
MAX(0, (ZIDZ(estimated engineering consultant project revenue shortfall at completion[project],
average workforce unit cost[project])*engineering consultant trust deficit to be filled by effort adjustment[project]))
~ person*Month

engineering consultant project gross profit margin[project]=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C11')
~ Dmnl

error fraction[project]=MIN(1, MAX(0, (base error fraction[project]+error fraction change due to project controls[project])))
~ Dmnl

error fraction change due to project controls[project]=error fraction change due to work intensity[project]
~ Dmnl

error fraction change due to work intensity[project]=(1-base error fraction[project])*(ZIDZ((Work Intensity[project]-1),
Work Intensity[project]))*work intensity policy ripple effect on error switch
~ Dmnl

estimated engineering consultant project revenue at completion[project]=Estimated Project Cost At Completion[project]
~ R

"estimated project cost variance % at completion"[project]=
estimated project cost variance at completion[project]/earned value at completion[project]
~ Dmnl

"estimated project cost variance % shortfall at completion"[project]=
"client project cost variance % at completion target"[project]-"estimated project cost variance % at completion"[project]
~ Dmnl

inception stage complete definition[project]=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C12')
~ Dmnl

incorrectly approve[project]=
quality assurance completion rate[project]*ZIDZ(Undiscovered Rework[project],
quality assurance backlog[project])*error fraction[project]
~ Tasks/Month

initial project contract ceiling price[project]=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C6')
~ R

initial project scope[project]=GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C4')
~ Tasks

Work Intensity[project]= INTEG (change work intensity[project], initial work intensity[project])
~ Dmnl

initial work intensity[project]=GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C60')
~ Dmnl

initial workforce[project]=GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C7')
~ person

initially planned project time schedule duration[project]=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C5')
~ Month

Invoices Approval And Payment Delay[project]= INTEG (
change invoices approval and payment delay[project], normal invoices approval and payment delay[project])
~ Month

invoices approval and payment delay adjustment delay[project]=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C48')
~ Month

"project % complete"[project]=Total Work Done[project]/Total Project Scope[project]
~ Dmnl

project complete definition[project]=GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C56')
~ Dmnl

Project Contract Ceiling Price[project]= INTEG (change project contract price[project], initial project contract ceiling price[project])
~ R

project cost performance index[project]= ZIDZ(earned value[project], Instantaneous Project Cost[project])
~ Dmnl

project cost variance[project]=earned value[project]-Instantaneous Project Cost[project]
~ R

"client project cost variance % at completion target"[project]=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C9')
~ Dmnl

lookup for effect of estimated project cost overrun at completion on client trust[project](
[(0,0)-(10,1)],(0,1),(1,1),(1.1,0.9),(1.25,0.73),(1.4,0.6),(1.6,0.5),(1.75,0.45),(2,0.4),(2.5,0.36),(5,0.28),(10,0.2))
~ Dmnl

"project cost variance % shortfall"[project]="client project cost variance % at completion target"[project]-
"project cost variance %"[project]
~ Dmnl

time inception stage was completed[project]=SAMPLE IF TRUE(
(("project % complete"[project]>=inception stage complete definition[project]):AND:
(time inception stage was completed[project]=0)), Time, 0)
~ Month

project time schedule performance index[project]=ZIDZ(planned time schedule duration[project], Project Time Schedule Duration[project])
~ Dmnl

normal client trust[project]=GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C61')
~ Dmnl

normal engineering consultant trust[project]=GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C71')
~ Dmnl

normal invoices approval and payment delay[project]=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C70')
~ Month

```
normal productivity[project]=GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C41')
        ~       Tasks/(Month*person)

normal progress meetings demand[project]=GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C66')
        ~       meetings/Month

normal progress reports demand[project]=GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C63')
        ~       reports/Month

normal work intensity[project]=GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C59')
        ~       Dmnl

rework discovery[project]=
        quality assurance completion rate[project]*ZIDZ(Undiscovered Rework[project] , quality assurance backlog[project] )*
        (1-error fraction[project])
        ~       Tasks/Month

original incorrect[project]=original work completion rate[project]*error fraction[project]
        ~       Tasks/Month

perform original work[project]=original work completion rate[project]
        ~       Tasks/Month

perform rework[project]=rework completion rate[project]
        ~       Tasks/Month

perform work[project]=original work completion rate[project]+quality assurance completion rate[project]+rework completion rate[project]
        ~       Tasks/Month

Planned Project Time Schedule Duration[project]= INTEG (extend deadline[project],initially planned project time schedule duration[project])
        ~       Month

planned time schedule duration[project]=Planned Project Time Schedule Duration[project]*"project % complete"[project]
        ~       Month

Total Work Done[project]= ACTIVE INITIAL (Work Released Without Errors[project]+Work Released With Errors[project], 0)
        ~       Tasks

Progress Meetings Demand[project]= INTEG (change progress meetings demand[project],normal progress meetings demand[project])
        ~       meetings/Month

Total Work Performed[project]= INTEG (perform work[project], 0)
        ~       Task

Progress Reports Demand[project]= INTEG (change progress reports demand[project],normal progress reports demand[project])
        ~       reports/Month

progress reports demand adjustment delay[project]=
        GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C45')
        ~       Month

Work Released Without Errors[project]= INTEG (correctly approve[project], 0)
        ~       Task

Workforce[project]= INTEG (change workforce size[project], initial workforce[project])
        ~       person

target progress reports demand[project]=
        IF THEN ELSE(
        (client trust deficit to be filled by progress reports demand[project]<=0), normal progress reports demand[project],
        IF THEN ELSE(
        (client trust deficit to be filled by progress reports demand[project]>=1), maximum progress reports demand[project],
        (maximum progress reports demand[project]-INTEGER((maximum progress reports demand[project]-
        normal progress reports demand[project])*(normal client trust[project]-
        client trust deficit to be filled by progress reports demand[project])))))
        ~       reports/Month

target quality assurance workforce fraction[project]=ZIDZ( quality assurance backlog[project] , total backlog[project] )
        ~       Dmnl

target rework workforce fraction[project]=ZIDZ( Rework To Do[project] , total backlog[project])
        ~       Dmnl

target work intensity[project]=
        IF THEN ELSE(change in workforce due to cash flow deficit[project]=0, MAX((MIN(indicated work intensity[project],
        maximum work intensity[project])),normal work intensity[project]), normal work intensity[project])
        ~       Dmnl

target workforce size[project]=MAX(0, (initial workforce[project]-change in workforce due to cash flow deficit[project]))
        ~       person

time remaining[project]=MAX(0,Planned Project Time Schedule Duration[project]-Time)
        ~       Month
```

"project cost variance %"[project]=ZIDZ(project cost variance[project], earned value[project])
~ Dmnl

engineering consultant project scope variation motivations target[project]=
MAX(0, estimated engineering consultant project revenue shortfall at completion[project]*
engineering consultant trust deficit to be filled by project scope variation motivations[project])
~ R

project time schedule delay[project]=Project Time Schedule Duration[project]-planned time schedule duration[project]
~ Month

quality assurance backlog[project]=Undiscovered Rework[project]+Work Done Correctly[project]
~ Tasks

relative effort for quality assurance[project]=GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C57')
~ Dmnl

rework correct[project]=rework completion rate[project]*(1-error fraction[project])
~ Tasks/Month

total resource rate[project]=effective workforce available to complete work remaining[project]*productivity[project]
~ Tasks/Month

rework incorrect[project]=rework completion rate[project]*error fraction[project]
~ Tasks/Month

Rework To Do[project]= INTEG ((rework discovery[project])-(rework correct[project]+rework incorrect[project]), 0)
~ Tasks

target invoices approval and payment delay[project]=
IF THEN ELSE((client trust deficit to be filled by delaying invoices approval and payments[project]<=0),
normal invoices approval and payment delay[project],
IF THEN ELSE((client trust deficit to be filled by delaying invoices approval and payments[project]>=1),
maximum invoices approval and payment delay[project], (maximum invoices approval and payment delay[project]-
INTEGER((maximum invoices approval and payment delay[project]-
normal invoices approval and payment delay[project])*(normal client trust[project]-
client trust deficit to be filled by delaying invoices approval and payments[project])))))
~ Month

target original work workforce fraction[project]=ZIDZ(Original Work To Do[project] , total backlog[project])
~ Dmnl

Work Done Correctly[project]= INTEG (original correct[project]+rework correct[project]-correctly approve[project], 0)
~ Tasks

target progress meetings demand[project]=
IF THEN ELSE(
(client trust deficit to be filled by progress meetings demand[project]<=0), normal progress meetings demand[project],
IF THEN ELSE((client trust deficit to be filled by progress meetings demand[project]>=1),
maximum progress meetings demand[project],
(maximum progress meetings demand[project]-INTEGER((maximum progress meetings demand[project]-
normal progress meetings demand[project])*(normal client trust[project]-
client trust deficit to be filled by progress meetings demand[project])))))
~ meetings/Month

Total Rework Performed[project]= INTEG (perform rework[project], 0)
~ Task

Undiscovered Rework[project]= INTEG (
original incorrect[project]+rework incorrect[project]-incorrectly approve[project]-rework discovery[project],0)
~ Tasks

Work Released With Errors[project]= INTEG (incorrectly approve[project], 0)
~ Tasks

Total Original Work Performed[project]= INTEG (perform original work[project], 0)
~ Task
total backlog[project]=Original Work To Do[project]+Undiscovered Rework[project]+Work Done Correctly[project]+Rework To Do[project]
~ Tasks

project:GET XLS SUBSCRIPT('Project Participants Competition Model Parameters.xlsx', 'Input', 'C2', 'L2', '')
~

work intensity policy=GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C21')
~ Dmnl

progress meetings policy ripple effect on productivity switch=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C27')
~ Dmnl

invoices approval and payment delay ripple effect on workforce switch=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C33')
~ Dmnl

progress reports policy ripple effect on productivity switch=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C24')
~ Dmnl

work intensity policy ripple effect on error switch=
GET XLS CONSTANTS('Project Participants Competition Model Parameters.xlsx', 'Input', 'C22')
~ Dmnl

closeout stage invoice amount[project]=SAMPLE IF TRUE(
((time closeout stage was completed[project]>0):AND:(closeout stage invoice amount[project]=0)),
(Instantaneous Project Cost[project]-(inception stage progress claim invoice amount[project]+
inception stage final invoice amount[project]+concept and viability stage progress claim invoice amount[project]+
concept and viability stage final invoice amount[project]+
design development stage 1st progress claim invoice amount[project]+
design development stage 2nd progress claim invoice amount[project]+
design development stage final invoice amount[project])), 0)
~ R

concept and viability stage final invoice amount[project]=SAMPLE IF TRUE(
((time concept and viability stage was completed[project]>0):AND:(concept and viability stage final invoice amount[project]=0)),
(Instantaneous Project Cost[project]-(inception stage progress claim invoice amount[project]+
inception stage final invoice amount[project]+concept and viability stage progress claim invoice amount[project])), 0)
~ R

concept and viability stage progress claim invoice amount[project]=SAMPLE IF TRUE(
((time concept and viability stage progress claim was completed[project]>0):AND:(
concept and viability stage progress claim invoice amount[project]=0)), (Instantaneous Project Cost[project]-
(inception stage progress claim invoice amount[project]+inception stage final invoice amount[project])), 0)
~ R

design development stage 1st progress claim invoice amount[project]=SAMPLE IF TRUE(
((time design development stage 1st progress claim was completed[project]>0):AND:(
design development stage 1st progress claim invoice amount[project]=0)), (Instantaneous Project Cost[project]-
(inception stage progress claim invoice amount[project]+inception stage final invoice amount[project]+
concept and viability stage progress claim invoice amount[project]+concept and viability stage final invoice amount[project])), 0)
~ R

design development stage 2nd progress claim invoice amount[project]=SAMPLE IF TRUE(
((time design development stage 2nd progress claim was completed[project]>0):AND:
(design development stage 2nd progress claim invoice amount[project]=0)), (Instantaneous Project Cost[project]-
(inception stage progress claim invoice amount[project]+inception stage final invoice amount[project]+
concept and viability stage progress claim invoice amount[project]+
concept and viability stage final invoice amount[project]+design development stage 1st progress claim invoice amount[project])),0)
~ R

design development stage final invoice amount[project]=SAMPLE IF TRUE(
((time design development stage was completed[project]>0):AND:(design development stage final invoice amount[project]=0)),
(Instantaneous Project Cost[project]-(inception stage progress claim invoice amount[project]+
inception stage final invoice amount[project]+concept and viability stage progress claim invoice amount[project]+
concept and viability stage final invoice amount[project]+design development stage 1st progress claim invoice amount[project]+
design development stage 2nd progress claim invoice amount[project])), 0)
~ R

inception stage final invoice amount[project]=SAMPLE IF TRUE(
((time inception stage was completed[project]>0):AND:(inception stage final invoice amount[project]=0)),
(Instantaneous Project Cost[project]-inception stage progress claim invoice amount[project]),0)
~ R

inception stage progress claim invoice amount[project]=SAMPLE IF TRUE(
((time inception stage progress claim was completed[project]>0):AND:(inception stage progress claim invoice amount[project]=0)),
Instantaneous Project Cost[project],0)
~ R

FINAL TIME = 50
~ Month

INITIAL TIME = 0
~ Month

SAVEPER = TIME STEP
~ Month [0,?]

TIME STEP = 0.03125
~ Month [0,?]

Appendix F: Reality Checks Constraints Checking Report

Constraints Checking Report

Starting testing of Constraint- RC No Client Trust very high Invoices Approval And Payment Delay
Test inputs :
TI Client Trust to zero[project]
. . . testing - RC No Client Trust very high Invoices Approval And Payment Delay[P0]

Starting testing of Constraint- RC No Client Trust very high Progress Meetings Demand
Test inputs :
TI Client Trust to zero[project]
. . . testing - RC No Client Trust very high Progress Meetings Demand[P0]

Starting testing of Constraint- RC No Client Trust very high Progress Reports Demand
Test inputs :
TI Client Trust to zero[project]
. . . testing - RC No Client Trust very high Progress Reports Demand[P0]

Starting testing of Constraint- RC No Engineering Consultant Trust very high Effort Adjustment
Test inputs :
TI Engineering Consultant Trust to zero[project]
TI large estimated engineering consultant project revenue shortfall at completion[project]
. . . testing - RC No Engineering Consultant Trust very high Effort Adjustment[P0]

Starting testing of Constraint- RC No Engineering Consultant Trust very high Project Scope Variation Motivations
Test inputs :
TI Engineering Consultant Trust to zero[project]
TI large estimated engineering consultant project revenue shortfall at completion[project]
. . . testing - RC No Engineering Consultant Trust very high Project Scope Variation Motivations[P0]

Starting testing of Constraint- RC No productivity no project work completion
Test inputs :
TI productivity to zero[project]
. . . testing - RC No productivity no project work completion[P0]

Starting testing of Constraint- RC No sufficient engineering consultant project operating cash no Workforce
Test inputs :
TI engineering consultant project operating cash sufficiency ratio to zero[project]
. . . testing - RC No sufficient engineering consultant project operating cash no Workforce[P0]

Starting testing of Constraint- RC No Work Backlog no project work completion
Test inputs :
TI Total Backlog to zero[project]
. . . testing - RC No Work Backlog no project work completion[P0]

Starting testing of Constraint- RC No Work Intensity no project work completion
Test inputs :
TI Work Intensity to zero[project]
. . . testing - RC No Work Intensity no project work completion[P0]

Starting testing of Constraint- RC No Workforce no project work completion
Test inputs :

TI Workforce to zero[project]
. . . testing - RC No Workforce no project work completion[P0]

Starting testing of Constraint- RC Too long Invoices Approval And Payment Delay no engineering consultant project cash inflow
Test inputs :
TI large Invoices Approval And Payment Delay[project]
. . . testing - RC Too long Invoices Approval And Payment Delay no engineering consultant project cash inflow[P0]

Starting testing of Constraint- RC Too many Progress Meetings no productivity
Test inputs :
TI large Progress Meetings Demand[project]
. . . testing - RC Too many Progress Meetings no productivity[P0]

Starting testing of Constraint- RC Too many Progress Reports no productivity
Test inputs :
TI large Progress Report Demand[project]
. . . testing - RC Too many Progress Reports no productivity[P0]

Starting testing of Constraint- RC Too much Work Intensity too many work errors
Test inputs :
TI large Work Intensity[project]
. . . testing - RC Too much Work Intensity too many work errors[P0]

Starting testing of Constraint- RC Very high Engineering Consultant Effort Adjustment no productivity
Test inputs :
TI maximum Effort Adjustment[project]
. . . testing - RC Very high Engineering Consultant Effort Adjustment no productivity[P0]

Starting testing of Constraint- RC Very high Engineering Consultant Project Scope Variation Motivations no productivity
Test inputs :
TI large Project Scope Variation Motivations[project]
. . . testing - RC Very high Engineering Consultant Project Scope Variation Motivations no productivity[P0]

Starting testing of Constraint- RC Very high estimated engineering consultant project revenue shortfall at completion no Engineering Consultant Trust
Test inputs :
TI large estimated engineering consultant project revenue shortfall at completion[project]
. . . testing - RC Very high estimated engineering consultant project revenue shortfall at completion no Engineering Consultant Trust[P0]

Starting testing of Constraint- RC Very high estimated project cost overrun at completion no Client Trust
Test inputs :
TI large estimated project cost overrun at completion[project]
. . . testing - RC Very high estimated project cost overrun at completion no Client Trust[P0]

****
18 successes and 0 failures testing 18 Reality Check equations
The Reality Check Index as run is 0.000436459
Closeness score is 100.0% on 18 measurements

Appendix G: Simulation model calibration Vensim configuration details

Vensim payoff definition *.vpd* file details text:

```
*P
All Projects Payoff/Project Payoff Weight
```

Vensim optimisation control *.voc* file details text:

```
:OPTIMIZER=Powell
:SENSITIVITY=Off
:MULTIPLE_START=Off
:RANDOM_NUMER=Default
:OUTPUT_LEVEL=On
:TRACE=Off
:MAX_ITERATIONS=1000
:RESTART_MAX=0
:PASS_LIMIT=2
:FRACTIONAL_TOLERANCE=0.0003
:TOLERANCE_MULTIPLIER=21
:ABSOLUTE_TOLERANCE=1
:SCALE_ABSOLUTE=1
:VECTOR_POINTS=25
:MCINITMETHOD=0
:MCPAYOFFTYPE=0
:MCRECORD=0
:MCSCHEDULE=0
:MCLIMIT=0
:MCBURNIN=0
:MCNCHAINS=2
:MCOUTLIER=0.05
:MCGAMMA=1
:MCEPSILON=0.01
:MCDELTA=0.0001
:MCJUMP=0.05
:MCUPDATEPAIRS=2
:MCXOVER=0.2
:MCTEMP=1
:MCFTEMP=1
:MCCOOLING=1000
0<=progress reports demand policy[project]<=1
0<=progress meetings demand policy[project]<=1
0<=invoice approval and payment delay policy[project]<=1
0<=effort adjustment policy[project]<=1
0<=project scope variation motivations policy[project]<=1
0.05<=base error fraction[project]<=0.4
1<=normal productivity[project]<=42
0.05<=progress reports demand adjustment delay[project]<=6
0.05<=progress meetings demand adjustment delay[project]<=6
0.05<=invoices approval and payment delay adjustment delay[project]<=6
0.05<=workforce adjustment delay<=6
0.05<=work intensity adjustment delay<=6
0.05<=workforce fraction adjustment delay<=6
0.05<=engineering consultant effort adjustment delay<=6
0.05<=project scope variation demand adjustment delay<=6
```

Appendix H: Simulated model outputs per project

Model simulations per project (asset management planning and support related projects)

Table H.1.1: Simulated project time schedule duration

Model Simulation Run-name	Project Number / Project Time Schedule Duration (months)									
	[P0]	[P1]	[P2]	[P3]	[P4]	[P5]	[P6]	[P7]	[P8]	[P9]
TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE	16.12	18.19	32.75	9.72	7.50	13.22	31.25	7.75	15.66	15.53
TC_WI+UE+CC_RMIap+UE+RC_SVM+UE	16.44	18.12	32.62	9.75	7.50	13.22	30.53	7.75	15.59	15.53
TC_WI+UE+CC_RMIap+UE+RC_EA+UE	16.06	17.59	32.84	9.69	7.50	13.22	30.44	7.75	15.56	14.53
TC_WI+UE+CC_RMIap+UE	15.41	17.56	29.00	9.69	7.38	13.22	30.00	7.75	15.22	14.19
TC_WI+UE+CC_RMIap	10.06	10.28	19.75	8.19	5.41	8.16	21.78	5.88	11.00	10.31
TC_WI+UE+CC_MIap+UE+RC_EASVM+UE	15.69	23.03	27.66	9.28	7.84	13.91	30.50	9.69	20.34	15.22
TC_WI+UE+CC_MIap+UE+RC_SVM+UE	15.69	23.03	27.62	9.28	7.84	13.91	30.59	9.72	20.34	15.16
TC_WI+UE+CC_MIap+UE+RC_EA+UE	15.66	22.97	27.56	9.25	7.84	13.91	30.50	9.69	20.38	15.22
TC_WI+UE+CC_MIap+UE	14.53	23.28	27.12	9.47	7.75	13.88	28.81	9.16	19.88	14.97
TC_WI+UE+CC_MIap	10.06	10.28	19.75	8.19	5.41	8.16	21.78	5.88	11.00	10.31
TC_WI+UE+CC_RIap+UE+RC_EASVM+UE	13.31	20.00	25.72	9.72	7.19	16.97	27.22	8.50	20.66	12.75
TC_WI+UE+CC_RIap+UE+RC_SVM+UE	13.31	20.09	25.72	9.75	7.22	16.97	27.16	8.50	20.66	12.75
TC_WI+UE+CC_RIap+UE+RC_EA+UE	13.22	20.00	25.62	9.72	7.19	16.97	28.22	8.50	20.66	12.75
TC_WI+UE+CC_RIap+UE	12.31	19.88	23.69	9.63	7.09	17.03	24.59	8.44	19.78	12.66
TC_WI+UE+CC_RIap	10.06	10.28	19.75	8.19	5.44	8.16	21.81	5.88	11.00	10.31
TC_WI+UE+CC_RM+UE+RC_EASVM+UE	22.09	22.31	24.38	8.41	5.78	16.91	50.00	7.34	32.25	12.50
TC_WI+UE+CC_RM+UE+RC_SVM+UE	22.12	22.31	24.38	8.41	5.78	16.91	50.00	7.34	32.25	12.50
TC_WI+UE+CC_RM+UE+RC_EA+UE	22.09	22.31	24.38	8.41	5.78	16.91	50.00	7.31	32.25	12.50
TC_WI+UE+CC_RM+UE	13.72	22.25	21.97	8.25	5.75	16.88	50.00	7.31	32.19	12.47
TC_WI+UE+CC_RM	10.06	10.28	19.75	8.19	5.41	8.13	21.78	5.88	11.00	10.31
TC_WI+UE+CC_Iap+UE+RC_EASVM+UE	13.59	19.50	28.78	9.53	7.97	11.81	31.94	9.22	20.12	15.28
TC_WI+UE+CC_Iap+UE+RC_SVM+UE	13.50	19.47	28.78	9.53	7.94	11.81	31.97	9.22	20.12	15.28
TC_WI+UE+CC_Iap+UE+RC_EA+UE	13.59	19.50	28.78	9.53	7.97	11.81	31.88	9.22	20.09	15.28
TC_WI+UE+CC_Iap+UE	13.25	19.44	28.06	9.47	7.88	11.41	30.66	9.22	19.94	15.03
TC_WI+UE+CC_Iap	10.12	10.34	19.75	8.31	5.44	8.16	21.84	5.88	11.03	10.34
TC_WI+UE+CC_M+UE+RC_EASVM+UE	13.38	16.81	21.91	8.44	5.75	11.44	49.31	7.00	23.41	11.03
TC_WI+UE+CC_M+UE+RC_SVM+UE	13.41	16.81	21.91	8.44	5.75	11.44	49.44	7.00	23.41	11.03
TC_WI+UE+CC_M+UE+RC_EA+UE	13.38	16.81	21.88	8.44	5.75	11.44	49.31	7.00	23.41	11.03
TC_WI+UE+CC_M+UE	12.97	16.78	21.03	8.31	5.75	11.38	44.72	6.97	23.34	10.97
TC_WI+UE+CC_M	10.06	10.28	19.72	8.19	5.41	8.16	21.78	5.88	11.00	10.31
TC_WI+UE+CC_R+UE+RC_EASVM+UE	13.66	22.25	20.50	8.41	5.59	16.50	28.81	6.28	28.16	10.62
TC_WI+UE+CC_R+UE+RC_SVM+UE	19.06	22.25	20.47	8.38	5.59	16.47	28.81	6.28	28.16	10.59
TC_WI+UE+CC_R+UE+RC_EA+UE	13.66	22.25	20.50	8.41	5.59	16.50	28.81	6.28	28.16	10.66
TC_WI+UE+CC_R+UE	12.88	22.16	20.03	8.25	5.56	16.41	23.50	6.28	28.09	10.47
TC_WI+UE+CC_R	10.06	10.28	19.75	8.19	5.44	8.16	21.78	5.88	11.00	10.31
TC_WI+UE	12.50	12.09	25.09	9.78	6.22	8.84	27.34	5.88	12.12	12.09

Table H.1.2: Simulated project cost / engineering consultant project revenue

Model Simulation Run-name	Project Number / Project Cost / Engineering Consultant Project Revenue (R million)									
	[P0]	[P1]	[P2]	[P3]	[P4]	[P5]	[P6]	[P7]	[P8]	[P9]
TC_WI+UE+CC_RMlap+UE+RC_EASVM+UE	15.910	16.820	45.510	6.059	3.854	6.942	22.630	3.517	14.360	11.660
TC_WI+UE+CC_RMlap+UE+RC_SVM+UE	16.070	16.750	45.660	6.087	3.854	6.942	22.090	3.517	14.310	11.660
TC_WI+UE+CC_RMlap+UE+RC_EA+UE	15.860	16.450	45.630	6.039	3.854	6.942	22.040	3.517	14.280	11.020
TC_WI+UE+CC_RMlap+UE	15.270	16.470	42.760	6.047	3.827	6.926	21.760	3.517	14.150	10.860
TC_WI+UE+CC_RMlap	11.590	12.870	35.330	5.232	3.460	5.430	17.830	3.203	11.160	9.101
TC_WI+UE+CC_Mlap+UE+RC_EASVM+UE	14.040	19.290	41.480	5.660	3.915	7.007	21.160	4.031	15.120	10.830
TC_WI+UE+CC_Mlap+UE+RC_SVM+UE	14.040	19.290	41.460	5.660	3.915	7.007	21.170	4.040	15.120	10.820
TC_WI+UE+CC_Mlap+UE+RC_EA+UE	14.020	19.220	41.390	5.641	3.915	7.007	21.160	4.031	15.130	10.830
TC_WI+UE+CC_Mlap+UE	13.660	19.430	40.910	5.786	3.904	7.004	20.400	3.913	14.900	10.770
TC_WI+UE+CC_Mlap	11.590	12.870	35.330	5.232	3.460	5.430	17.830	3.203	11.160	9.101
TC_WI+UE+CC_Rlap+UE+RC_EASVM+UE	13.100	17.670	40.770	6.059	3.706	7.937	20.220	3.718	15.520	10.020
TC_WI+UE+CC_Rlap+UE+RC_SVM+UE	13.100	17.710	40.770	6.079	3.716	7.937	20.200	3.718	15.520	10.020
TC_WI+UE+CC_Rlap+UE+RC_EA+UE	13.080	17.670	40.690	6.059	3.711	7.937	20.490	3.718	15.520	10.020
TC_WI+UE+CC_Rlap+UE	12.620	17.620	38.900	6.008	3.695	7.935	19.030	3.704	15.110	9.958
TC_WI+UE+CC_Rlap	11.590	12.870	35.330	5.232	3.480	5.430	17.850	3.203	11.160	9.101
TC_WI+UE+CC_RM+UE+RC_EASVM+UE	25.450	27.930	43.610	5.372	3.700	11.260	40.920	4.004	32.710	11.030
TC_WI+UE+CC_RM+UE+RC_SVM+UE	25.490	27.930	43.610	5.372	3.700	11.260	40.920	4.004	32.710	11.030
TC_WI+UE+CC_RM+UE+RC_EA+UE	25.450	27.930	43.610	5.372	3.700	11.260	40.920	3.987	32.710	11.030
TC_WI+UE+CC_RM+UE	15.800	27.850	39.300	5.272	3.680	11.240	40.920	3.987	32.640	11.000
TC_WI+UE+CC_RM	11.590	12.870	35.330	5.232	3.460	5.410	17.830	3.203	11.160	9.101
TC_WI+UE+CC_Iap+UE+RC_EASVM+UE	12.080	15.040	39.830	5.437	3.584	5.865	20.330	3.476	13.130	10.060
TC_WI+UE+CC_Iap+UE+RC_SVM+UE	12.050	15.030	39.810	5.437	3.564	5.865	20.320	3.476	13.110	10.040
TC_WI+UE+CC_Iap+UE+RC_EA+UE	12.100	15.040	39.830	5.437	3.584	5.865	20.320	3.476	13.120	10.070
TC_WI+UE+CC_Iap+UE	11.910	15.020	39.310	5.398	3.574	5.804	19.790	3.476	13.080	9.976
TC_WI+UE+CC_Iap	11.660	12.950	35.330	5.312	3.480	5.430	17.880	3.203	11.190	9.128
TC_WI+UE+CC_M+UE+RC_EASVM+UE	15.410	21.050	39.190	5.392	3.680	7.615	40.360	3.817	23.740	9.735
TC_WI+UE+CC_M+UE+RC_SVM+UE	15.440	21.050	39.190	5.392	3.680	7.615	40.460	3.817	23.740	9.735
TC_WI+UE+CC_M+UE+RC_EA+UE	15.410	21.050	39.140	5.392	3.680	7.615	40.360	3.817	23.740	9.735
TC_WI+UE+CC_M+UE	14.940	21.010	37.630	5.312	3.680	7.573	36.600	3.799	23.680	9.680
TC_WI+UE+CC_M	11.590	12.870	35.280	5.232	3.460	5.430	17.830	3.203	11.160	9.101
TC_WI+UE+CC_R+UE+RC_EASVM+UE	15.730	27.850	36.680	5.372	3.580	10.990	23.580	3.425	28.560	9.377
TC_WI+UE+CC_R+UE+RC_SVM+UE	21.960	27.850	36.620	5.352	3.580	10.960	23.580	3.425	28.560	9.349
TC_WI+UE+CC_R+UE+RC_EA+UE	15.730	27.850	36.680	5.372	3.580	10.990	23.580	3.425	28.560	9.404
TC_WI+UE+CC_R+UE	14.830	27.740	35.840	5.272	3.560	10.920	19.230	3.425	28.490	9.239
TC_WI+UE+CC_R	11.590	12.870	35.330	5.232	3.480	5.430	17.830	3.203	11.160	9.101
TC_WI+UE	14.400	15.140	44.890	6.251	3.980	5.888	22.380	3.203	12.300	10.670

Table H.1.3: Simulated project time schedule duration

Model Simulation Run-name	Project Number / Project Time Schedule Duration (months)									
	[P0]	[P1]	[P2]	[P3]	[P4]	[P5]	[P6]	[P7]	[P8]	[P9]
TC_WI+UE+RC_EASVM+CC_RMIap+UE	16.12	18.19	32.75	9.72	7.50	13.22	31.25	7.75	15.66	15.53
TC_WI+UE+RC_EASVM+CC_RMIap	10.31	10.38	20.28	8.38	5.44	8.19	22.62	5.88	11.12	10.47
TC_WI+UE+RC_EASVM+CC_MIap+UE	15.69	23.03	27.66	9.25	7.84	13.91	30.56	9.72	20.53	15.25
TC_WI+UE+RC_EASVM+CC_MIap	10.31	10.38	20.28	8.34	5.44	8.19	22.59	5.88	11.12	10.47
TC_WI+UE+RC_EASVM+CC_RIap+UE	13.31	20.00	25.72	9.75	7.19	16.97	28.34	8.50	20.88	12.75
TC_WI+UE+RC_EASVM+CC_RIap	10.31	10.38	20.28	8.38	5.47	8.19	22.62	5.88	11.12	10.47
TC_WI+UE+RC_EASVM+CC_RM+UE	22.09	22.31	24.38	8.41	5.78	16.91	50.00	7.34	32.28	12.50
TC_WI+UE+RC_EASVM+CC_RM	10.31	10.38	20.28	8.38	5.44	8.19	22.62	5.88	11.12	10.47
TC_WI+UE+RC_EASVM+CC_Iap+UE	13.59	19.50	28.78	9.53	7.97	11.81	32.06	9.22	20.25	15.25
TC_WI+UE+RC_EASVM+CC_Iap	10.34	10.41	20.28	8.41	5.47	8.19	22.59	5.88	11.12	10.50
TC_WI+UE+RC_EASVM+CC_M+UE	13.38	16.81	21.91	8.44	5.75	11.44	49.44	7.00	23.47	11.03
TC_WI+UE+RC_EASVM+CC_M	10.31	10.38	20.28	8.34	5.44	8.19	22.59	5.88	11.12	10.47
TC_WI+UE+RC_EASVM+CC_R+UE	13.66	22.25	20.50	8.41	5.59	16.50	28.84	6.28	28.22	10.94
TC_WI+UE+RC_EASVM+CC_R	10.31	10.38	20.28	8.38	5.50	8.19	22.62	5.88	11.12	10.47
TC_WI+UE+RC_EASVM	12.50	12.09	25.09	9.78	6.22	8.84	27.34	5.88	12.12	12.09
TC_WI+UE+RC_SVM+CC_RMIap+UE	16.44	18.12	32.62	9.75	7.50	13.22	30.53	7.75	15.59	15.53
TC_WI+UE+RC_SVM+CC_RMIap	10.31	10.38	20.28	8.34	5.44	8.19	22.53	5.88	11.06	10.47
TC_WI+UE+RC_SVM+CC_MIap+UE	15.69	23.03	27.62	9.28	7.84	13.91	30.59	9.72	20.34	15.16
TC_WI+UE+RC_SVM+CC_MIap	10.31	10.38	20.28	8.34	5.44	8.19	22.50	5.88	11.06	10.44
TC_WI+UE+RC_SVM+CC_RIap+UE	13.31	20.09	25.72	9.75	7.22	16.97	27.16	8.50	20.66	12.75
TC_WI+UE+RC_SVM+CC_RIap	10.31	10.38	20.28	8.34	5.47	8.19	22.53	5.88	11.06	10.47
TC_WI+UE+RC_SVM+CC_RM+UE	22.12	22.31	24.38	8.41	5.78	16.91	50.00	7.34	32.25	12.50
TC_WI+UE+RC_SVM+CC_RM	10.31	10.38	20.28	8.34	5.44	8.19	22.53	5.88	11.06	10.47
TC_WI+UE+RC_SVM+CC_Iap+UE	13.50	19.47	28.78	9.53	7.94	11.81	31.97	9.22	20.12	15.28
TC_WI+UE+RC_SVM+CC_Iap	10.31	10.41	20.28	8.41	5.47	8.19	22.50	5.88	11.09	10.47
TC_WI+UE+RC_SVM+CC_M+UE	13.41	16.81	21.91	8.44	5.75	11.44	49.44	7.00	23.41	11.03
TC_WI+UE+RC_SVM+CC_M	10.31	10.38	20.28	8.34	5.44	8.19	22.50	5.88	11.06	10.44
TC_WI+UE+RC_SVM+CC_R+UE	19.06	22.25	20.47	8.38	5.59	16.47	28.81	6.28	28.16	10.59
TC_WI+UE+RC_SVM+CC_R	10.31	10.38	20.28	8.34	5.50	8.19	22.53	5.88	11.06	10.47
TC_WI+UE+RC_SVM	12.50	12.09	25.09	9.78	6.22	8.84	27.34	5.88	12.12	12.09
TC_WI+UE+RC_EA+CC_RMIap+UE	16.06	17.59	32.84	9.69	7.50	13.22	30.44	7.75	15.56	14.53
TC_WI+UE+RC_EA+CC_RMIap	10.31	10.38	20.28	8.38	5.44	8.19	22.53	5.88	11.06	10.47
TC_WI+UE+RC_EA+CC_MIap+UE	15.66	22.97	27.56	9.25	7.84	13.91	30.50	9.69	20.38	15.22
TC_WI+UE+RC_EA+CC_MIap	10.31	10.38	20.28	8.34	5.44	8.19	22.53	5.88	11.06	10.47
TC_WI+UE+RC_EA+CC_RIap+UE	13.22	20.00	25.62	9.72	7.19	16.97	28.22	8.50	20.66	12.75
TC_WI+UE+RC_EA+CC_RIap	10.31	10.38	20.28	8.38	5.47	8.19	22.53	5.88	11.09	10.47
TC_WI+UE+RC_EA+CC_RM+UE	22.09	22.31	24.38	8.41	5.78	16.91	50.00	7.31	32.25	12.50
TC_WI+UE+RC_EA+CC_RM	10.31	10.38	20.28	8.38	5.44	8.19	22.53	5.88	11.06	10.47
TC_WI+UE+RC_EA+CC_Iap+UE	13.59	19.50	28.78	9.53	7.97	11.81	31.88	9.22	20.09	15.28
TC_WI+UE+RC_EA+CC_Iap	10.34	10.41	20.28	8.41	5.47	8.19	22.53	5.88	11.09	10.50
TC_WI+UE+RC_EA+CC_M+UE	13.38	16.81	21.88	8.44	5.75	11.44	49.31	7.00	23.41	11.03
TC_WI+UE+RC_EA+CC_M	10.31	10.38	20.28	8.34	5.44	8.19	22.53	5.88	11.06	10.47
TC_WI+UE+RC_EA+CC_R+UE	13.66	22.25	20.50	8.41	5.59	16.50	28.81	6.28	28.16	10.66
TC_WI+UE+RC_EA+CC_R	10.31	10.38	20.28	8.38	5.50	8.19	22.53	5.88	11.09	10.47
TC_WI+UE+RC_EA	12.50	12.09	25.09	9.78	6.22	8.84	27.34	5.88	12.12	12.09
TC_WI+UE	12.50	12.09	25.09	9.78	6.22	8.84	27.34	5.88	12.12	12.09

Table H.1.4: Simulated project cost / engineering consultant project revenue

Model Simulation Run-name	Project Number / Project Cost / Engineering Consultant Project Revenue (R million)									
	[P0]	[P1]	[P2]	[P3]	[P4]	[P5]	[P6]	[P7]	[P8]	[P9]
TC_WI+UE+RC_EASVM+CC_RMIap+UE	15.910	16.820	45.510	6.059	3.854	6.942	22.630	3.517	14.360	11.660
TC_WI+UE+RC_EASVM+CC_RMIap	11.880	12.990	36.280	5.352	3.480	5.451	18.520	3.203	11.280	9.239
TC_WI+UE+RC_EASVM+CC_MIap+UE	14.040	19.290	41.480	5.641	3.915	7.007	21.190	4.040	15.200	10.840
TC_WI+UE+RC_EASVM+CC_MIap	11.880	12.990	36.280	5.332	3.480	5.451	18.490	3.203	11.280	9.239
TC_WI+UE+RC_EASVM+CC_RIap+UE	13.100	17.670	40.770	6.079	3.706	7.937	20.550	3.718	15.600	10.030
TC_WI+UE+RC_EASVM+CC_RIap	11.880	12.990	36.280	5.352	3.500	5.451	18.520	3.203	11.280	9.239
TC_WI+UE+RC_EASVM+CC_RM+UE	25.450	27.930	43.610	5.372	3.700	11.260	40.920	4.004	32.740	11.030
TC_WI+UE+RC_EASVM+CC_RM	11.880	12.990	36.280	5.352	3.480	5.451	18.520	3.203	11.280	9.239
TC_WI+UE+RC_EASVM+CC_Iap+UE	12.080	15.040	39.830	5.437	3.584	5.865	20.380	3.476	13.140	10.050
TC_WI+UE+RC_EASVM+CC_Iap	11.920	13.030	36.280	5.372	3.500	5.451	18.490	3.203	11.280	9.266
TC_WI+UE+RC_EASVM+CC_M+UE	15.410	21.050	39.190	5.392	3.680	7.615	40.460	3.817	23.800	9.735
TC_WI+UE+RC_EASVM+CC_M	11.880	12.990	36.280	5.332	3.480	5.451	18.490	3.203	11.280	9.239
TC_WI+UE+RC_EASVM+CC_R+UE	15.730	27.850	36.680	5.372	3.580	10.990	23.610	3.425	28.620	9.652
TC_WI+UE+RC_EASVM+CC_R	11.880	12.990	36.280	5.352	3.520	5.451	18.520	3.203	11.280	9.239
TC_WI+UE+RC_EASVM	14.400	15.140	44.890	6.251	3.980	5.888	22.380	3.203	12.300	10.670
TC_WI+UE+RC_SVM+CC_RMIap+UE	16.070	16.750	45.660	6.087	3.854	6.942	22.090	3.517	14.310	11.660
TC_WI+UE+RC_SVM+CC_RMIap	11.880	12.990	36.280	5.332	3.480	5.451	18.440	3.203	11.220	9.239
TC_WI+UE+RC_SVM+CC_MIap+UE	14.040	19.290	41.460	5.660	3.915	7.007	21.170	4.040	15.120	10.820
TC_WI+UE+RC_SVM+CC_MIap	11.880	12.990	36.280	5.332	3.480	5.451	18.410	3.203	11.220	9.211
TC_WI+UE+RC_SVM+CC_RIap+UE	13.100	17.710	40.770	6.079	3.716	7.937	20.200	3.718	15.520	10.020
TC_WI+UE+RC_SVM+CC_RIap	11.880	12.990	36.280	5.332	3.500	5.451	18.440	3.203	11.220	9.239
TC_WI+UE+RC_SVM+CC_RM+UE	25.490	27.930	43.610	5.372	3.700	11.260	40.920	4.004	32.710	11.030
TC_WI+UE+RC_SVM+CC_RM	11.880	12.990	36.280	5.332	3.480	5.451	18.440	3.203	11.220	9.239
TC_WI+UE+RC_SVM+CC_Iap+UE	12.050	15.030	39.810	5.437	3.564	5.865	20.320	3.476	13.110	10.040
TC_WI+UE+RC_SVM+CC_Iap	11.880	13.030	36.280	5.372	3.500	5.451	18.410	3.203	11.250	9.239
TC_WI+UE+RC_SVM+CC_M+UE	15.440	21.050	39.190	5.392	3.680	7.615	40.460	3.817	23.740	9.735
TC_WI+UE+RC_SVM+CC_M	11.880	12.990	36.280	5.332	3.480	5.451	18.410	3.203	11.220	9.211
TC_WI+UE+RC_SVM+CC_R+UE	21.960	27.850	36.620	5.352	3.580	10.960	23.580	3.425	28.560	9.349
TC_WI+UE+RC_SVM+CC_R	11.880	12.990	36.280	5.332	3.520	5.451	18.440	3.203	11.220	9.239
TC_WI+UE+RC_SVM	14.400	15.140	44.890	6.251	3.980	5.888	22.380	3.203	12.300	10.670
TC_WI+UE+RC_EA+CC_RMIap+UE	15.860	16.450	45.630	6.039	3.854	6.942	22.040	3.517	14.280	11.020
TC_WI+UE+RC_EA+CC_RMIap	11.880	12.990	36.280	5.352	3.480	5.451	18.440	3.203	11.220	9.239
TC_WI+UE+RC_EA+CC_MIap+UE	14.020	19.220	41.390	5.641	3.915	7.007	21.160	4.031	15.130	10.830
TC_WI+UE+RC_EA+CC_MIap	11.880	12.990	36.280	5.332	3.480	5.451	18.440	3.203	11.220	9.239
TC_WI+UE+RC_EA+CC_RIap+UE	13.080	17.670	40.690	6.059	3.711	7.937	20.490	3.718	15.520	10.020
TC_WI+UE+RC_EA+CC_RIap	11.880	12.990	36.280	5.352	3.500	5.451	18.440	3.203	11.250	9.239
TC_WI+UE+RC_EA+CC_RM+UE	25.450	27.930	43.610	5.372	3.700	11.260	40.920	3.987	32.710	11.030
TC_WI+UE+RC_EA+CC_RM	11.880	12.990	36.280	5.352	3.480	5.451	18.440	3.203	11.220	9.239
TC_WI+UE+RC_EA+CC_Iap+UE	12.100	15.040	39.830	5.437	3.584	5.865	20.320	3.476	13.120	10.070
TC_WI+UE+RC_EA+CC_Iap	11.920	13.030	36.280	5.372	3.500	5.451	18.440	3.203	11.250	9.266
TC_WI+UE+RC_EA+CC_M+UE	15.410	21.050	39.140	5.392	3.680	7.615	40.360	3.817	23.740	9.735
TC_WI+UE+RC_EA+CC_M	11.880	12.990	36.280	5.332	3.480	5.451	18.440	3.203	11.220	9.239
TC_WI+UE+RC_EA+CC_R+UE	15.730	27.850	36.680	5.372	3.580	10.990	23.580	3.425	28.560	9.404
TC_WI+UE+RC_EA+CC_R	11.880	12.990	36.280	5.352	3.520	5.451	18.440	3.203	11.250	9.239
TC_WI+UE+RC_EA	14.400	15.140	44.890	6.251	3.980	5.888	22.380	3.203	12.300	10.670
TC_WI+UE	14.400	15.140	44.890	6.251	3.980	5.888	22.380	3.203	12.300	10.670

Model Simulations per Project (renewals related projects)

Table H.2.1: Simulated project time schedule duration

Model Simulation Run-name	Project Number / Project Time Schedule Duration (months)							
	[P10]	[P11]	[P12]	[P13]	[P14]	[P15]	[P16]	[P17]
TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE	14.25	6.47	4.78	7.53	11.78	8.00	13.03	5.50
TC_WI+UE+CC_RMIap+UE+RC_SVM+UE	14.25	6.53	4.78	7.53	11.78	7.94	13.03	5.50
TC_WI+UE+CC_RMIap+UE+RC_EA+UE	14.25	6.53	4.78	7.53	11.78	7.97	13.03	5.50
TC_WI+UE+CC_RMIap+UE	14.16	6.72	4.78	6.88	11.78	8.25	12.94	5.47
TC_WI+UE+CC_RMIap	8.75	4.69	4.22	5.59	9.44	5.59	7.06	4.69
TC_WI+UE+CC_MIap+UE+RC_EASVM+UE	15.88	6.63	4.81	7.13	17.19	7.47	14.66	5.47
TC_WI+UE+CC_MIap+UE+RC_SVM+UE	15.88	6.63	4.81	7.13	17.19	7.47	14.66	5.47
TC_WI+UE+CC_MIap+UE+RC_EA+UE	15.88	6.63	4.81	7.13	17.19	7.47	14.66	5.47
TC_WI+UE+CC_MIap+UE	15.81	6.63	4.81	7.09	17.19	7.34	14.47	5.47
TC_WI+UE+CC_MIap	8.75	4.66	4.25	5.59	9.44	5.59	7.06	4.72
TC_WI+UE+CC_RIap+UE+RC_EASVM+UE	14.38	6.28	4.81	6.69	17.69	6.75	17.16	5.59
TC_WI+UE+CC_RIap+UE+RC_SVM+UE	14.38	6.28	4.81	6.69	17.69	6.75	17.16	5.59
TC_WI+UE+CC_RIap+UE+RC_EA+UE	14.38	6.28	4.81	6.69	17.69	6.75	17.16	5.59
TC_WI+UE+CC_RIap+UE	14.12	6.22	4.81	6.69	17.69	6.75	17.16	5.56
TC_WI+UE+CC_RIap	8.75	4.75	4.25	5.56	9.44	5.59	7.06	4.78
TC_WI+UE+CC_RM+UE+RC_EASVM+UE	18.66	5.03	4.31	6.09	19.75	6.16	14.00	4.84
TC_WI+UE+CC_RM+UE+RC_SVM+UE	18.66	5.03	4.31	6.09	19.75	6.16	14.00	4.84
TC_WI+UE+CC_RM+UE+RC_EA+UE	18.66	5.03	4.31	6.09	19.75	6.16	14.00	4.84
TC_WI+UE+CC_RM+UE	18.62	5.00	4.31	6.06	19.75	5.84	13.97	4.81
TC_WI+UE+CC_RM	8.75	4.66	4.22	5.56	9.44	5.59	7.06	4.69
TC_WI+UE+CC_Iap+UE+RC_EASVM+UE	14.59	8.50	5.59	8.56	14.91	8.44	11.16	6.28
TC_WI+UE+CC_Iap+UE+RC_SVM+UE	14.59	8.50	5.59	8.56	14.91	8.44	11.16	6.28
TC_WI+UE+CC_Iap+UE+RC_EA+UE	14.59	8.50	5.59	8.56	14.91	8.44	11.16	6.28
TC_WI+UE+CC_Iap+UE	14.44	8.31	5.59	8.63	14.91	8.44	11.09	6.28
TC_WI+UE+CC_Iap	8.81	4.78	4.44	5.75	9.50	5.75	7.09	4.84
TC_WI+UE+CC_M+UE+RC_EASVM+UE	10.88	5.00	4.34	5.91	17.03	5.91	12.06	4.81
TC_WI+UE+CC_M+UE+RC_SVM+UE	10.88	5.00	4.34	5.91	17.03	5.91	12.06	4.81
TC_WI+UE+CC_M+UE+RC_EA+UE	10.88	5.00	4.34	5.91	17.03	5.91	12.06	4.81
TC_WI+UE+CC_M+UE	10.84	5.00	4.34	5.88	17.03	5.88	12.00	4.81
TC_WI+UE+CC_M	8.72	4.66	4.22	5.59	9.44	5.59	7.06	4.72
TC_WI+UE+CC_R+UE+RC_EASVM+UE	18.84	4.94	4.31	5.78	19.38	5.78	14.41	4.88
TC_WI+UE+CC_R+UE+RC_SVM+UE	18.84	4.94	4.31	5.78	19.38	5.78	14.41	4.88
TC_WI+UE+CC_R+UE+RC_EA+UE	18.84	4.94	4.31	5.78	19.38	5.78	14.41	4.88
TC_WI+UE+CC_R+UE	18.81	4.91	4.31	5.69	19.38	5.69	14.38	4.88
TC_WI+UE+CC_R	8.75	4.75	4.25	5.56	9.44	5.59	7.06	4.78
TC_WI+UE	10.53	5.41	4.72	6.59	10.69	6.63	7.53	5.28

Table H.2.2: Simulated project cost / engineering consultant project revenue

Model Simulation Run-name	Project Number / Project Cost / Engineering Consultant Project Revenue (R million)							
	[P10]	[P11]	[P12]	[P13]	[P14]	[P15]	[P16]	[P17]
TC_WI+UE+CC_RMIap+UE+RC_EASVM+UE	7.344	2.876	2.807	4.754	8.321	3.781	8.126	2.635
TC_WI+UE+CC_RMIap+UE+RC_SVM+UE	7.344	2.891	2.807	4.754	8.321	3.755	8.126	2.635
TC_WI+UE+CC_RMIap+UE+RC_EA+UE	7.344	2.891	2.807	4.754	8.321	3.764	8.126	2.635
TC_WI+UE+CC_RMIap+UE	7.297	2.927	2.807	4.457	8.319	3.865	8.087	2.623
TC_WI+UE+CC_RMIap	5.706	2.678	2.674	4.034	7.164	3.087	5.889	2.468
TC_WI+UE+CC_MIap+UE+RC_EASVM+UE	7.090	2.945	2.748	4.364	9.502	3.395	8.032	2.612
TC_WI+UE+CC_MIap+UE+RC_SVM+UE	7.090	2.945	2.748	4.364	9.502	3.395	8.032	2.612
TC_WI+UE+CC_MIap+UE+RC_EA+UE	7.090	2.945	2.748	4.364	9.502	3.395	8.032	2.612
TC_WI+UE+CC_MIap+UE	7.069	2.942	2.748	4.336	9.495	3.339	7.976	2.612
TC_WI+UE+CC_MIap	5.706	2.661	2.694	4.034	7.164	3.087	5.889	2.484
TC_WI+UE+CC_RIap+UE+RC_EASVM+UE	7.069	2.828	2.804	4.441	9.862	3.378	8.885	2.643
TC_WI+UE+CC_RIap+UE+RC_SVM+UE	7.069	2.828	2.804	4.441	9.862	3.378	8.885	2.643
TC_WI+UE+CC_RIap+UE+RC_EA+UE	7.069	2.828	2.804	4.441	9.862	3.378	8.885	2.643
TC_WI+UE+CC_RIap+UE	7.022	2.813	2.804	4.439	9.862	3.386	8.888	2.631
TC_WI+UE+CC_RIap	5.706	2.714	2.694	4.011	7.164	3.087	5.889	2.517
TC_WI+UE+CC_RM+UE+RC_EASVM+UE	12.170	2.875	2.733	4.394	14.990	3.398	11.670	2.550
TC_WI+UE+CC_RM+UE+RC_SVM+UE	12.170	2.875	2.733	4.394	14.990	3.398	11.670	2.550
TC_WI+UE+CC_RM+UE+RC_EA+UE	12.170	2.875	2.733	4.394	14.990	3.398	11.670	2.550
TC_WI+UE+CC_RM+UE	12.140	2.857	2.733	4.372	14.990	3.225	11.650	2.534
TC_WI+UE+CC_RM	5.706	2.661	2.674	4.011	7.164	3.087	5.889	2.468
TC_WI+UE+CC_Iap+UE+RC_EASVM+UE	6.233	3.109	2.857	4.483	7.927	3.358	6.292	2.703
TC_WI+UE+CC_Iap+UE+RC_SVM+UE	6.233	3.109	2.857	4.483	7.927	3.358	6.292	2.703
TC_WI+UE+CC_Iap+UE+RC_EA+UE	6.233	3.109	2.857	4.483	7.927	3.358	6.292	2.703
TC_WI+UE+CC_Iap+UE	6.195	3.087	2.857	4.500	7.921	3.362	6.278	2.703
TC_WI+UE+CC_Iap	5.746	2.732	2.813	4.146	7.212	3.174	5.915	2.550
TC_WI+UE+CC_M+UE+RC_EASVM+UE	7.091	2.857	2.753	4.259	12.930	3.260	10.060	2.534
TC_WI+UE+CC_M+UE+RC_SVM+UE	7.091	2.857	2.753	4.259	12.930	3.260	10.060	2.534
TC_WI+UE+CC_M+UE+RC_EA+UE	7.091	2.857	2.753	4.259	12.930	3.260	10.060	2.534
TC_WI+UE+CC_M+UE	7.071	2.857	2.753	4.237	12.930	3.243	10.010	2.534
TC_WI+UE+CC_M	5.685	2.661	2.674	4.034	7.164	3.087	5.889	2.484
TC_WI+UE+CC_R+UE+RC_EASVM+UE	12.290	2.821	2.733	4.169	14.710	3.191	12.010	2.566
TC_WI+UE+CC_R+UE+RC_SVM+UE	12.290	2.821	2.733	4.169	14.710	3.191	12.010	2.566
TC_WI+UE+CC_R+UE+RC_EA+UE	12.290	2.821	2.733	4.169	14.710	3.191	12.010	2.566
TC_WI+UE+CC_R+UE	12.270	2.803	2.733	4.101	14.710	3.139	11.990	2.566
TC_WI+UE+CC_R	5.706	2.714	2.694	4.011	7.164	3.087	5.889	2.517
TC_WI+UE	6.867	3.089	2.991	4.755	8.113	3.657	6.279	2.780

Table H.2.3: Simulated project time schedule duration

Model Simulation Run-name	Project Number / Project Time Schedule Duration (months)							
	[P10]	[P11]	[P12]	[P13]	[P14]	[P15]	[P16]	[P17]
TC_WI+UE+RC_EASVM+CC_RMIap+UE	14.25	6.47	4.78	7.53	11.78	8.00	13.03	5.50
TC_WI+UE+RC_EASVM+CC_RMIap	8.88	4.72	4.22	5.69	9.44	5.69	7.06	4.72
TC_WI+UE+RC_EASVM+CC_MIap+UE	15.88	6.63	4.81	7.13	17.19	7.47	14.66	5.47
TC_WI+UE+RC_EASVM+CC_MIap	8.84	4.69	4.25	5.69	9.44	5.69	7.09	4.72
TC_WI+UE+RC_EASVM+CC_RIap+UE	14.38	6.28	4.81	6.69	17.69	6.75	17.16	5.59
TC_WI+UE+RC_EASVM+CC_RIap	8.88	4.78	4.25	5.69	9.44	5.69	7.06	4.78
TC_WI+UE+RC_EASVM+CC_RM+UE	18.66	5.03	4.31	6.09	19.75	6.16	14.00	4.84
TC_WI+UE+RC_EASVM+CC_RM	8.88	4.72	4.22	5.66	9.44	5.69	7.06	4.72
TC_WI+UE+RC_EASVM+CC_Iap+UE	14.59	8.53	5.59	8.56	14.91	8.44	11.16	6.28
TC_WI+UE+RC_EASVM+CC_Iap	8.91	4.81	4.44	5.78	9.50	5.78	7.09	4.88
TC_WI+UE+RC_EASVM+CC_M+UE	10.88	5.03	4.34	5.91	17.03	5.91	12.06	4.81
TC_WI+UE+RC_EASVM+CC_M	8.84	4.69	4.25	5.66	9.44	5.69	7.06	4.72
TC_WI+UE+RC_EASVM+CC_R+UE	18.84	4.94	4.31	5.78	19.38	5.78	14.41	4.88
TC_WI+UE+RC_EASVM+CC_R	8.88	4.78	4.25	5.69	9.44	5.69	7.06	4.81
TC_WI+UE+RC_EASVM	10.53	5.41	4.72	6.59	10.69	6.63	7.53	5.28
TC_WI+UE+RC_SVM+CC_RMIap+UE	14.25	6.53	4.78	7.53	11.78	7.94	13.03	5.50
TC_WI+UE+RC_SVM+CC_RMIap	8.88	4.72	4.22	5.69	9.44	5.69	7.06	4.72
TC_WI+UE+RC_SVM+CC_MIap+UE	15.88	6.63	4.81	7.13	17.19	7.47	14.66	5.47
TC_WI+UE+RC_SVM+CC_MIap	8.84	4.69	4.25	5.69	9.44	5.69	7.09	4.72
TC_WI+UE+RC_SVM+CC_RIap+UE	14.38	6.28	4.81	6.69	17.69	6.75	17.16	5.59
TC_WI+UE+RC_SVM+CC_RIap	8.88	4.78	4.25	5.69	9.44	5.69	7.06	4.78
TC_WI+UE+RC_SVM+CC_RM+UE	18.66	5.03	4.31	6.09	19.75	6.16	14.00	4.84
TC_WI+UE+RC_SVM+CC_RM	8.88	4.72	4.22	5.66	9.44	5.69	7.06	4.72
TC_WI+UE+RC_SVM+CC_Iap+UE	14.59	8.50	5.59	8.56	14.91	8.44	11.16	6.28
TC_WI+UE+RC_SVM+CC_Iap	8.91	4.81	4.44	5.78	9.50	5.78	7.09	4.88
TC_WI+UE+RC_SVM+CC_M+UE	10.88	5.00	4.34	5.91	17.03	5.91	12.06	4.81
TC_WI+UE+RC_SVM+CC_M	8.84	4.69	4.25	5.66	9.44	5.69	7.06	4.72
TC_WI+UE+RC_SVM+CC_R+UE	18.84	4.94	4.31	5.78	19.38	5.78	14.41	4.88
TC_WI+UE+RC_SVM+CC_R	8.88	4.78	4.25	5.69	9.44	5.69	7.06	4.78
TC_WI+UE+RC_SVM	10.53	5.41	4.72	6.59	10.69	6.63	7.53	5.28
TC_WI+UE+RC_EA+CC_RMIap+UE	14.25	6.53	4.78	7.53	11.78	7.97	13.03	5.50
TC_WI+UE+RC_EA+CC_RMIap	8.88	4.72	4.22	5.69	9.44	5.69	7.06	4.72
TC_WI+UE+RC_EA+CC_MIap+UE	15.88	6.63	4.81	7.13	17.19	7.47	14.66	5.47
TC_WI+UE+RC_EA+CC_MIap	8.84	4.69	4.25	5.69	9.44	5.69	7.09	4.72
TC_WI+UE+RC_EA+CC_RIap+UE	14.38	6.28	4.81	6.69	17.69	6.75	17.16	5.59
TC_WI+UE+RC_EA+CC_RIap	8.88	4.78	4.25	5.69	9.44	5.69	7.06	4.78
TC_WI+UE+RC_EA+CC_RM+UE	18.66	5.03	4.31	6.09	19.75	6.16	14.00	4.84
TC_WI+UE+RC_EA+CC_RM	8.88	4.72	4.22	5.66	9.44	5.69	7.06	4.72
TC_WI+UE+RC_EA+CC_Iap+UE	14.59	8.50	5.59	8.56	14.91	8.44	11.16	6.28
TC_WI+UE+RC_EA+CC_Iap	8.91	4.81	4.44	5.78	9.50	5.78	7.09	4.88
TC_WI+UE+RC_EA+CC_M+UE	10.88	5.00	4.34	5.91	17.03	5.91	12.06	4.81
TC_WI+UE+RC_EA+CC_M	8.84	4.69	4.25	5.66	9.44	5.69	7.06	4.72
TC_WI+UE+RC_EA+CC_R+UE	18.84	4.94	4.31	5.78	19.38	5.78	14.41	4.88
TC_WI+UE+RC_EA+CC_R	8.88	4.78	4.25	5.69	9.44	5.69	7.06	4.81
TC_WI+UE+RC_EA	10.53	5.41	4.72	6.59	10.69	6.63	7.53	5.28
TC_WI+UE	10.53	5.41	4.72	6.59	10.69	6.63	7.53	5.28

Table H.2.4: Simulated project cost / engineering consultant project revenue

Model Simulation Run-name	Project Number / Project Cost / Engineering Consultant Project Revenue (R million)							
	[P10]	[P11]	[P12]	[P13]	[P14]	[P15]	[P16]	[P17]
TC_WI+UE+RC_EASVM+CC_RMlap+UE	7.344	2.876	2.807	4.754	8.321	3.781	8.126	2.635
TC_WI+UE+RC_EASVM+CC_RMlap	5.787	2.696	2.674	4.101	7.164	3.139	5.889	2.484
TC_WI+UE+RC_EASVM+CC_Mlap+UE	7.090	2.945	2.748	4.364	9.502	3.395	8.032	2.612
TC_WI+UE+RC_EASVM+CC_Mlap	5.767	2.678	2.694	4.101	7.164	3.139	5.915	2.484
TC_WI+UE+RC_EASVM+CC_Rlap+UE	7.069	2.828	2.804	4.441	9.862	3.378	8.885	2.643
TC_WI+UE+RC_EASVM+CC_Rlap	5.787	2.732	2.694	4.101	7.164	3.139	5.889	2.517
TC_WI+UE+RC_EASVM+CC_RM+UE	12.170	2.875	2.733	4.394	14.990	3.398	11.670	2.550
TC_WI+UE+RC_EASVM+CC_RM	5.787	2.696	2.674	4.079	7.164	3.139	5.889	2.484
TC_WI+UE+RC_EASVM+CC_lap+UE	6.233	3.116	2.857	4.483	7.927	3.358	6.292	2.703
TC_WI+UE+RC_EASVM+CC_lap	5.808	2.750	2.813	4.169	7.212	3.191	5.915	2.566
TC_WI+UE+RC_EASVM+CC_M+UE	7.091	2.875	2.753	4.259	12.930	3.260	10.060	2.534
TC_WI+UE+RC_EASVM+CC_M	5.767	2.678	2.694	4.079	7.164	3.139	5.889	2.484
TC_WI+UE+RC_EASVM+CC_R+UE	12.290	2.821	2.733	4.169	14.710	3.191	12.010	2.566
TC_WI+UE+RC_EASVM+CC_R	5.787	2.732	2.694	4.101	7.164	3.139	5.889	2.534
TC_WI+UE+RC_EASVM	6.867	3.089	2.991	4.755	8.113	3.657	6.279	2.780
TC_WI+UE+RC_SVM+CC_RMlap+UE	7.344	2.891	2.807	4.754	8.321	3.755	8.126	2.635
TC_WI+UE+RC_SVM+CC_RMlap	5.787	2.696	2.674	4.101	7.164	3.139	5.889	2.484
TC_WI+UE+RC_SVM+CC_Mlap+UE	7.090	2.945	2.748	4.364	9.502	3.395	8.032	2.612
TC_WI+UE+RC_SVM+CC_Mlap	5.767	2.678	2.694	4.101	7.164	3.139	5.915	2.484
TC_WI+UE+RC_SVM+CC_Rlap+UE	7.069	2.828	2.804	4.441	9.862	3.378	8.885	2.643
TC_WI+UE+RC_SVM+CC_Rlap	5.787	2.732	2.694	4.101	7.164	3.139	5.889	2.517
TC_WI+UE+RC_SVM+CC_RM+UE	12.170	2.875	2.733	4.394	14.990	3.398	11.670	2.550
TC_WI+UE+RC_SVM+CC_RM	5.787	2.696	2.674	4.079	7.164	3.139	5.889	2.484
TC_WI+UE+RC_SVM+CC_lap+UE	6.233	3.109	2.857	4.483	7.927	3.358	6.292	2.703
TC_WI+UE+RC_SVM+CC_lap	5.808	2.750	2.813	4.169	7.212	3.191	5.915	2.566
TC_WI+UE+RC_SVM+CC_M+UE	7.091	2.857	2.753	4.259	12.930	3.260	10.060	2.534
TC_WI+UE+RC_SVM+CC_M	5.767	2.678	2.694	4.079	7.164	3.139	5.889	2.484
TC_WI+UE+RC_SVM+CC_R+UE	12.290	2.821	2.733	4.169	14.710	3.191	12.010	2.566
TC_WI+UE+RC_SVM+CC_R	5.787	2.732	2.694	4.101	7.164	3.139	5.889	2.517
TC_WI+UE+RC_SVM	6.867	3.089	2.991	4.755	8.113	3.657	6.279	2.780
TC_WI+UE+RC_EA+CC_RMlap+UE	7.344	2.891	2.807	4.754	8.321	3.764	8.126	2.635
TC_WI+UE+RC_EA+CC_RMlap	5.787	2.696	2.674	4.101	7.164	3.139	5.889	2.484
TC_WI+UE+RC_EA+CC_Mlap+UE	7.090	2.945	2.748	4.364	9.502	3.395	8.032	2.612
TC_WI+UE+RC_EA+CC_Mlap	5.767	2.678	2.694	4.101	7.164	3.139	5.915	2.484
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TC_WI+UE+RC_EA+CC_RM+UE	12.170	2.875	2.733	4.394	14.990	3.398	11.670	2.550
TC_WI+UE+RC_EA+CC_RM	5.787	2.696	2.674	4.079	7.164	3.139	5.889	2.484
TC_WI+UE+RC_EA+CC_lap+UE	6.233	3.109	2.857	4.483	7.927	3.358	6.292	2.703
TC_WI+UE+RC_EA+CC_lap	5.808	2.750	2.813	4.169	7.212	3.191	5.915	2.566
TC_WI+UE+RC_EA+CC_M+UE	7.091	2.857	2.753	4.259	12.930	3.260	10.060	2.534
TC_WI+UE+RC_EA+CC_M	5.767	2.678	2.694	4.079	7.164	3.139	5.889	2.484
TC_WI+UE+RC_EA+CC_R+UE	12.290	2.821	2.733	4.169	14.710	3.191	12.010	2.566
TC_WI+UE+RC_EA+CC_R	5.787	2.732	2.694	4.101	7.164	3.139	5.889	2.534
TC_WI+UE+RC_EA	6.867	3.089	2.991	4.755	8.113	3.657	6.279	2.780
TC_WI+UE	6.867	3.089	2.991	4.755	8.113	3.657	6.279	2.780

Appendix I: Simulation model policy optimisation Vensim configuration details

Vensim payoff definition *.vpd* file details text:

```
*P
Project Optimisation Payoff[project]/Project Optimisation Payoff Weight
```

Vensim optimisation control *.voc* file details text:

```
:OPTIMIZER=Powell
:SENSITIVITY=Off
:MULTIPLE_START=Off
:RANDOM_NUMER=Default
:OUTPUT_LEVEL=On
:TRACE=Off
:MAX_ITERATIONS=1000
:RESTART_MAX=0
:PASS_LIMIT=2
:FRACTIONAL_TOLERANCE=0.0003
:TOLERANCE_MULTIPLIER=21
:ABSOLUTE_TOLERANCE=1
:SCALE_ABSOLUTE=1
:VECTOR_POINTS=25
:MCINITMETHOD=0
:MCPAYOFFTYPE=0
:MCRECORD=0
:MCSCHEDULE=0
:MCLIMIT=0
:MCBURNIN=0
:MCNCHAINS=2
:MCOUTLIER=0.05
:MCGAMMA=1
:MCEPSILON=0.01
:MCDELTA=0.0001
:MCJUMP=0.05
:MCUPDATEPAIRS=2
:MCXOVER=0.2
:MCTEMP=1
:MCFTEMP=1
:MCCOOLING=1000
0<="client project cost variance % at completion target"[project]<=0.5
```