MODELLING METHODOLOGY FOR ASSESSING THE IMPACT OF NEW TECHNOLOGY ON COMPLEX SOCIOTECHNICAL SYSTEMS

by

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ABSTRACT

MODELLING METHODOLOGY FOR COMPLEX SOCIOTECHNICAL SYSTEMS

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Abstract

Developing complex sociotechnical systems often involves integrating new technology into existing systems by applying systems engineering processes. This requires an understanding of the problem space and the possible impact of the new technology. Systems engineering uses modelling to explore the structural, functional, and operational elements of the problem and solution space (Hitchins 2008). Historically, systems engineering has however struggled with complex sociotechnical systems projects, as it cannot cope with the dynamic behaviour of complex sociotechnical systems.

The hypothesis of this thesis is that addressing the contribution of humans performing work in a complex, constrained and dynamic environment using modelling will result in a better understanding in the analysis phase; it should also lead to improved requirements, designs, selection of technologies, and implementation strategies, enabling sociotechnical systems to cope with complex operating environments.

A sociotechnical system consists of humans applying technology to perform work through processes within a social structure (organisation) aimed at achieving a defined objective (Bostrom & Heinen 1977, Walker et al. 2009). Work can become complex due to non-linear and dynamic interaction among the people themselves, among people and technology, as well as among people and the environment. Complexity may lead to "wicked and messy" problems, as many unintended or unpredicted consequences may be experienced. The new technology may also lead to new task possibilities that evolve user requirements (Carroll & Rosson 1992).

Systems engineering, as developed in the 1950s, forms the basis of developing systems, including sociotechnical systems. Classic systems engineering processes assume that problems can be isolated and decomposed, making the development of complex sociotechnical systems difficult. One way to improve the success of systems engineering is to ensure that the problem to be solved is properly understood. Analysis of the problem and solution space involves capturing and modelling the knowledge and mental models of the stakeholders, to support understanding the system's requirements. A good description of the problem situation through a model is the first step towards designing and developing a solution.

The aim of this study is to develop and demonstrate a modelling methodology for complex sociotechnical systems, in support of the systems engineering process. The two approaches used in the modelling methodology are cognitive work analysis and system dynamics. Cognitive work analysis is a framework for analysing the way people perform work in an organisation, while taking the environmental constraints into consideration. The outputs of cognitive work analysis are constructs or models that capture the structure of the problem. Functions provided by different technological elements are linked to the functional requirements of the system, to achieve its purpose (Lintern 2012). However, cognitive work analysis is limited in investigating the dynamic effect of decisions and policies on the system (Cummings 2006). The dynamic behaviour of complex sociotechnical systems can be analysed using system dynamics, which uses the structure of the system in simulation. System dynamics analyse the effect of feedback and delays on operating the system, as a result of decisions based on policies (Sterman 2000).

The design science research framework, which also supports the research design of this thesis, is used to implement the modelling and structure the methodology. Design science research aims at creating technology for a human purpose, unlike the natural sciences, which are geared towards attempting to understand and define reality (March & Smith 1995). The proposed methodology is demonstrated in a case study using modelling and analysis of the impact of a new collaboration technology on command and control systems. Command and control is a good example of a complex sociotechnical system, as humans use technology to assemble and analyse information for situation assessment in support of planning operations (Walker et al. 2009). These systems are also used to control the successful implementation of plans in constrained and variable operating environments.

The modelling methodology is demonstrated by modelling and assessing the effect of a new command and control technology for border safeguarding operations, anti-poaching operations and community policing forums. The new technology to be implemented in these complex sociotechnical systems is called “Cmore”. It is a web-based collaboration system that uses smartphones to capture information and track users. Even though the three demonstrations constitute similar systems, the different contextual situations result in diverse behaviour and issues to be investigated.

The demonstrations centre on the functions of situation awareness and decision support. The different output models for the command and control systems are used in system dynamics simulations to assess the effect of new technology on the operating and effectiveness of a system. The case studies demonstrated that the modelling methodology support learning about the implementation of a new technology in various complex sociotechnical systems. The developed models and constructs also supported developing evaluation templates during the planning of experiments through identifying key issues.

The system dynamics simulations used parametric inputs to investigate the behaviour of the system. In most cases, the simulation outputs identified interesting and counter-intuitive behaviour for deeper assessment. The community policing forum case study also gathered qualitative empirical evidence on the system's behaviour, during a field experiment. The outcomes are compared with the models and simulation outputs to improve the system behavioural models. The learning and improved understanding of the complex sociotechnical system behaviour gained through the modelling methodology, demonstrated its utility.

Papers and Publications by the Author:

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LIST OF ACRONYMS

Acronym	Description
ADH	Abstraction Decomposition Hierarchy
APO	Anti-Poaching Operations
BSO	Border Safeguarding Operations
C2	Command and Control
CLD	Causal Loop Diagrams
ConOps	Concept of Operation
CPF	Community Policing Forums
CWA	Cognitive Work Analysis
DSR	Design Science Research
KNP	Kruger National Park
M&S	Modelling and Simulation
MBSE	Model-Based Systems Engineering
MoE	Measures of Effectiveness
NW	Neighbourhood Watch
OODA	Observe Orientate Decide Act
RoE	Rules of Engagement
SAP	Situation Awareness Picture
SART	Situation Awareness Rating Technique
SD	System Dynamics
SE	Systems Engineering
SFD	Stock and Flow Diagrams
SME	Subject Matter Expert
SSM	Soft Systems Methodology
STS	Sociotechnical System
WDA	Work Domain Analysis

1 INTRODUCTION, PURPOSE AND EXPECTED CONTRIBUTION OF THIS STUDY

Human beings, viewed as behaving systems, are quite simple. The apparent complexity of our behaviour over time is largely a reflection of the complexity of the environment in which we find ourselves.

Herbert Simon

1.1 Introduction

The structure of the thesis, as discussed in this chapter, is presented in the form of the concept map in Figure 1. Most organisations consist of people performing work with the assistance of technological artefacts. Such a system with interaction between *social* humans and *technical* systems is referred to as a sociotechnical system (STS). The key characteristic is that interaction occurs in a social structure or organisation to achieve an objective of the organisation. This interaction can be linear and/or non-linear, sometimes leading to unexpected and unpredictable complex relationships. In addition, an STS also tends to be open where interactions exist with the environment or other systems (Bostrom & Heinen 1977, Walker et al. 2009).

The concept of an STS originates from the work of Fred Emery, Eric Trist and others during the 1950s on the introduction of new technology in the mining industry (Trist 1981). The STS approach encourages knowledge sharing, learning and innovation within the organisational context to enable collaboration and flexibility for a competitive advantage. Failures of modern systems can also be attributed to ignoring the role of the cognitive and social human in the system. As a result, the successful development or improvement of an STS is difficult, and an isolated implementation of new technology may not be adequate (Walker et al. 2008, Stanton et al. 2010).

The new artefact often leads to new task possibilities, and system user requirements may evolve (Carroll & Rosson 1992). A technical artefact may afford system users many different tasks. On implementing new technical equipment, its acceptance by the users may not be clear. In addition, the technology's supplementary possibilities for accomplishing tasks or solving problems only become clear after permanent use and innovative application (Walker et al. 2009).

Complexity in the task and environment, combined with complex human behaviour, gives rise to complex missions (Alberts 2011). Changes in the context or operational environment may affect the success of an STS, resulting in a requirement for changes in technological artefacts. These may include changes in tasks (processes) or physical technology. Integration between systems also creates more opportunities. Today, modern communications technology increases integration between systems, which may also afford performing tasks differently and possibly more effectively.

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These systems create new opportunities for the flow of information to and within organizations. Organisational complexity increases as a result of the interconnectedness of different systems and openness to the effects of the environment. Stakeholders may not always have control over these interactions (Walker et al. 2008).

Developing or improving an STS often consists of integrating new technological artefacts into existing systems, by applying systems engineering (SE) processes. The objective of SE is to solve problems experienced by people by bringing systems into being through applying systems thinking (Stensson 2010). Hitchins (2008) also defines SE as "… the art and science of creating whole solutions to complex problems …" The Systems Approach aims to understand only the part in the context of the whole, while interacting with and adapting to the environment. This leads to systems thinking, which has evolved to the modelling of system behaviour (Hitchins 2008). This goes beyond a bottom-up integration of elements, where emergent properties are isolated and contained. Behavioural modelling investigates the dynamic and non-linear interaction between different systems of interest to identify possible future outcomes. Other phases of SE include implementing, deploying, sustaining and disposing of the system, which are not addressed in this thesis (Oliver et al. 2009).

However, classic SE processes, as standardised for narrow and decomposable problems, can struggle with complex STSs where dynamic behaviour leads to unintended or unpredicted consequences. As a result, many STS development projects tend to overrun cost and schedule, without being as successful as intended (Bar-Yam 2003).

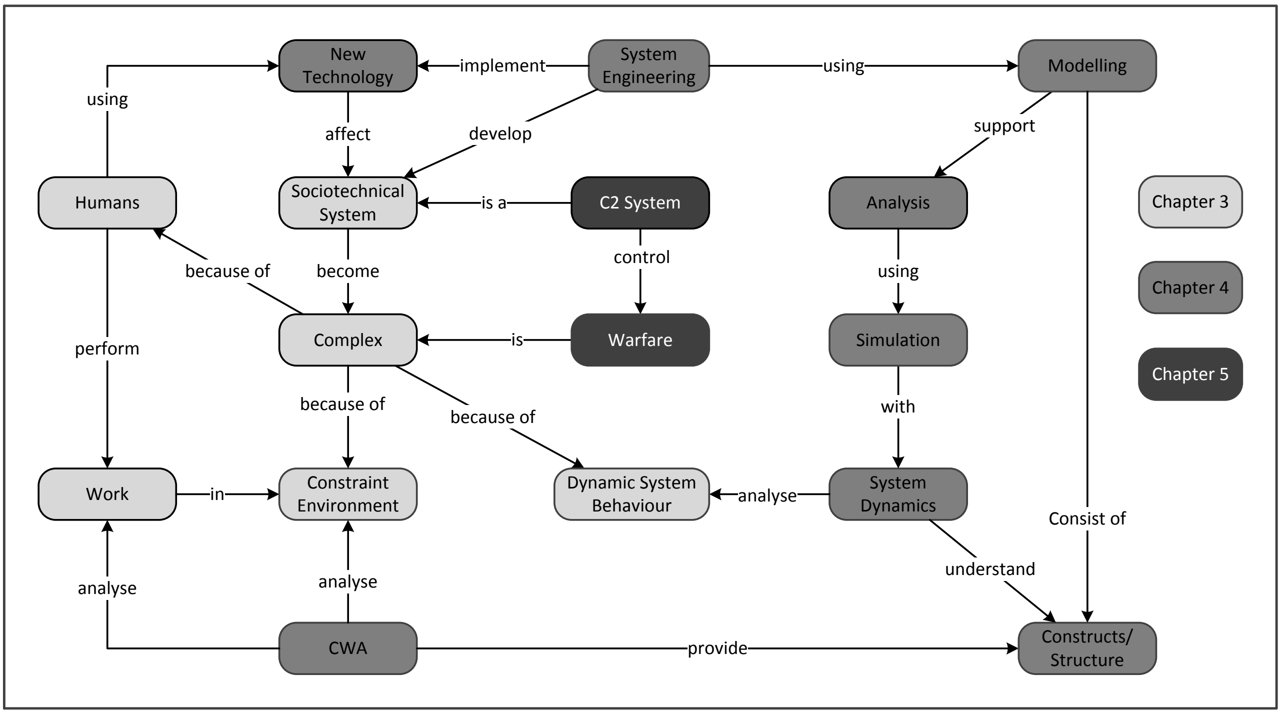

Figure 1: Thesis Concept Map

Even when such a system is implemented, it tends to be out of date and not suited to the new situation. The problems experienced with classic SE processes lead to developing complex system engineering (complex SE) through introducing complexity science (Kuras 2006). In effect, complex SE applies complexity science theory to complex problems.

Instead of relying on order in the system to identify the problem and derive a solution, complex SE addresses the evolutionary behaviour in existing systems and tries to affect certain characteristics to implement more desired results (Sheard & Mostashari 2009). Complex SE identifies the elements that cause complexity to guide the design of the system, in order to manage and utilise them. The emergence of the desired behaviour of the system is embraced and analysed through modelling, to explore the problem and solution space. Experiments with this knowledge are used to support an understanding the dynamics of the system (Johnson 2006, Ryan 2007).

The basis of SE is modelling based on systems thinking to capture the system stakeholder's mental model for communicating it to others. Models consist of the structural, functional and operational elements of the problem (Hitchins 2008). They are used throughout the SE life-cycle process. The model of the system describes how the system will change internal states as a result of external inputs. Models support experimentation with knowledge on the problem and develop an understanding of the implication of different solutions. Complex systems must be abstracted through modelling to gain insight and support in answering questions on the system. Conceptual models describe and represent selected aspects of the structure, behaviour, operation and characteristics associated with system (Buede 2000, Hybertson 2009, Polack et al. 2008, Ramos et al. 2012, Maria 1997, Haskins 2010, Maier & Rechtin 2000).

Humans are often the most flexible aspect of the system, and have to receive special consideration in designing one (Stanton et al. 2010). However, human functions are not always deterministic, as different humans have different cognitive capabilities, skills and experience (Macleod 1996). For complex STSs these models should address the human element as well as the endogenous and exogenous dynamic interaction.

Exploratory literature research on developing and modelling complex STSs identified a list of characteristics and requirements. These were compared to the characteristics of various modelling approaches which could address the complexity due to human (social) interaction and dynamic behaviour. The possible frameworks identified to address these aspects in modelling complex STSs are cognitive work analysis (CWA) and system dynamics (SD). Other candidate approaches could also address the requirements, but the possible synergy identified between CWA and SD lead to their selection.

CWA is a formative framework to analyse the way people perform work in an organisation, while taking the environmental constraints into consideration. The outputs of CWA are constructs or models that capture the structure of the problem. Functions provided by different technological and task elements are linked to the functional requirements of the system, to achieve its purpose (Lintern 2012). However, CWA is limited in investigating the dynamic effect of decisions and policies on the system (Cummings 2006). Here, SD supports analysis of the complex STS's dynamic behaviour. SD models the effect of feedback, delays and policy-based decisions on the behaviour of the system (Sterman 2000).

SD supports understanding the complexities and challenges in information systems, with insights into development, implementation and flexible infrastructures. SD simulation examines the aggregate emergent and dynamic effects of embedded mechanisms in processes, technology and resources in complex STSs (Georgantzas & Katsamakas 2008). Behaviour, caused by the system structure, observed over a long time leads to dynamic patterns of behaviour of the system that supports learning about the underlying structure and other latent behaviours. SD supports an assessment of complex STSs to gain an understanding of the social and technical interaction in a dynamic environment (Lofdahl 2006). Introducing new technology in a system cannot rely on historic case studies and associated data for analysis, as it results in too many changes in the complex system (Papachristos 2011).

The analysis methodology must look at different ways to understand the future implications of the new technology. Obtaining data on a complex STS is often difficult, due to the complexity of the real world and difficulty in creating realism in experiments. SD modelling and simulation provides an alternative qualitative and quantitative approach. Experiments with the complex STS model support further learning about the problem situation, requirements and the effects of possible solutions.

As seen above, CWA and SD are two fundamentally different methodologies with different levels of analysis, which need integration through a suitable framework. Because the aim of the experiment is to assess the usability of a design solution, the design science research (DSR) framework is applied. DSR aims at creating technological artefacts for a human purpose, as opposed to a natural science one, which tries to understand and define reality (March & Smith 1995). In this thesis the DSR guides the research design and is employed in the artefact, the proposed modelling methodology.

The proposed modelling approach is applied in the complex STS environment of command and control (C2). Although C2 originated with the military, its principles are applied in emergency and other organisational control systems. Military, security and emergency operations require a C2 system for operations management, to ensure that the desired goals are achieved. In this thesis C2 in anti-poaching operations (APO) and community policing forums (CPF), in addition to a traditional military application of border safeguarding operations (BSO) is used to demonstrate the modelling methodology.

The C2 system has to design courses of action through problem solving and control their execution (Van Creveld 1985). The purpose of C2, as a force multiplier, is to bring all available information and assets to bear on an objective, to ensure the desired effects through effectively utilising limited resources. The C2 system includes human commanders or managers for sense-making, decision making, planning and execution within an organisation supported with communication and information systems (decision support systems and interfaces). C2 is a knowledge system, embedded in the operational system, required for integrating different systems, subsystems and sources of information. Commanders have to make sense of complex and often unpredictable situations to support decisions about actions (Smith 2007, Van Creveld 1985).

A major contributor to complexity in C2 systems is delays in the whole system that cause late solutions to be implemented with out-of-date information (Brehmer & Thunholm 2011). Commanders also have to make decisions in a changing environment, while the impact of the decisions also changes the environment. This leads to dynamic decision making due to a series of interdependent decisions that have to be made in real time on a changing problem (Brehmer 2000). Management of this complex dynamic system requires careful modelling to understand all the implications (Sterman 1994).

1.2 Problem Statement

The problem to be solved is usually identified during the requirements analysis phase of a typical SE process. This leads to a concept system solution for a perceived problem. The concept solution or concept of operation (ConOps) guides the process of generating requirements for the system. SE uses modelling and analysis to characterise the problem and solution space of a system under development. However, this process as applied for complex STS is problematic.

Designing and developing a complex STS to operate in a complex environment requires an understanding of the problem, complex environment and dynamic interaction between the elements. Building models and experimenting with them increases this understanding. It supports defining requirements and synthesising designs of the STS that address humans, the organisation (structure), the work (processes) and the technology. Therefore, the problem statement for this study is as follows:

“It is difficult to model and assess the problem and solution domain of complex STSs as part of the SE process.”

Here, the problem and solution domain include the impact of new technology on a complex STS. Typical development projects for complex STSs consist of implementing a new technology in the system. New technology can consist of new communication, displays, decision-support systems, or even a new process. Modelling and experimentation help generate knowledge of the impact of the solution technology on the system as a whole. Successful experimentation is dependent on models of the impact of the new technology for the success of an STS. These models need to capture the influence of humans performing work and dynamic interaction. Therefore, the hypothesis of this research is as follows:

> *"A modelling methodology that addresses human work and dynamic interaction will support understanding the effect of new technology on complex STSs."*

This thesis demonstrates the ability of the modelling methodology in a real operational environment with real complex C2 systems in different operational applications (military and civilian). The case study observations in the demonstrations are compared with the behaviour of the system derived from the modelling phases.

1.3 Research Objective

The main objective of this study is to establish a modelling methodology to understand the effect of new technology on a complex STS. The specific contribution is to address systemic and environmental complexity, with a focus on the human element and dynamic interaction. This is demonstrated by modelling the contribution of a new technology integrated into different instantiations (military and civilian) of a C2 system.

The first objective is to perform a literature search to define the characteristics and requirements for a modelling methodology for complex STSs. This includes the theory on STSs, complexity, SE and modelling.

The second objective is to identify research and modelling frameworks that are capable of addressing the requirements of SE and complex STSs. The output models of the methodology have to help to understand how the new technology will affect the STS.

The third objective is to combine the modelling frameworks into a methodology that will support experimentation with the new technology in complex STSs.

The fourth objective is to demonstrate the methodology through modelling the effect of integrating a new technology with different instantiations (military and civilian) of a C2 system. These are used to identify key parameters that will determine the behaviour of the system. SD modelling and simulation play a major role in this phase.

The fifth and final objective is to evaluate the modelling methodology by comparing data on the key variable captured during experimental implementation of the new technology in a C2 system with the developed models.

1.4 Research Questions

The aim of this study is to answer the following research questions on the hypothesis as they apply to the impact of a new technology on a complex STS:

a) Why is developing a complex STS with standard SE processes problematic?

b) What is the role of modelling in the engineering of a complex STSs?

c) What are the characteristics of complex STSs that make modelling and analysis problematic?

d) Which methodologies will assist in modelling a complex STS?

e) What framework is required to support modelling a complex STS with the identified methodologies?

f) Can the proposed modelling methodology identify key parameters and variables related to the performance of the new technology in the complex STS?

g) Do models of the complex STSs support understanding the internal and environmental constraints?

h) Will the models improve the success of engineering complex STSs?

1.5 Research Contribution

The expected output of this study is to support SE in developing and improving complex STSs through effective modelling. The modelling methodology developed and investigated in this thesis has not been published yet. The methodology is useful to systems engineers and researchers involved in designing, assessing and developing complex STSs, with a focus on operational management systems. These may be situated in industry and supporting research organisations. Examples of these systems include command and control (military, aviation, police and emergency services), healthcare, education, communication and security services. Specific contributions of this study are the following:

a) The research in this thesis establishes a modelling methodology that is tested with representative case studies, which will contribute to the SE body of knowledge.

b) SD modelling and simulation is difficult in heterogeneous environments where the focus is on the micro level (Borshchev & Filippov 2004). Applying CWA should assist in understanding the impact of humans on a micro level to derive macro-level system behaviour. The two methodologies have been applied to various problems in the past, but it is the first time that they are used in combination, despite fundamental differences. Applying CWA and SD in a complementary fashion will also enhance the field of SD modelling.

c) Many authors have alluded to applying SD in operational management systems, such as C2, but its true application has not yet been demonstrated. This study develops a generic SD model for assessing new technological artefacts in complex STSs similar to C2.

d) The constructs and model outputs of the modelling methodology should support planning experiments and measuring tools to be used in the experiments. This is normally a difficult task with complex STSs, but the modelling construct may enable researchers to identify and relate variables in the system and operational environments.

1.6 Research Design

Research within the field of SE can be related to business research as well as process, information systems, aeronautical, manufacture systems engineering, etc. However, the business related research can be problematic due to the complexity of the systems under investigation, varying contexts and the relative immaturity of the field. This is further complicated by a lack of access to data and the long time frames required for research (Valerdi & Davidz 2009, Muller 2013, Cooper & Schindler 2003). Therefore, the research design for this thesis required careful consideration and a close look at related fields, such as information systems.

The research framework for this thesis is based on DSR, as seen in Figure 2, because the focus was on developing a modelling methodology in support of designing a complex STS. DSR has been proposed as a framework for developing information systems by creating artefacts for a human purpose (Hevner et al. 2004, Venable, 2006). The two basic activities in DSR methodologies are designing a novel and useful technological artefact for a specific purpose, and evaluating its utility. DSR supports developing and assessing an abstract artefact, such as a construct, model, method, instantiation, process, set of measures, methodology or framework. The artefact in this study is the methodology for modelling a complex STS (March & Smith 1995, Hevner 2007, Baskerville et al. 2009, Simon 1996).

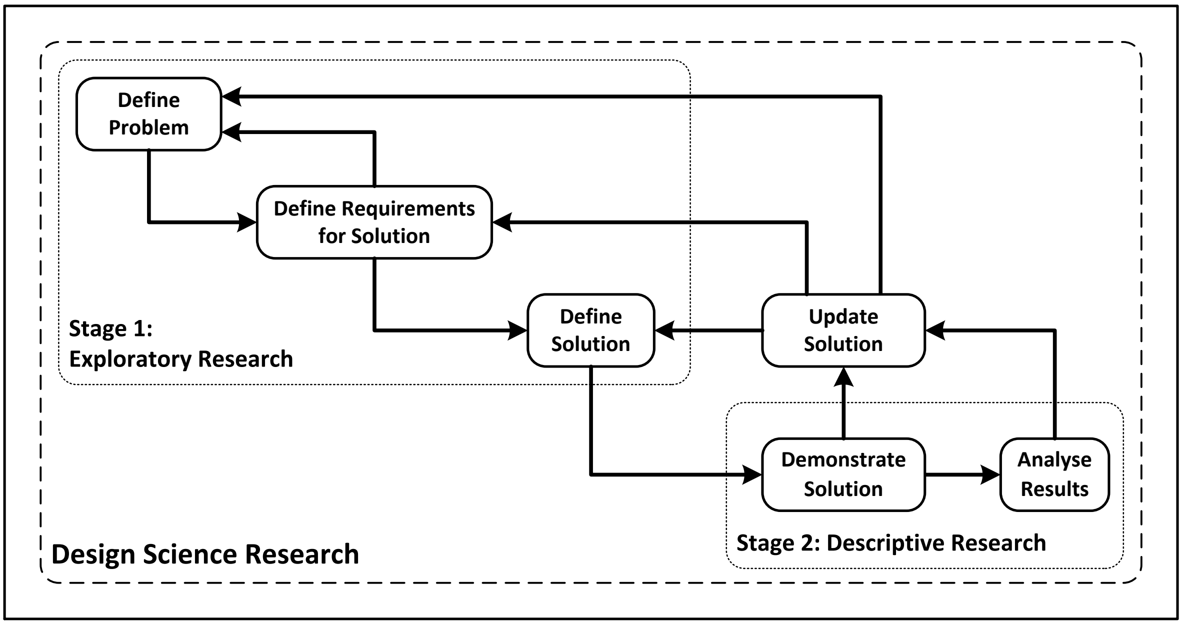

Figure 2: Research Method Design

The focus is not only on a specific solution or product for implementation, but on applying the design methodology to assess its usability in support of developing complex STSs. This research does not use falsification and deductive logic (Popper 1972), but rather focuses on the successes and lessons learnt from using the artefact to model and analyse complex STSs (Kuhn 1962, Lintern 2012).

Initial exploratory research is applied through a deductive literature research on STSs, complexity and SE to define the problem of developing complex STSs. Candidate modelling frameworks are then compared with these requirements. Combining frameworks may be required to provide a suitable solution. The final product of the first stage is to propose a solution in the form of a modelling methodology.

The second stage of the research takes the form of descriptive research, where the methodology is demonstrated through simulation and an empirical case study. The introduction of a new web-based collaboration technology to different complex STSs is modelled and simulated. The complex STSs are C2-based systems for border safeguarding, anti-poaching operations and neighbourhood watch patrols. The first two case studies are limited to simulations using the models, with the outputs being assessed by a focus group. The neighbourhood watch system involves an empirical demonstration, and data is captured to be compared with the modelling and simulation results. These are analysed and compared with the behaviour exhibited by the models. These different approaches in the triangulation of methodologies ensure rigour in this study.

Lessons learnt through this process are used to confirm and validate the modelling methodology if there is a strong correlation between the behaviour of the model and the actual observed behaviour. In the event of discrepancies, the information is used to update and improve the modelling methodology.

It is also important to note that the artefact of the thesis, the modelling methodology, actually mimics the research method applied. The DSR framework is employed to integrate the CWA and SD modelling methodologies. These two should not be confused, as many similarities exist. Also, the focus is not on different technological instantiations or implementing solution products in an STS. The focus of the assessment approach is on applying the modelling methodology, which is supported in the DSR framework.

1.7 Thesis Layout

The layout of the thesis indicates the structure of reasoning to be followed throughout the chapters of the thesis. The actual roadmap (layout) of this thesis is presented in Figure 3.

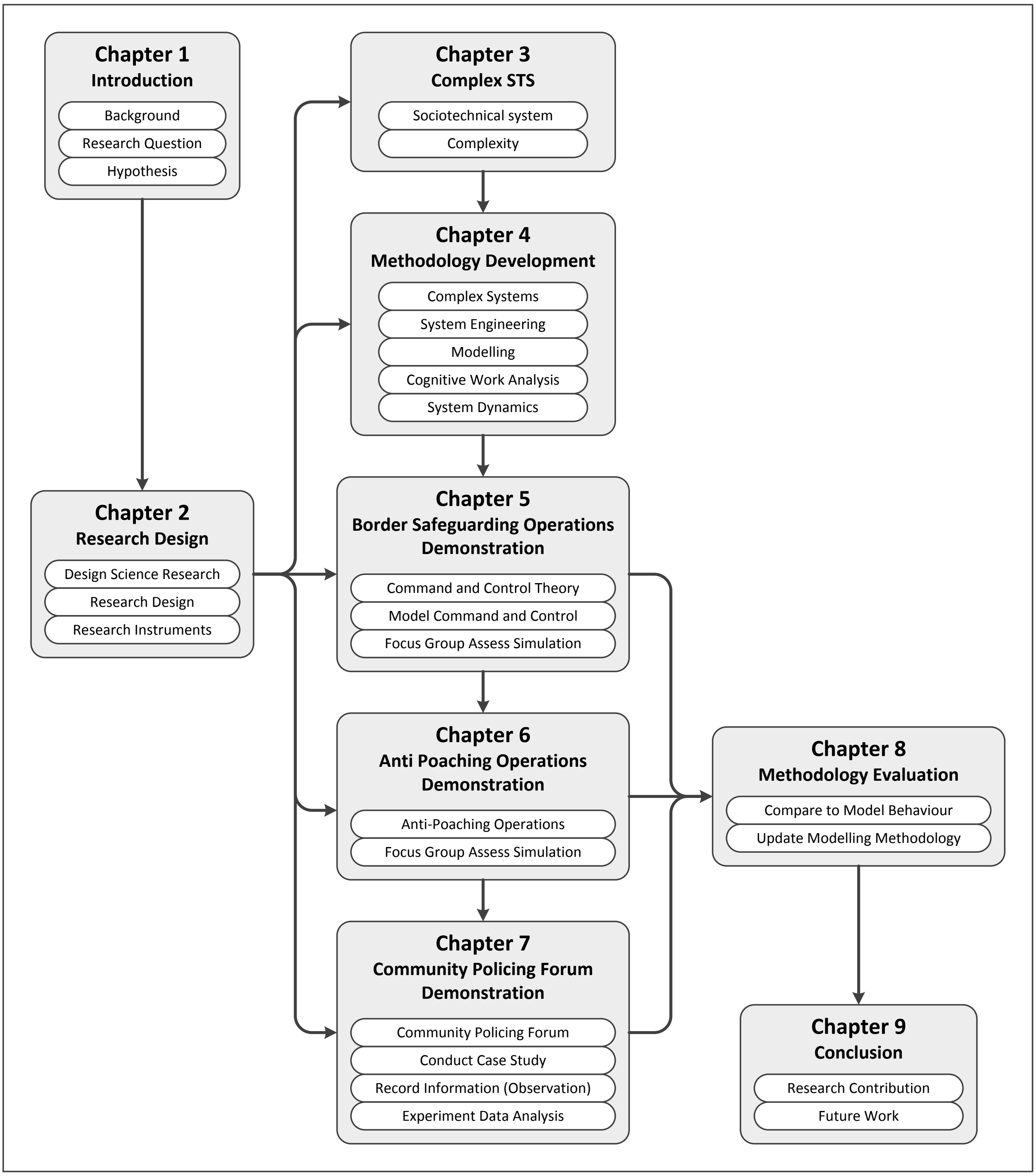

Figure 3: Thesis Study Roadmap

Chapter 1 provides an introduction and overview of the research in relation to the objectives pursued in this thesis.

Chapter 2 defines the research methodology applied in this study. The difficulties of SE research and the theory of DSR are summarised as background information. This is used as motivation for the specific research design implemented in this study. This includes a short overview of the case study design and the research instruments applied.

Chapter 3 introduces the field of STS, with a broad description of the theory and specific references to systems theory and complexity. The aim of this chapter is to understand the need for a specialised approach in designing or improving a complex STS. Research question (a) is covered in this chapter.

The aim of Chapter 4 is to find a solution to the problem of modelling and analysing complex STSs. This is linked to the classic SE approaches and the role of modelling. The limitations and problems of these methods in developing complex STSs are highlighted to guide the development of the modelling methodology. This comparison shows that the modelling methodology must address the technical aspect of the system, but also both the human using the technology and the dynamic interaction between systems. Candidate development methodologies for complex STSs are compared with the requirements in Chapter 3. This chapter concludes with the presentation of a modelling methodology for complex STSs based on CWA and SD. This is where some elements of the novel contribution of this thesis are presented. Research questions (b), (c), (d) and (e) are also addressed in this chapter.

In Chapter 5 the modelling methodology is demonstrated by implementing a new technology in a C2 system. A discussion on military C2 contextualises the STS framework and highlights the problem to be addressed in this study. The methodology is applied using the inputs of exploratory and confirmatory focus groups. Models of the implementation of a new technology in a C2 system are assessed using SD simulation. This is a crucial step, as it assists in identifying variables and parameters to be monitored during an actual implementation. The output of this chapter is a model for analysing the impact of a new technology in a C2 system for border safeguarding. This is to ensure that the developed modelling methodology adds real value to the SE effort of in developing C2 systems. Research questions (f), (g) and (h) are addressed in this chapter.

Chapter 6 also theoretically demonstrates the methodology for modelling, with simulated results. A different case study is provided by modelling the effect of a new C2 technology for application in anti-poaching operations. As in Chapter 5, a similar approach, based on focus groups, is followed in this chapter. Research questions (f), (g) and (h) are addressed in this chapter.

Chapter 7 empirically demonstrates and evaluates the modelling methodology. A different case study is provided through modelling the effect of a new C2 technology for community policing and neighbourhood watch systems. Empirical qualitative data are gathered from a field implementation. Research questions (f), (g) and (h) are addressed in this chapter.

In Chapter 8 the results are analysed and compared with the models and simulation outputs, to determine the utility of the modelling methodology. This may lead to improvements to, or modifications of the modelling methodology. This chapter captures all the lessons learnt and knowledge gained from the research in this thesis. The aim is to determine whether the research questions were addressed and the hypothesis was proven or falsified.

The final chapter concludes by identifying additional contributions as well as possible future research on the topic.

1.8 Thesis Constraints and Boundaries

This thesis does not develop a technology product, but rather focuses on modelling and assessing the abilities of the artefact when used in a complex environment. A technology currently being developed in the workplace of the author is modelled to demonstrate the methodology. Due to time and resource constraints, the following additional methods for modelling and analysis do not form part of this research:

a) Morphological analysis. This methodology is also useful in analyses of complex wicked and messy problems. However, it is aimed more at defining the root causes of a problem and not so much at providing system models on the human contribution or dynamic interaction.

b) Complex adaptive systems. Complex adaptive SE is a separate field where a system element may evolve over time. However, the focus here is on the human and sociotechnical aspects of a system.

c) SE standards. This study does not address the standard SE lifecycle processes, as the focus is on modelling and understanding the problem before the definition of requirements phase.

1.9 Conclusion

This chapter explains the motivation and reasons for the research, and presents the approach followed. The problem situation and possible contributions of the research are also discussed. The next chapter provides the research approach as well as the reasons for its selection. This leads to executing the research in developing a complex STS.

2 RESEARCH DESIGN AND METHODOLOGY

"If a thing can be observed in any way at all, it lends itself to some type of measurement method. No matter how 'fuzzy' the measurement is, it's still a measurement if it tells you more than you knew before."

Hubbard, 2010

2.1 Introduction

The aim of this chapter is to develop and establish the research methodology and research design for this thesis. First, the philosophical issues on research approaches are discussed to choose the most suited for the demands of systems engineering (SE), command and control (C2) and related complex sociotechnical systems (STS). Complex STS tend to be open systems with integration in a higher-level system of systems. This causes research into development processes to be difficult as causes and effects cannot be readily isolated. The research design is therefore aimed at developing and demonstrating a modelling methodology for complex STS in support of an SE process.

The design science research (DSR) framework and its application in information systems are used to develop the research methodology followed in this thesis. Design science provides descriptive knowledge to understand and improve human performance in complex STS. This is more important than determining the absolute truth of a phenomenon. In this thesis, the deductive research of literature is integrated to design a solution for specific problems. This supports the development of technological rules instead of causal truth. However, qualitative research requires grounding to ensure that the artefact results in observed or desired performance. Applying the technological rule must be justified through evaluation in a representative context to ensure that the artefact addresses the problem. The feedback of knowledge ensures that the literature and theory on the development of the artefact are improved (Van Aken 2005).

DSR allows the development and demonstration of a more abstract artefact, such as a process, set of measures or framework for developing and evaluating a system, with qualitative measurements to evaluate its utility. This forms the foundation of the research design. The DSR framework still requires various research instruments to support the process through triangulation for research rigour. The instruments included in the framework are document analysis, focus groups, computer simulation and a case study. In the case study, specific situation awareness measurements are used to capture empirical evidence to demonstrate the utility of the modelling methodology.

2.2 Systems Engineering and Business Research

Research attempts to understand, explain and predict behaviour or phenomena (Cooper & Schindler 2003). The two major research paradigms in the philosophy of literature are logical positivism and idealism. Idealism tends to be an inductive-qualitative paradigm that addresses the holistic, subjective and social-orientated world. Logical positivism tends to be a hypothetical deductive-quantitative paradigm that is based on empiricism and observations through human senses. These are the cornerstones of scientific thinking that support the reasons behind understanding the world (Deshpande 1983). An inductive research approach starts with observed effects and proceeds to their causes; deductive research on the other hand starts with a theory and makes deductions about its application. Despite the possibility of taking a long time, inductive methods can be used in theory building. In this research a deductive approach is used to gather information from the literature on complex STS observations to develop a modelling methodology (Golden-Biddle & Locke 2007).

According to Popper (1972), progress in science is achieved through successively rejecting falsified theories (Lintern 2012). As a result, a hypothesis may only be accepted as scientifically valid if no grounds for falsification exist. As this falsification criterion is based on deductive logic, it is applicable only to events where causality can be used to explain outcomes. Kuhn (1962), on the other hand, observed that scientific progress is not always achieved through this strict falsification approach, but instead through a softer approach of conceptual growth, negotiation, and compromise.

The general aim of quantitative methods is to verify or confirm theories, while qualitative methods want to discover or generate theories. The quantitative paradigm seeks facts and causes of social phenomena without considering the subjective and complex nature of humans. However, qualitative methods can support quantitative surveys in survey design, data collection and analysis. Both paradigms are used in business-orientated research through method triangulation (Deshpande 1983). In this thesis the evaluation of qualitative models can be accepted because of their success or usefulness in guiding design.

Despite business research not being conducted like physical research under controlled conditions, the effectiveness of an artefact must be evaluated objectively. The claim of success of an artefact must be articulated with criteria. It is nearly impossible to claim the success of a method if not all the causes of success can be unravelled (Muller 2013). Research on SE artefacts falls within the domain of business research, and is difficult for the following reasons (Valerdi & Davidz 2009, Muller 2013, Cooper & Schindler 2003):

a) <u>Relative immaturity of the field</u>. SE arose in the 1950s in the Bell Labs but was formally defined as a field only in the early 1990s. Standards of proof in SE have not been established. Valid research is difficult, as convergence in SE metrics and definitions is lacking.

b) Lack of access to data. Researchers require laboratories where variables can be manipulated and effects observed. The laboratory for SE is the real world, with its real-world problems, which makes identifying control groups difficult. SE uses qualitative and quantitative data for scientific purposes.

c) Complexity of systems. Due to the complexity of systems investigated through SE research, it is hard to isolate variables, standardise treatments and identify control cases. This has to deal with soft factors such as human attitudes, behaviour and performance, which are difficult to measure as they occur in complex STS.

d) Timeframe. The success of SE methods may only be visible far in the future. Therefore, data that can be recorded at present may not be what is required in analysing the artefact.

e) System context. The contexts of implementing a system or artefact tend to be uncontrolled and dynamic. Research in SE is complicated by the uniqueness of every problem and implementation. This is especially relevant for military C2, which requires a war to provide an actual implementation environment.

SE is related to information systems and software engineering. Currently there is no formal or accepted general research and design theory for information systems. However, the success of SE research is improved by properly formulating a claim, capturing relevant data, and performing analysis and interpretation. This requires designing a research process that consists of the correct combination of technical and social science research methods (Muller 2013, Valerdi & Davidz 2009, Khalid 2013).

In empirical research the evidence (data) for or against a stated hypothesis must be directly or indirectly observable in some tangible manifestation. The analysis of evidence can be done quantitatively or qualitatively. Experimentation variables in different trials are manipulated to support an inference of causation of detected effects. However, the empirical method aggregates direct and indirect observations (Valerdi & Davidz 2009).

The empirical cycle, according to de Groot (Heitink 1999), consists of the steps observation, induction, deduction, testing and evaluation executed in a loop to improve methods and findings. This relates to the relationship between induction and deduction in research, which is demonstrated in Figure 4 (Rudestam 2007). Through hypothetical deductive logic, literature and theory are reviewed to develop an idea or theoretical framework and set of assumptions, to deduce possible consequences through a hypothesis. These are used to gather data or evidence on the selected case.

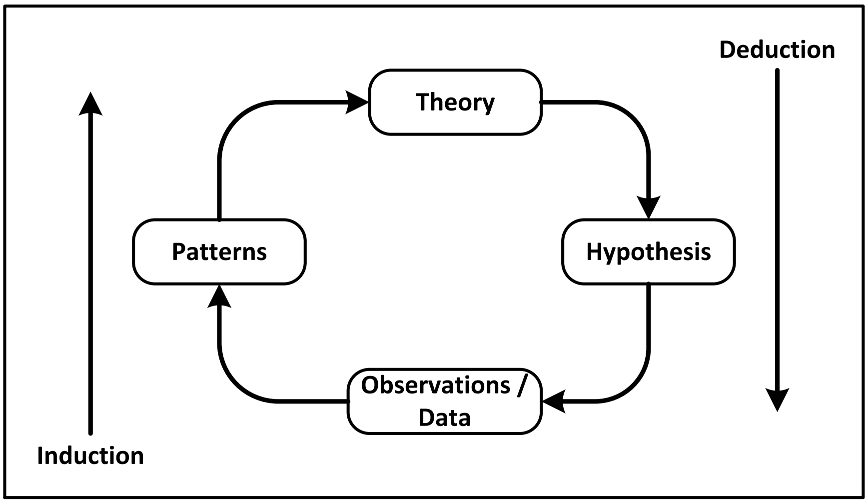

Figure 4: Induction and Deduction in Research (Rudestam 2007)

Analysis of the data is undertaken to test that the hypothesis and observations are compared with the existing literature. This approach may struggle with complex, stochastic and messy problems (Harrison et al. 2007). Through deductive logic, the literature is also used in support of empirical analysis. With this framework some event, pattern, behaviour or relationship is observed (ethnography) in captured data. This is linked or compared with the current theoretical understanding to identify supporting evidence, contradictions or gaps in knowledge. The theoretical predictions may be tested through inductive research.

However, the required data is sometimes not available, as key variables may be unobservable. Here computer simulation may assist to overcome the problems of deductive and inductive approaches. Numerical methods can handle the mathematically intractable problems, and virtual data can be produced for complex situations. Simulation relates to deductive research, as outcomes follow directly from the assumptions made. Inductive research is also resembled, as the relationships among variables may be inferred from an analysis of simulation output data (Harrison et al. 2007).

2.3 Design Science Research

2.3.1 Overview

Research is generally defined as an activity that contributes to the understanding of a phenomenon (Kuhn 1996, Lakatos 1978). The phenomenon may be in the form of behaviours or observations that a researcher finds interesting. The knowledge created through the research may then lead to some level of prediction of the behaviour of the phenomenon. Research methods or techniques are the activities that the research community consider appropriate to produce a reliable understanding. Design science aims at creating technology for a human purpose, as opposed to natural science, which aims at understanding and defining reality (March & Smith 1995). To design is to invent something or bring it into being. Therefore, design is the process of creating something

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new, or an artefact, which does not already exist in nature. Simon (1996) explains that design is a "science of the artificial", meaning objects and phenomena made by man for a specific purpose.

DSR has been proposed as an alternative to the predominant positivist and interpretivist research approaches, especially for information systems (Hevner et al. 2004, Venable, 2006). While behavioural sciences strive to explain and predict human or organisational behaviour, DSR aims to create new and innovative artefacts to improve human and organisational capabilities. In other words, DSR is more concerned with utility as opposed to focusing on the truth of other scientific approaches.

Design can be a form of research. DSR, like the natural sciences, confirms its theories by observing natural objects and artificial structures. However, DSR aims at solving practical and theoretical problems through artefacts (Hevner et al. 2004). A knowledge base is built through the design and construction of artefacts, followed by evaluation and post-hoc observation. This forms the knowledge base for architecture as a profession (Alexander 1964). Another recent example is the progression of aeronautical engineering, which started with the Montgolfier balloon and climaxed after the Second World War. Experimentation with intuitively guided designs provided the aeronautical engineering knowledge base. The output of DSR is theory building through practical artefact design, implementation and evaluation. This contrasts with behavioural science, which tries to understand only the current state and behaviour of the world.

Owen (2007) explains the DSR process using the model in Figure 5 for generating and accumulating knowledge. Action generates and accumulates knowledge if the result of the action, or artefact, is evaluated. Applying accumulated knowledge to real-world problems leads to new knowledge. The channels in the model represent the systems and rules of the discipline that are built into the knowledge base, as developed over time.

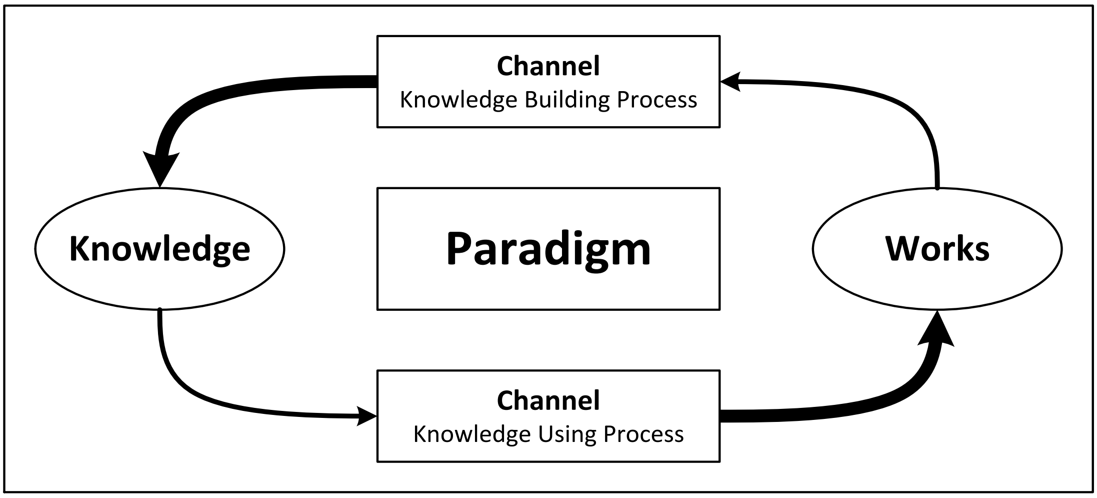

Figure 5: General Model for Generating and Accumulating Knowledge (Owen 2007)

A foundational requirement for research is the presence of relevance and rigour within the process. Hevner (2007) and Hevner et al. (2004) present a three-cycle view of DSR, represented in Figure 6, as follows:

a) Relevance cycle. As a rule, DSR starts by identifying an opportunity or problem within the application domain. Therefore, the artefact designed will have relevance as it is applied, and may lead to future uses. A spin-off of this cycle is identifying the acceptance criteria to be used when evaluating the artefact. As the artefact is evaluated in the application environment, new opportunities for advances are identified; thus forming a feedback loop for continuous learning.

b) Rigour cycle. Every design effort depends on an existing theoretical and methodological (artefacts) knowledge base. When designing a new artefact, the researcher searches for appropriate theories and methods, thus providing the rigour in the process. The advantage of DSR is that often different theories and methods are combined to support the design of an artefact. The output of the design can be fed back into the knowledge base to support or extend existing theories.

c) Design cycle. The design cycle utilises the relevance and rigour cycles to support the design, development and evaluation of artefacts. This is a rapid and balanced cycle, with repeated design and evaluation cycles taking place to solve the identified problem. The success of both of these activities depends on the balance between relevance and rigour.

DSR provides a framework to solve problems through creating artefacts (March & Smith, 1995). This framework can be extended to address wicked problems, which are poorly formulated, confusing, with conflicting values of many stakeholders (Pries-Heje & Baskerville, 2008). Examples of wicked problems include climate change, natural hazards, healthcare, international drug trafficking, nuclear weapons, nuclear energy, waste and social injustice. The principles of the DSR are also applied inside the artefact in this study, the modelling methodology for complex STS.

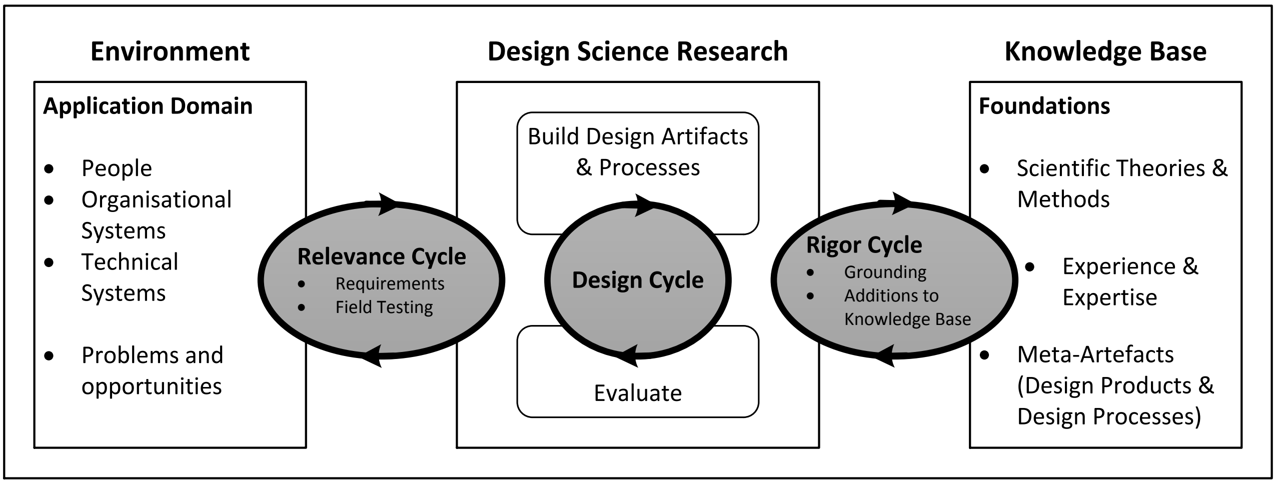

Figure 6: Three-Cycle View on DSR (Hevner 2007)

Table 1 provides some guidelines on the application of DSR (Hevner et al. 2004). These are used in this study to ensure that the DSR process is properly executed.

Table 1: Design Science Research Guidelines

Guideline	Description	Discussion
Guideline 1: Design as an artefact	DSR must produce a viable artefact in the form of a construct, a model, a method, or an instantiation.	The artefact in this study is a modelling methodology suited for complex STS.
Guideline 2: Problem relevance	The objective of DSR is to develop technology-based solutions to important and relevant business problems.	It is difficult to develop complex STS such as C2, where human cognition and social interaction are involved. Operators may reject the new technology or use it in different ways than were anticipated. Effective modelling should ensure that complex STS reduce risk in the implementation project.
Guideline 3: Design evaluation	The utility, quality, and efficacy of a design artefact must be rigorously demonstrated via well-executed evaluation methods.	The modelling methodology is applied to C2-related case studies. The introduction of new technology into anti-poaching operations and community policing forums, in addition to a traditional military application of border safeguarding operations are modelled and simulated. The accuracy and usefulness of the models and other outputs are assessed through simulations, focus groups, and a field experiment with the CPF.
Guideline 4: Research contributions	Effective DSR must provide clear and verifiable contributions in the areas of the design artefact, design foundations, and/or design methodologies.	The approach to designing complex STS is improved through an analysis of human contributions and dynamic interactions in the system.
Guideline 5: Research rigour	DSR relies on applying rigorous methods in both constructing and evaluating the design artefact.	Initially, rigour is achieved with an in-depth literature study on complexity, STS requirements and development approaches. The artefact is also applied to real-world problems, to find effective solutions that are assessed through focus groups. Further evaluating the demonstrated artefacts through focus groups and empirical data enhances the rigour.
Guideline 6: Design as a search process	The search for an effective artefact requires utilising available means to reach desired ends, while satisfying laws in the problem environment.	The development of the modelling methodology utilises multidisciplinary research, with a focus on STS. It combines cognitive and dynamic aspects of STS.
Guideline 7: Communication of research	DSR must be presented effectively both to technology-oriented as well as management-oriented audiences.	The results are published in a thesis report, conference proceedings and journal publications.

2.3.2 Design Science Research Artefacts

The two basic activities in DSR methodologies are building (construct) a technological artefact for a specific purpose that is novel and useful, as well as evaluating it to determine the level of success (March & Smith 1995). Artefacts can be any of the following (March & Smith 1995):

a) Constructs. Constructs conceptually describe the problem and solution domain and are refined throughout the design cycle. As the construct provides the language to describe all the entities and their relationships in the artefact, it may be practically impossible for an empirical experiment to encapsulate all aspects of the construct.

b) Models. A model describes the relationships among the constructs for the artefact, therefore being the problem and solution statements. Here the focus is more on the utility of the artefact, rather than a scientific truth.

c) Methods. The method provides an algorithm or guideline on how to perform a task in solving a particular problem. These are the problem and solution statements, expressing the solution space, using the construct vocabulary. In DSR, the problem-solving methodology may also be a viable artefact.

d) Instantiations. An instantiation is the technical implementation of a construct, model and method in the operational environment. The instantiation may be conducted before a complete articulation of the supporting concepts, models or theories exists. As seen in the aeronautical engineering example, aircraft flew long before the theories on flight matured.

The artefact developed in the research process of this thesis is a modelling methodology, as seen in (b) and (c).

2.3.3 Design Science Research Methodology

2.3.3.1 General

Since *design* is mainly a creative process, defining a formalised research method is difficult (Hooker 2004). However, Peffers (et al. 2007) proposed a general model for reasoning in the design cycle, as seen in Figure 7. Artefacts are developed as part of a sequential problem solving or performance improvement process. This process supports the analysis of the creative effort, which results in new knowledge that arises from design activities. However, the process need not be strictly sequential, as it can start at any step and proceed outward. A problem-centred approach may start at the first step, while an objective-centred solution starts at the second step. The third step is used for a design and development-centred approach where the objective and use of an artefact has not yet been established. The steps in Figure 7 are subsequently discussed in detail.

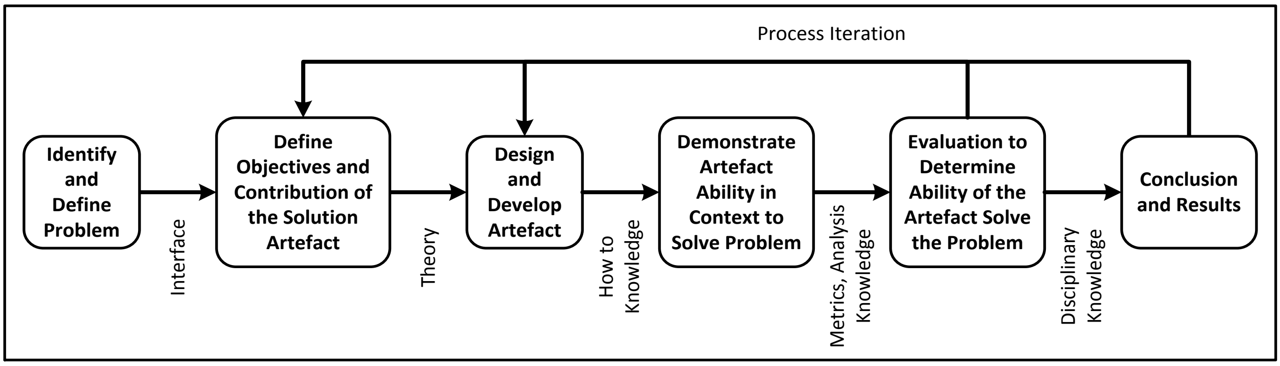

Figure 7: The General Methodology of Design Research (Peffers et al. 2007)

2.3.3.2 Problem Identification and Motivation

New problems or opportunities may be discovered through new developments in industry or in a reference discipline as well as in cross-disciplinary research. A relevant issue needs to be identified and is characterised by the perceived state of the problem and value of a possible solution. The first step of Figure 7 defines the specific research problem as well as motivates why the problem requires solving. This sets the context and viewpoint from which the problem is approached. This is to ensure that the artefact being developed solves a real problem. The inputs of this step are knowledge on the problem space and the contribution a solution will make. The output is some problem scope or proposal for research (Peffers et al. 2007).

2.3.3.3 Define Objectives and Contribution of the Solution Artefact

During this step knowledge of the problem is analysed to determine the objectives and contribution of the solution artefact. This tends to focus on what is possible and feasible. Depending on the problem, the objective may be quantitative or qualitative. The functionality of the new artefact is envisioned by analysing the environmental restrictions (Peffers et al. 2007).

2.3.3.4 Design and Develop Artefact

In the Design and develop phase of Figure 7, the suggested solution artefact is created through design and development. The research artefact can be any of the types discussed above (constructs, models, methods or instantiations) that contain a research contribution. Creativity is applied with knowledge of the relevant theory to provide a solution framework aligned with the state of the problem and the value of the solution. The suggestion may include different configurations of either existing or new and existing elements that determine the artefact's desired functionality, architecture and construction. The method used for implementation is not required to be novel but has to serve the purpose of the project. The act of implementation is also important, as new knowledge is gained from the environment and techniques are applied (Peffers et al. 2007).

2.3.3.5 Demonstrate Artefact Ability in Context to Solve Problem

A demonstration is required to evaluate the ability of the artefact to solve the perceived problem, thereby ensuring the value of the research, as seen in Figure 7. This is conducted through simulation, experimentation, case studies or other accepted research methods in a practical environment, and its success is measured. The aim is to gain knowledge and experience in applying the artefact to solve a problem. All deviations from expectations, regardless of whether quantitative or qualitative, must be recorded and tentatively explained (Peffers et al. 2007).

2.3.3.6 Evaluation to Determine Ability of the Artefact Solve the Problem

The outcomes measured in the previous stage are compared with the objectives of the perceived problem state and solution values. This phase requires various quantitative and qualitative analysis techniques and knowledge of relevant metrics. Here, a hypothesis is made about the behaviour of the artefact. Despite the hypothesis being confirmed or contradicted, the results and additional information gained are iterated to the definition of objectives, or design phase. The original hypothesis is not discarded, but rather amended or improved to guide a new design or literature search (Peffers et al. 2007).

2.3.3.7 Conclusion and Communication

Communication of the results of the problem solution, analysis design and evolution is important for rigour in the DSR process. Despite deviations or problems in the solution existing, the results can be *good enough* if the facts about the problem are firm enough for the repeatable behaviour of an artefact within a given context. The focus is on the knowledge gained throughout the process. Unsolved issues will then serve as the subject of further research. The results and findings need to be communicated to other researchers through scholarly publications (Peffers et al. 2007).

2.4 Research Design

2.4.1 General

The theoretical discussion on research up to this point is provided to support the research design for the thesis. In Figure 8 the steps of the DSR framework from Figure 7 are mapped to the induction-deduction cycle of Figure 4. This can be related to Kolb’s Learning Cycle (Kolb & Kolb 2005). DSR has been proposed as a framework where research claims can be validated through the realisation of artefacts such as prototypes, proof-of-concept implementations, models, and simulations. If improvement by a process in organisational performance is claimed, a model of the organisation can be used to provide insight in the relationship between the process and performance. However, the researcher must be aware of the quality and validity of the artefact (Muller 2013). Therefore, it may not necessary to prove causality for the research to be of value.

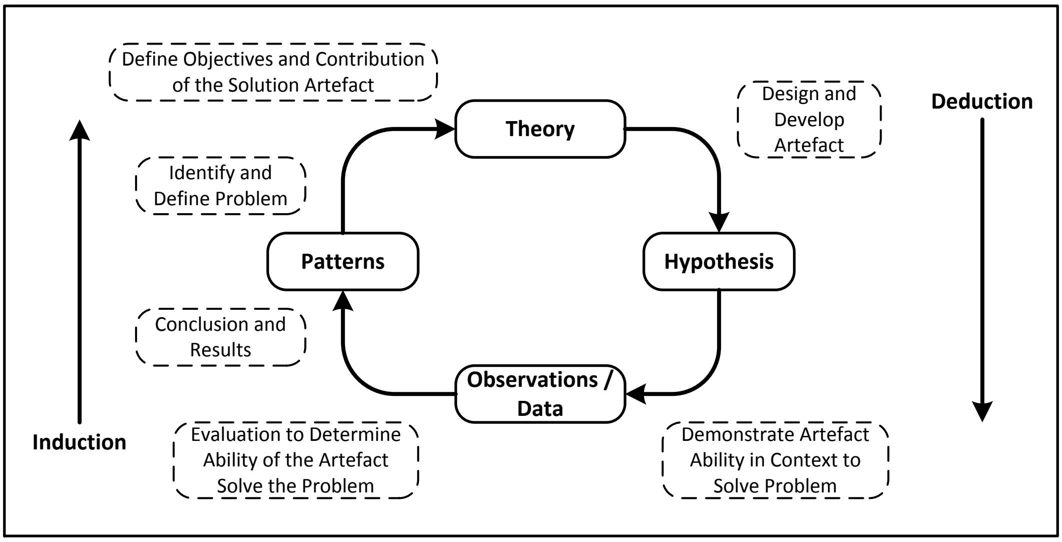

Figure 8: **The General Methodology of Design Research**

This research is based on a two-stage design approach described in Cooper & Schindler (2003). The first stage follows exploratory literature research with deductive reasoning to develop the modelling approach. The characteristics of complex STS are investigated to highlight the problems experienced by SE in modelling and developing these systems. Concepts are developed and priorities established to guide the research through an initial investigation of (secondary) literature. Exploratory research ends when the dimensions and boundaries of the problem have been established (Cooper & Schindler 2003). The output of this stage is a modelling methodology for complex STS.

The second stage comprises inductive and descriptive studies to demonstrate the modelling methodology from the first stage, using the DSR framework. The relationship between variables is also captured and discussed. As opposed to exploratory studies, formal studies require a clear and structured hypothesis for describing phenomena with their characteristics associated with a subject population (Cooper & Schindler 2003). The modelling methodology is applied to understand the impact of a new technology in a C2 system.

The first level of demonstration consists of computer simulation to assess and understand the impact of certain variables on the system. This helps to characterise the variables associated with such an implementation. Empirical data on these variables are captured when the actual technology is implemented in a real C2 system for CPF during a field experiment. Data gathered on these variables are used to indicate the value of the knowledge gained through the modelling methodology. Final validation takes the form of analysis of the empirical data captured from the modelling during implementation of the actual system. The system is used to perform work in a specific scenario, and not necessarily through a formal experiment. These stages are mapped onto a DSR framework in accordance with the detailed research approach taken in this thesis, as seen in Figure 9.

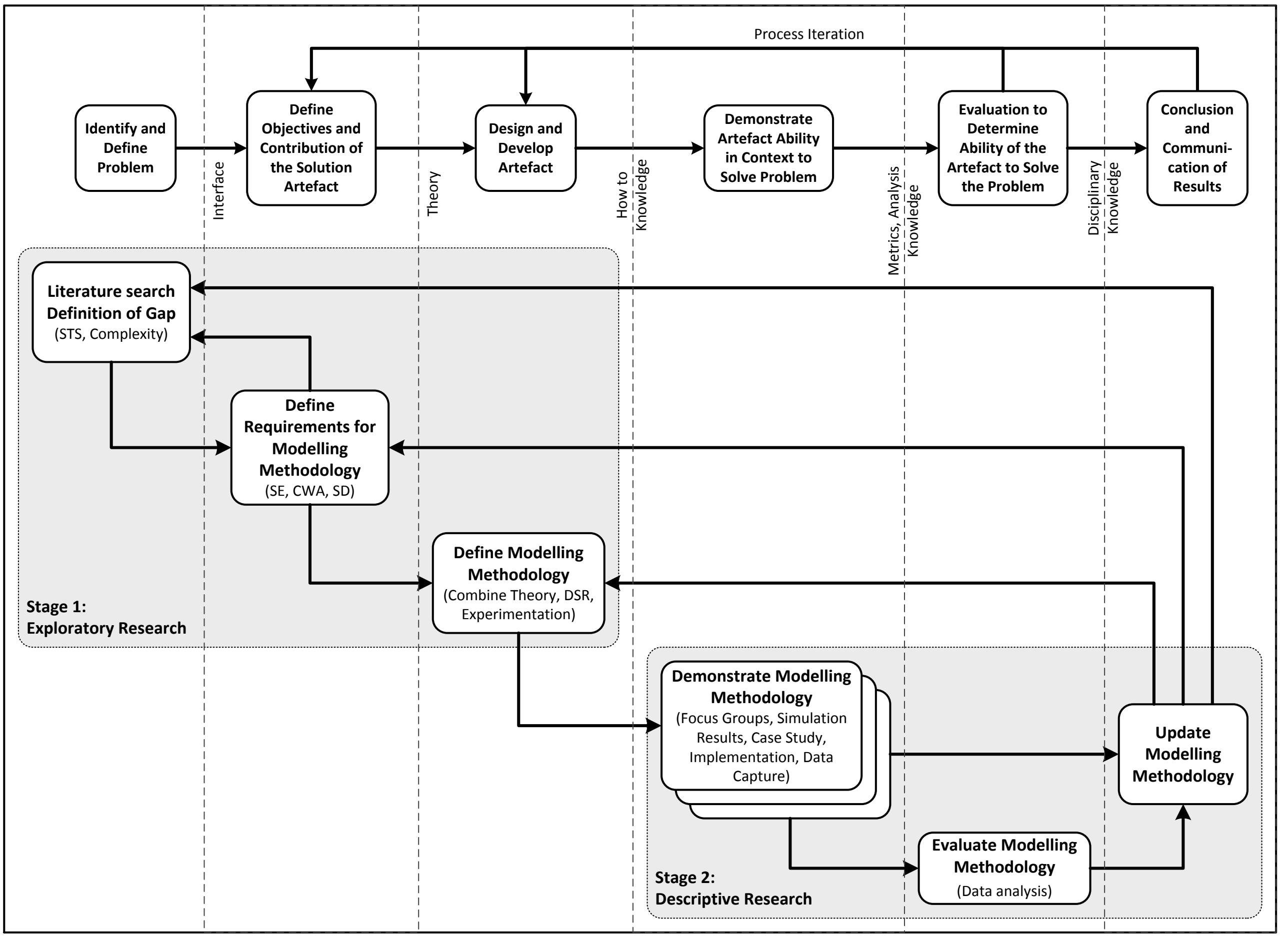

Figure 9: Research Design

2.4.2 Identify and Define Problem

The problem to be addressed in this research is the difficulty of developing technology solutions for complex STS. C2 is an example of a complex STS where technologies, such as decision support and information management, support human work. Chapter 3 provides a literature search on systems, STS and complexity theory to define the problems in developing complex STS systems. This leads to an identification of the requirements for a modelling methodology to support the development of successful complex STS. Traditional SE approaches focus mostly on the technical aspects and tend to neglect the human part of the STS as well as the dynamic complexities experienced during operation.

2.4.3 Define Objectives and Contribution of the Solution Artefact

The aim of the second step is to address the deficiencies of classic SE methods currently applied during the design and development of complex STS. The literature search in the first half of Chapter 4 focuses on the requirements for a suitable modelling methodology.

2.4.4 Design and Develop Artefact

The modelling methodology is developed and refined in this phase, which is discussed in the remainder of Chapter 4. The focus is on different approaches to modelling that may satisfy the identified requirements. Research into different design approaches in the previous step lead to compiling a design method suited for complex STS. The aim of the modelling methodology is to understand the problem space and the effect different technological solutions may have on it. Since the main sources of complexity in STS are the way humans perform work and the dynamic interaction, it needs to address the cognitive (human), organisational and technical solutions to the problem as well as dynamic interaction. These still have to be applied within a suitable framework, such as DSR, to support experimentation and the building of knowledge on the complex problem to be solved. The framework used to guide the research in this thesis is also therefore used in the solution artefact.

2.4.5 Demonstrate Artefact Ability in Context to Solve Problem

Rigour in the research process is achieved through demonstrating and evaluating the artefact. Firstly, the modelling methodology is demonstrated in Chapter 5, by showing that a model for C2 that addresses the human element and dynamic interaction can be developed – in this instance, in border safeguarding. The model is used to assess the impact of a new web-based collaboration technology on the C2 system, through simulation. The output of the simulation is validated through a focus group consisting of subject-matter experts (SME). This can lead to understanding the behaviour of the system with new technology. The second demonstration in Chapter 6 is similar to that in Chapter 5, but in a different operational environment. Here the same technology is modelled for supporting anti-poaching operations in a game reserve.

The final demonstration is in the form of a case study with the same collaboration technology in a neighbourhood watch system. The aim is to demonstrate that the artefact can solve the problem defined in the first step of the research design. During this phase the characteristics of the key variables in successfully implementing the system are identified. A field demonstration with the new technology in a complex STS provides empirical-qualitative data on the system's behaviour.

2.4.6 Evaluation to Determine Ability of the Artefact to Solve the Problem

The original hypothesis of the research – which is that a modelling methodology that addresses human work and dynamic interaction will support understanding the effect of new technology on complex STS systems – is considered in analysing the modelling methodology (artefact). The ability of the modelling methodology (artefact) to add value to the SE process must be demonstrated with empirical evidence. The evidence must show that the outputs of the modelling methodology make a contribution, because the human role in performing work as well as the dynamic interaction are included. Here possible changes to the hypothesis can be identified for future cycles of the DSR process.

The results of the assessment of the prototypes lead to experience in the modelling methodology, to support improvements. These are compared with the literature research and the premises for the artefact. The results of the research should be published to ensure that the knowledge gained in this research can lead to further improvements. The success of the model and associated analysis are compared with the criteria identified in the literature search. This is to improve the relevance of the research, and the artefact.

2.4.7 Updates to the Artefact

Lessons learnt from the two demonstrations are combined and discussed. The outputs are compared with the initial requirements derived for the modelling methodology. If required, the modelling methodology can be improved through updates.

2.5 Research Methodology and Instruments

2.5.1 Overview

Any research approach has inherent flaws, which may limit the ability to make certain conclusions. Therefore, selecting the correct combination of research methods through triangulation improves the validation of results. The concept of triangulation is derived from navigation and military strategy, which use multiple reference points to find an accurate position. Different sources of data provide different perspectives on the phenomenon for more robust and generalizable findings. This approach has been used in business and management research since the middle 1980s (Scandura & Williams 2000, Barry 2011).

Research methods available in support of DSR are document analysis, case studies, or action research. These may be used in combination, as long as the common fundamental philosophical assumptions are aligned. The key is not to focus on the technical issues alone, but to include the managerial and organisational, as well as social aspects (Galliers 1993, Mingers 2003). The research instruments chosen for this study, which support validity through triangulation, are literature surveys, focus groups, computer simulation and case studies (field demonstrations).

The artefact developed in this thesis, the modelling methodology for complex STS, is based on DSR and contains most of the research instruments discussed in this section. As the research methodology is executed as part of the artefact, applying the case studies can be used to demonstrate its utility. Therefore, the need for external validation is negated.

2.5.2 Literature Search

Literature is used to gather primary and secondary observations and research on the field under investigation. Researchers summarise the available information to conceptualise models for empirical testing that can be achieved through a combined inductive and deductive process. This method is highly generalizable, due to the amount of available literature on the subject. However, it is low on realism relating to the context and the precision of measurement, as it is based on specific cases and the interpretations of other researchers (Scandura & Williams 2000). These are used to identify problems experienced; also information is used to support the modelling method. This can also be the source of synthetic data to be used in simulations.

2.5.3 Focus Groups

2.5.3.1 Theory

Focus groups have been used in numerous instances to gather data to support constructing the abstraction decomposition hierarchy in the work domain analysis for a CWA as well as system dynamic (SD) modelling (Birrell et al. 2012, Pejtersen & Rasmussen 2004, Stanton & McIlroy 2012, Luna-Reyes & Andersen 2003). Focus groups fall into the category of judgement tasks. Where the participants are asked to judge or rate observations and behaviours. Focus groups can be generalised through selecting the participants with the right knowledge and experience, and the outcomes can provide measurements with acceptable precision (Scandura & Williams 2000).

Within complex STS numerical data is not readily available to estimate statistically the nonlinear interaction functions. Modelling of C2 is then based on qualitative information, which includes endogenous and exogenous variables and relationships. This information often exists tacitly in mental models of SMEs (Sterman 2000). Focus groups provide a method for gathering qualitative information, which is a moderated and directed discussion in a group of six to twelve people on a specific topic. This can lead to a snowball effect, as synergy is invoked between participants (Blackburn 2000). Focus is achieved by limiting the number of issues and using carefully predetermined open-ended questions. This is useful as an exploratory method when data on the subject is limited, as well as a confirmatory method to test hypotheses. The success of the focus group is dependent on the experience present in the selected members (Blackburn 2000, Gibbs 1997, Robinson 1999).

The disadvantages of focus groups include the ability of participants to participate without intimidation and the risk of one individual dominating. Researchers also have limited control over the data recorded, due to the open-ended nature of the questions (Gibbs 1997, Blackburn 2000). An alternative for capturing the inputs of SMEs is the Delphi Method. It begins with a set of open-ended questions on a specific issue that is distributed to various SMEs. The responses to these questions are summarised and a second set of clarifying questions on areas of agreement and disagreement is formulated and distributed to the same group. Typical disadvantages are isolation of the participants, elimination of extreme positions and time taken to complete the process. Focus groups, on the other hand, are quick and convenient while profiting on the group interaction (Hohman 2006, Hsu & Sandford 2007).

Despite difficulty in demonstrating rigour, focus groups are used by market researchers as well as in the behavioural and social sciences. Focus groups have been used in medical applications, government improvements, business and entrepreneurship research, the social sciences and in market research (Gibbs 1997). Lately, they have been used in the information technology industry as an evaluation and knowledge elicitation technique for human-computer interfaces. The advantages of focus groups are flexibility, direct interaction with respondents, large amounts of rich data with diverse views, and building on other respondents' comments through shared understanding (Tremblay et al. 2010). In this study the focus group is used for capturing the following information:

a) Problem definition.
b) Main parameters to measure system success.
c) Boundary values for variables.
d) Accuracy and value of modelling and simulation.
e) Level of success of modelling methodology.

2.5.3.2 Implementation

The DSR goals for implementing focus groups are to incrementally improve the design of the artefact as well as to demonstrate its utility; hence, both exploratory and confirmatory focus groups are employed (Tremblay et al. 2010). Therefore, focus groups are incorporated in the modelling methodology (artefact) developed through the research. Selecting stakeholders with diverse views and experience helps in identifying many of the characteristics and variables in the problem situation.

Focus groups are implemented as a formalised and structured brainstorming session to identify important functions and variables in the complex STS. They also serve as inputs to the development of constructs and system models on the problem situation and application context. Despite being included in the artefact of this study, the modelling methodology – the focus group outputs – can still be used to trace the utility of the artefact.

2.5.3.3 Analysis and Interpretation of Data

Formalised interpretation of the focus group data is required to instil the rigour required in DSR. Importantly, the findings derived from the data must be reliable and replicable. Typical qualitative data analysis approaches such as grounded theory and interpretive phenomenological analysis are available (Tremblay et al. 2010).

Template analysis employs predefined codes to guide a flexible analysis of the focus group data. Codes are labels attached to a section of text to indicate its relationship to a theme or issue. These codes may be identified through a preliminary review of the focus group transcripts for common themes, literature, or the researcher's own experience. The template from the exploratory focus group is also applied in the confirmatory focus group (Tremblay et al. 2010).

The outcomes of the focus group can be reported using the main themes and short quotes in the summary tables. The tables include evidence and counter-evidence corroborated with quotes. However, in this study the exploratory focus group outputs are captured in constructs to support the modelling. The confirmatory focus group utilises the templates to validate the output of the simulation results (Tremblay et al. 2010).

Within the realm of CWA, the abstraction decomposition hierarchy (ADH) of the work domain analysis, as initially constructed from the literature, will form the template for the focus group analysis. The transcripts are scrutinised to confirm elements in the ADH as well as their relationships. This information is used to improve the ADH.

2.5.4 Computer Simulation

Simulation modelling has not yet been fully embraced in management research as opposed to in other social science disciplines. However, modelling and simulation provide a powerful methodology to advance theory and research on the behaviour of complex systems (Harrison et al. 2007). Complex systems often consist of multiple interdependent and nonlinear processes, with feedback operating simultaneously, making them difficult to analyse and for which to develop theories. Even if the individual processes are understood, analysis of their interdependent behaviour is still difficult due to unforeseen interactions. Here the ability of empirical analysis with a linear model has limited value when samples are sparse in the specific regions of interest (Harrison et al. 2007).

Simulations based on formal models provide a viable alternative. A formal model has a precise mathematical formulation of the dynamic values of variables as well as of the relationships among variables (Harrison et al. 2007). The act of developing a simulation model constitutes an exercise in theory development, as it involves identifying the underlying processes, its interactions and formalizing them as mathematical equations. It is informed by previous theory and empirical research to develop new theory and research feedback into the process. A formal modelling and simulation approach introduces theoretical rigour in the research (Harrison et al. 2007).

One example of modelling and simulation for management theory is SD. Its models aim at modelling the whole system's behaviour, instead of just modelling the behaviours of actors within the system. Simulation on a computer is defined as a computational model of systems behaviour, which consists of system components or variables and the processes for changes in the variables, coupled with an experimental design. The five elements of the experimental design are initial conditions, time structure, outcome determination, iterations and variations (Harrison et al. 2007). The general uses of simulation modelling are the following (Harrison et al. 2007):

a) Prediction. Simulation outputs may reveal relationships among variables, which are predictions of the system's behaviour. If this can be empirically confirmed, the theory embodied in the model of the underlying (unobserved) processes is supported.

b) Proof. A simulation demonstrates the ability of modelled processes to produce behaviour. This can be used to examine the utility of models and to demonstrate that the resulting system behaviours meet certain boundary conditions.

c) Discovery. Unexpected consequences of simple processes interacting can be discovered using simulations.

d) Explanation. Observed behaviours may be difficult to explain through empirical observations. The underlying processes can be modelled, and their behaviour examined with a simulation.

e) Critique. Existing theoretical explanations for system behaviour can be investigated with simulations.

f) Prescription. Alternative or improved solutions to organisational problems can be suggested through simulation.

g) Empirical guidance. Planning of experiments, or empirical strategies, can be supported and informed through models and simulation.

However, some issues do exist with modelling and simulation in research. Firstly, the degree of complexity in simulation models needs to be addressed. Trade-offs always exist between simplicity and elaboration. Although elaborate and complete models offer clear benefits from the level of alignment with the system in question, populating the system variables and simulating such models can however be rather difficult. Simple models may not always reflect true behaviour, because of excluding important elements. One approach is to start with a simple model and then elaborate it by adding complexity as knowledge increases. Another problem is the empirical grounding of models and simulations. The model must be related to the real world through previous empirical work or comparing simulation results with subsequent empirical studies. Other limitations of modelling and simulation include presenting the model in sufficient detail, limited analysis to investigate all the relationships implied by the model, bugs in computer simulation programs and the possible reliable inferences to be drawn from simulation findings (Harrison et al. 2007).

Simulation with models derived from literature surveys and refined through focus groups adds to the generalizability as well as the realism of the context. Computer simulations can be used to create artificial data or to demonstrate a process. Parameters can be estimated through the Monte Carlo method when it is difficult to obtain numerical data. Due to using artificial data, the actual precision of measurement is low, while generalisation of the population and context realism are high (Scandura & Williams 2000).

Modelling and simulation with SD are used to gain an understanding of the dynamic complexity of the STS under investigation, as applied in the first demonstration of the artefact. The outputs of the simulations are compared with the existing literature as well as with available statistics, in the case study. Focus groups are used to judge the utility of the simulation output as a form of evaluation. Despite being included in the artefact of this study, the modelling methodology, the SD simulation outputs can still be used to trace the utility of the artefact. Simulation makes it possible to address complex problems as experience in a complex STS. As many of the behaviours and characteristics are not always observable or explicitly available from the stakeholders, simulation can guide the empirical work, explore complex system behaviours, examine possible consequences of assumptions and demonstrate the outcomes of hypotheses. This provides theoretical rigour and promotes scientific progress (Harrison et al. 2007).

2.5.5 Case Study

2.5.5.1 Case Study Theory

Primary data (empirical) to test and update the models on complex STS are gathered through a case study in the form of a field implementation and demonstration. The case study is useful to determine how an artefact performs in real life where there is limited control over the behaviour of elements and events. This should be sufficient where the objective is to demonstrate or test a theory. The utility of a theoretical artefact still requires implementation and demonstration in real life to capture actual primary data. This provides a high degree of realism, as it is used in real life, but has lower generalizability (one context), and precise measurements may be difficult due to the complex nature of human behaviour. The case studies are used to perform the following (Yin 2009):

a) Explain presumed causal links that are too complex for surveys or experiments.
b) Describe intervention of the context upon an occurrence.
c) Illustrate topics within an intervention in a descriptive mode.
d) Enlighten those situations where no singular or clear explanation exists.

A case study implements an empirical inquiry for a specific situation within its real-life context (physical and social environment) with rich and deep data. Case studies are useful where the boundaries between the research object and its context cannot be clearly identified. This demonstration and evaluation of the case study comprises an aspect of the actual modelling methodology (Scandura & Williams 2000, Yin 2009). The aim of a case study is to understand complex social phenomena, while retaining the holistic and meaningful characteristics of real-life events (Yin 2009). A typical process for performing a case study is presented in Figure 10 (George & Bennett 2005, Yin 2009).

First, the case study is designed to identify the method required to capture information, using a data collection plan. Next, the case study is prepared to ensure the required equipment or subjects are available. Aspects to consider include case study questions, case study propositions, and units of analysis. The case study is then executed to gather information through monitoring the subjects, in order to record observations on the required characteristics. These are analysed in line with a predetermined approach. Finally, the outcomes are reported in the thesis.

2.5.5.2 Case Study Method

Models developed through the modelling methodology predict how technology is used in the STS along with the typical effects and improvements. The actual technology still has to be implemented in an STS during a realistic exercise or scenario, to capture information on the variables as identified in the modelling process. This forms a case study for the modelling methodology. The demonstration has to show how variables relate to the simulations, and improve the model.

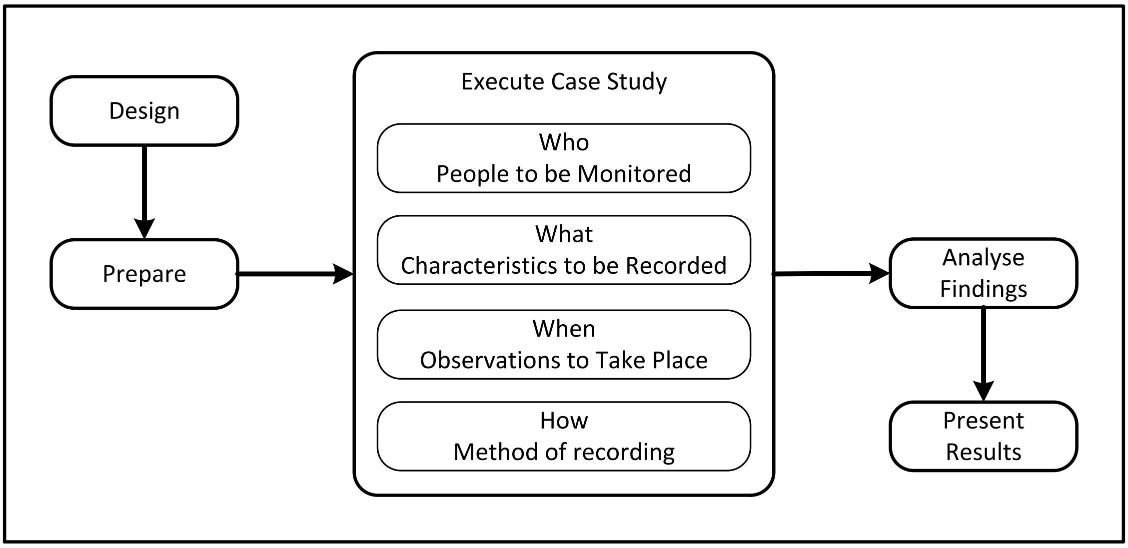

Figure 10: Case Study Process (George & Bennett 2005)

The case study comprises demonstrating a new web-based collaboration technology in the C2 system for a neighbourhood watch (NW) in a community policing forum (CPF). The purpose of the new technology, called Cmore, is to provide situation awareness for a NW, as well as to capture information for intelligence analysis. The other demonstrations of the modelling will not be a complete case study but will execute the methodology to model the impact of the technology in complex STS such as APO and BSO.

A survey through structured interviewing with a questionnaire is the main source of data. Despite the apparent advantages, questionnaires as a data-capturing tool do have limitations. The relative strengths and weaknesses of interviews and observations for a case study are listed in Table 2 (George & Bennett 2005, Yin 2009).

Table 2: Comparison of Interviews or Direct Observations

	Strength	Weakness
Interview	**Targeted** – Focuses directly on the case study topic **Insightful** – Provides perceived causal inferences and explanations	**Bias** – Poorly articulated questions **Response bias** – Inaccuracies due to poor recall **Reflexivity** – Interviewee gives what the interviewer wants to hear
Direct Observation	**Reality** – Covers events in real time **Contextual** – Covers the context of the case	**Time consuming** **Selectivity** – Broad coverage is difficult without a team of observers **Reflexivity** – Events may proceed differently because they are observed **Cost** – Takes many hours to observe an extensive event

2.5.5.3 Case Study Survey Design

2.5.5.3.1 General

As the modelling methodology addresses how a new technology will affect a complex STS, the two main approaches for collecting evidence in the field are through structured interviews and actual recorded data with the collaboration technology. The structured interview is in the form of a questionnaire to be completed by users of the technology in the CPF. The interviews are completed before and after exposure to the technology to determine its contribution.

Analysis of the collected data may consist of pattern matching, explanation building, time series analysis and logic models to match empirically observed events with theoretically predicted events. In this study the field observations are matched to the simulations and models through building logical models. The specific design of the case study is determined through the outputs of the modelling methodology. These are to confirm that what is identified through modelling does actually occur in the real-life system. They focus on the level of situation awareness achieved and the utility of the technology to support work.

The utility of the modelling methodology is substantiated if the STS behaviour exhibited by the models is demonstrated in a case study. This confirms that the modelling has led to an adequate understanding of the problem situation and impact of the solution technology on the complex STS.

2.5.5.3.2 Experimental Measurement

In this study the case study is executed in the form of a demonstration to gather empirical and comparative data on field deployment of the new technology in a CPF NW system. The objective is to compare the behaviour predicted in the STS models with the actual implementation behaviour of the system. Knowing what level of accuracy is required in the measurement will determine the type of measurement as well as the data analysis plan. The different classifications of measurement are the following (Alberts 2002, Yin 2009):

a) Nominal measurement. Observations are assigned to categories without a natural order.

b) Ordinal measurement. A natural order exists between the different categories, but the values are unimportant.

c) Interval measurement. The distances between the points on a scale are meaningful, resulting in the ability to compare different values. However, there may not be a meaningful anchor point.

d) Ratio measurement. Here a meaningful anchor point (such as 0) exists and allows for analysis with many analytical tools.

This research utilises a Likert scale that implements interval measurement in questionnaires to determine the opinions of the users (people) in the STS on the utility of the new technology. The Likert scale supports experiments where the opinion before and after an applied effect needs to be measured. This summated rating scale is the most used one in surveys to determine favourable or unfavourable attitudes towards a statement. The questionnaire determines whether the users agree or disagree on different factors concerning the new technology. This method enables the researcher to compare an individual’s score with a distribution of scores from a well-defined group of respondents (Cooper & Schindler 2003).

The empirical evidence to be captured during experiments must adhere to the principles of validity (measure what the experiment is trying to achieve), reliability (same value of an attribute in the same situation) and credibility (understand, believe and trust the measurements). The interviewer must ensure that respondents understand questions in relation to what the researcher asks. This requires simplicity in the wording of the questionnaire. Respondents must be able to compute answers on problems from their memory of their experiences with the new technology.

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2.5.5.3.3 Situation Awareness Methods, Tools and Metrics

Part of the questionnaire is used to measure the level of the situation awareness achieved through the new technology in the STS. Measuring situation awareness is not an easy task, as it is an internally constructed mental picture or model of the current and possible future situations (Endsley et al., 2003). Current assessment methods rely either on inferring situation awareness from related artefacts that are simple to measure or on direct assessment of the operator’s situation awareness. The observable processes follow, behaviours are exhibited, the level of success of the outcomes are assessed, and the level of situation awareness is inferred. Figure 11 explains where the different measurements of situation awareness take place in a C2 system (Endsley et al. 2003). Even if it is more difficult, the direct measurement of situation awareness is more accurate.

The indirect measures infer situation awareness by measuring other observable constructs. They focus on cognitive processes and performance measurements by interaction between an operator and the system. Typical methods for indirect measures are process measures (verbal protocols, communication analysis and psychophysiological metrics), behaviour measures (observable actions) and performance-based measures (task outcomes) (Endsley et al. 2003). Direct measures focus on the situation awareness of the system operators themselves. Typical methods used for direct measures are the following (Endsley et al. 2003):

a) <u>Subjective Measures</u>. A subjective measure considers only what behaviour is observable by the operators themselves or by the observers.

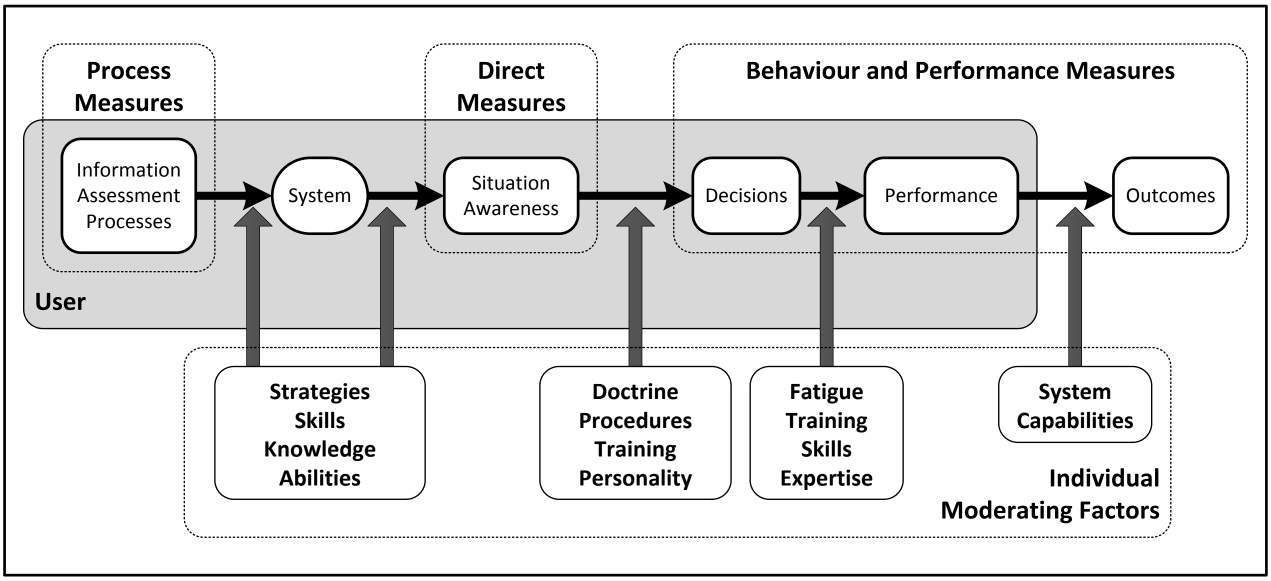

Figure 11: Approaches to Situation Awareness Assessment (Endsley et al. 2003)

i) Situation awareness rating technique. The situation awareness rating technique (SART) is widely used, as it is reasonably robust and sensitive to task difficulty, operator experience and design variables. The SART measures general situation awareness constructs and relies on operators' understanding the situation, in order to make decisions. This understanding is often conscious, explicit and quantifiable. It is possible to be used in either field of laboratory settings.

ii) Observer ratings. The observers may have a better understanding of the situation and the system than the operators in self-ratings. However, the observer may not comprehend the operator's perception of the situation, and observations on performance have to be correlated with the experience of the observer. Observable actions and behaviours are required and must be planned for in the scenarios.

b) Objective measures. Objective measures are achieved by comparing the observed (actual) and reported situation awareness of the operator with reality.

i) Post-test questionnaires. A set of questions are posed to the operator after a test or exercise. This method is less intrusive and does not disrupt the tempo of the exercise. It also allows for enough time for a thorough investigation. However, this requires a good memory from the participants, and problems from early in the exercise are easily forgotten.

ii) Situation awareness global assessment techniques. The situation awareness global assessment techniques (SAGAT) use operator in the loop exercises to test the situation awareness of interface concepts. Questions are posed to operators at various stages through the exercise on their situation awareness, using automated software, while the displays are blanked. Upon operators completing the questionnaire, the experiment is continued until the next stop point. The simulation is frozen for the assessment, which may influence the pace and rhythm of the exercise. Operators must not be able to predict when a freeze will happen. The freezes can be a problem for real-time field exercises, as opposed to simulated exercises.

iii) Online queries. Here, the simulation is not stopped, and the questions are posed online. The speed with which operators provide answers indicates their situation awareness. The queries are to be embedded in the tasks performed by operators. However, this approach intrudes on executing the assigned task, and can change it or shift the situation awareness due to the questions. The workload of operators is increased, and only a limited set of situation awareness requirements may be assessed.

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2.5.5.3.4 Method for Situation Awareness Measurement in this Thesis

Situation awareness in this study is measured using the SART. The aim of the case study is to compare the behaviour of the complex STS using the new technology with the understanding derived through the modelling methodology. The aim is not to achieve an accurate and absolute assessment of the situation awareness of operators through using the system. The SART provides a subjective estimate of the situation awareness of the system users. Despite being developed to assess aircrew situation awareness, the SART provides useful insight into the changes experienced in situation awareness with the introduction of a new technology (Taylor 1990).

The SART is inexpensive, nonintrusive and easy to execute, as operators rate their own situation awareness. It does not require expensive simulators and can be conducted post-trial. The analysis is often easy and is based on real world situations. Performance assessment data can be used in conjunction with self-ratings to determine the correlation between actual and self-reported situation awareness. It is also not feasible to perform freeze tests, e.g. SAGAT, as operators are in the field doing their actual tasks while using the system. However, participants may not be aware of what they do not know, and ratings may be influenced by their level of success in the assessment (Salmon et al. 2006, Taylor 1990). The aim is to measure the confidence of users in the situation awareness provided by the system in relation to system behaviour models. SART allows operators to rate a system design (via bipolar scales) by the degree (seven degree scales) of perception experienced:

a) The amount of demand on attentional resources (demand).
    i) Instability of the situation (likeliness to change suddenly).
    ii) Complexity of the situation (degree of complication).
    iii) Variability of the situation (number of variables and factors changing).
b) Supply of attentional resources and perceived workload (supply).
    i) Arousal (degree of alertness or readiness for action).
    ii) Concentration of attention (degree to which thoughts are brought to bear).
    iii) Division of attention (distribution and spread of focus).
    iv) Spare mental capacity (mental ability available for new variables).
c) Understanding of the situation provided (understanding).
    i) Information quantity (amount of knowledge received and understood).
    ii) Information quality (accuracy and value of the knowledge communicated).
    iii) Familiarity with the situation (degree of prior experience and knowledge).

Assessment outcomes can be correlated with the performances of individuals, despite participants' ability to rate their own situation awareness being questionable (Salmon et al. 2006). However, it is not easy to relate workload elements with the measured situation awareness. The overall situation awareness rating or score, which is useful for comparison, is calculated using the following equation (Taylor 1990):

$$\textit{Situation Awareness} = \textit{Understanding} - (\textit{Demand} - \textit{Supply}).$$

2.5.6 Implementation of Research Instruments

The various research instruments, as discussed in the previous sections, are applied throughout this thesis. Table 3 provides guidance on how and when the research instruments are applied. The theoretical discussions in Chapters 2, 3 and 4 mainly use literature to describe the theory. This is also a form of document analysis, as books and publications are used.

Document analysis is used in the bulk of the literature research. A selected list of publications and books on the relevant fields are scrutinised to support understanding the problem and building a theory. The information used in planning and executing the demonstration and case studies are also derived from the document analysis.

Focus groups are applied as part of the methodology during the demonstration and case studies. The aim is to assist in interpreting the information from documents as well as to interpret the results of simulation and field observations.

Computer simulation of system dynamics is also part of the proposed methodology and is used to gain an understanding of the dynamic behaviour in the complex STS. In Chapter 5 and 6, simulation is the only method used to test the modelling approach. In the final chapter, further simulation assists in validating the models.

Table 3: Use of Research Instruments

Instrument	**Chapter 2**	**Chapter 3**	**Chapter 4**	**Chapter 5**	**Chapter 6**	**Chapter 7**
Document Analysis	✓	✓	✓	✓	✓	✓
Focus Groups				✓	✓	✓
Computer Simulation				✓	✓	✓
Case Study						✓

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The case study is the main form of evaluation of the effect and success of the modelling methodology in a real environment. The case study is used to gather data from the field implementation of a prototype technology for comparison with the models from the methodology.

2.5.7 Limitations

The possible problems and limitations in assessing the modelling methodology are the following:

a) The availability, objectivity and experiences of the SMEs.
b) Technology usability and availability for prototype development.
c) Availability of test subjects with the required skills and experience.
d) Subjectivity of situation awareness measurements.
e) Experience in applying situation awareness measurements.

2.6 Ethical Procedures

The standard ethics process of the University of Pretoria is adhered to. Participants of the focus group and case study each complete a consent form. There is no incentive for participation in the focus group; hence, participation is voluntary. The focus is on the ability of the modelling methodology to support C2 system development.

2.7 Conclusion

As seen in this chapter, DSR presents a suitable foundation and approach to guide the development and assessment of a modelling methodology for complex STS. The main reason for this is that DSR is meant to addresses the theory of design. It is aligned to the softer side of systems development through its flexibility in assigning the artefact to different levels of abstraction (construct, model, method or instantiation).

The research tools used in testing the modelling methodology are also presented, as well as the triangulation achieved for the required rigour. The tools are used at different stages of the modelling methodology, and complement one another. A complete case study with empirical evidence is used to confirm the methodology. The details of the assessment are discussed in Chapter 7.

The next chapter introduces the environment of complex STS, with a description of the perceived and general problems. This forms the “awareness of problem” statement and proposal for the proposed DSR process.

3 COMPLEX SOCIOTECHNICAL SYSTEMS

Fools ignore complexity. Pragmatists suffer it. Some can avoid it. Geniuses remove it.

Alan Perlis

3.1 Introduction

The aim of this chapter is to introduce the concept of the complex sociotechnical system (STS) as part of the literature study. This chapter forms the first step in the first stage of the research design, as seen in Figure 12. It identifies, defines and characterises the problem to be addressed in this study through a literature search on STS and complexity theory. The problem to be addressed in this study is the difficulty of developing solutions for perceived problems in complex STS.

This research focuses on modelling complex STSs to support the system engineering (SE) process. The hypothesis of this thesis is that through addressing the contribution of humans performing work in a complex, constrained and dynamic environment in the modelling and analysis phase, a better understanding and a more complete derivation of the requirements for the STS can be achieved. This should lead to improved designs, selection of technologies and implementation strategies of STSs to cope with complex operating environments and support humans with sense-making and decision-making in support of their work in the system or as part of the system.

Firstly, the concept of a system is defined and described within the context of this thesis. As systems and their operating environments are getting more integrated, there is a need to understand the concept of complexity. Therefore, complexity is defined and explained along with the phenomenon of emergence, which leads to “wicked and messy” problems.

The notion of complexity is then extended to the concept of complex systems. Humans, in a structure or organisation, interacting with a technical system result in an STS. One of the main factors contributing to complexity in systems is the human actor. The modelling approach and system design have to cope with complex and dynamic human behaviour under complex environmental constraints to enhance successful and safe operation.

This leads to identifying requirements for a modelling methodology to support developing successful complex STSs. The current development of systems, mostly through applying SE, tends to neglect the human part of the STS, as well as the dynamic complexities experienced during operation. The difficulty with classic SE techniques and approaches in developing complex systems gives rise to adaptations such as complex SE and cognitive SE, which are discussed in Chapter 4.

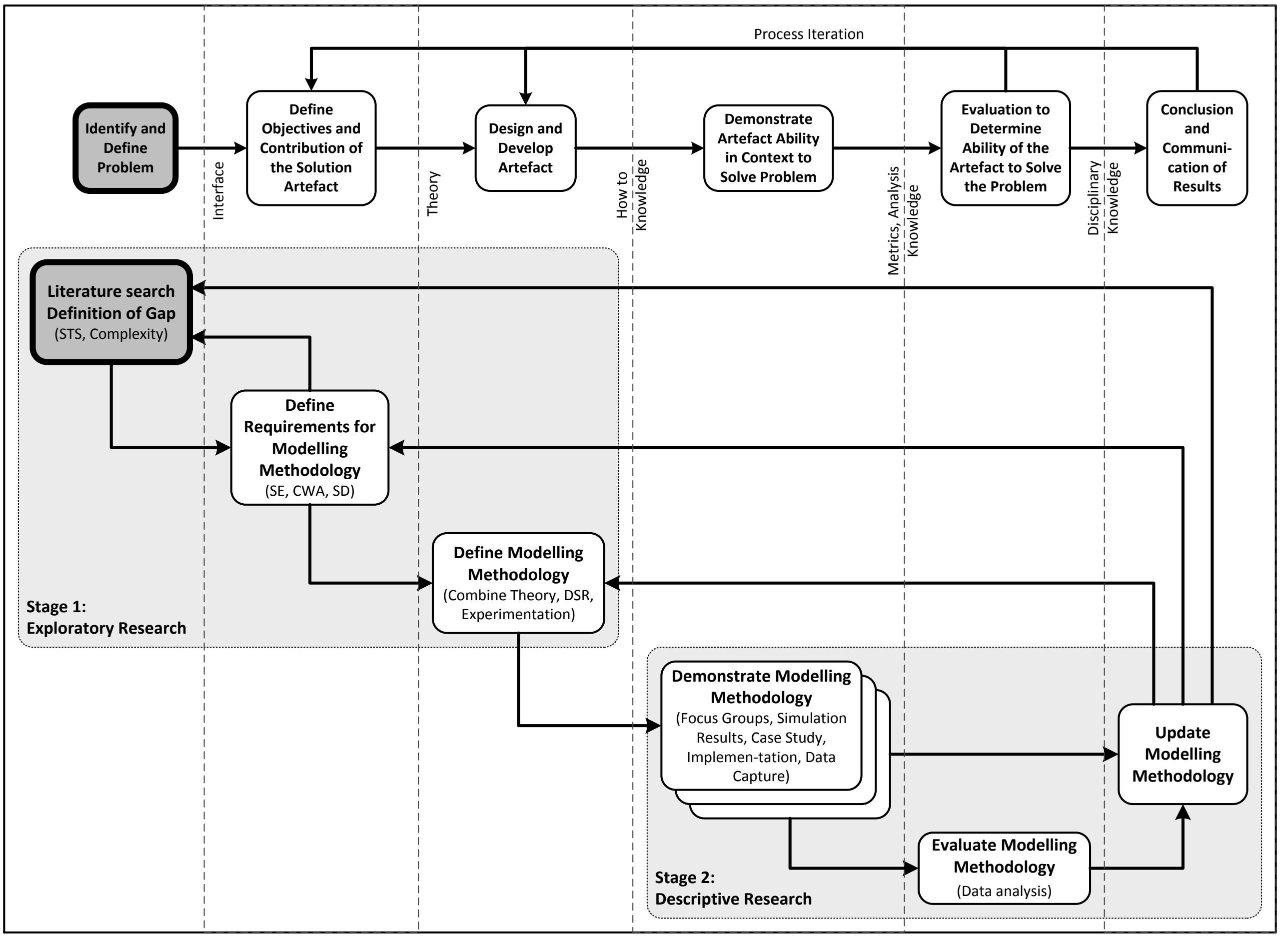

Figure 12: Chapter 3 Relation to Research Design

3.2 System Defined

A system is generally defined as an integrated collection of elements organised to achieve a purposeful result (Nemeth 2004, Haskins 2010). The system elements may include various combinations of products (hardware, software, firmware), processes, people, information, techniques, facilities, services and other support elements that exist and operate in an environment. As seen in Figure 13, the system has a purpose that satisfies or exploits an opportunity.

This is used to derive the goal and objective of the system in order to guide its analysis, design and development. The performance of the system provides a result that should satisfy the original purpose, goal and objectives. The typical basic functions executed by a system are the following (Nemeth 2004):

a) Input. Inputs to a system can consist of information, materials or energy.

b) Sensing. Receiving information from the external environment or internally, from within the system.

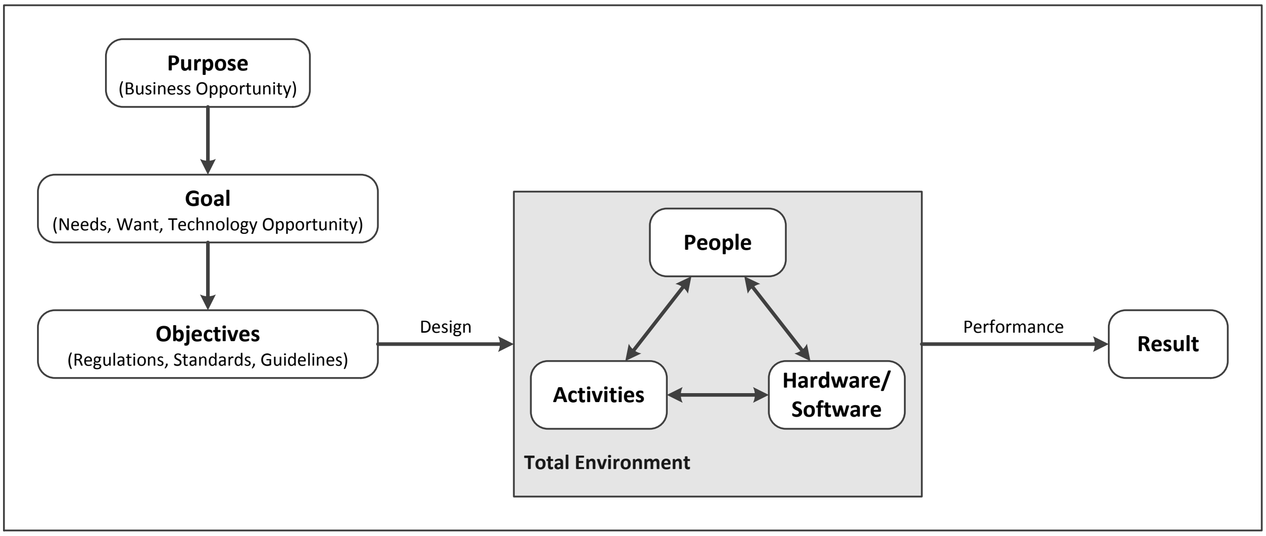

Figure 13: System Elements (Nemeth 2004)

c) Information processing and/or decision. A human can use the information to decide whether or not to act. A machine requires some form of programming for a required response to an anticipated input.

d) Storage. Machines store information in a physical medium, while humans use short-term (working) memory and long-term memory.

The aim of a system is to perform its designed task using the organisation and interaction of internal elements. This takes place within an external environment that can support or affect the execution of work (Nemeth 2004, Haskins 2010). It is important to notice the roles of people that are supported through organisational and technical means. The success of the system is dependent on the mutual interaction of these, as well as on the influences of the external environment. Since systems can be of a complex nature or exist in a complex environment, the notion of complexity is discussed in the next section.

3.3 Complexity

3.3.1 Definition

Pagels (1988) notes that complexity as a concept has been with us for a long time, but it is only since the development of computer systems and cybernetics that it has reached real prominence. The Merriam-Webster dictionary defines the word *complex* as “a whole made up of complicated or interrelated parts”. Gell-Mann (1994) traces the definition back to the Latin word *plexus*, meaning braided or entwined. Therefore, *complexus* means braided or entwined together. From this, we derive that *complexity* refers to a number of elements or effects from the environment and a system that are intricately intertwined with a high-level of interconnectivity. A simple system, or artefact, consists of few elements, with linear and easy-to-understand relations between them. This contrasts with complexity, which has many interrelated parts with non-linear interactions between them. These are not easy to understand, nor enable one to predict behaviour under different and dynamic internal or external environments (Hollnagel 2012).

The term *connectivity* includes not only technical integration, but also describes where humans are involved in the system. The effects of a decision or action by one actor influence the behaviour of another human or element. Due to complexity, the behaviour (impact) as a result of the action may not always be consistent, and is dependent on the different initial states of the system and the environment. This implies that the context of information, decisions and actions plays a major role in the outcome (Stepney et al. 2006).

3.3.2 Emergence

Emergence is a result of complexity in a system. Aristotle provided one of the earliest definitions of emergence as "... things which have several parts and in which the totality is not, as it were, a mere heap, but the whole is something beside the parts" (Stepney et al. 2006). This is nowadays phrased as the "Whole is greater than the sum of its parts." The observed high-level novel behaviour is a result of the generally nonlinear interactions between the elements and/or the environment. Everyday life, from nature to modern combat and the internet, is full of examples of emergent behaviour, which include the following (Stepney et al. 2006, Johnson 2006, Ryan 2007):

a) Nature and living systems. Ant colonies, bees, termites.
b) Non-living emergence. Colour, friction, patterned ground, weather.
c) Organizational systems. Economics, political processes, combat, traffic patterns, cities, World Wide Web, Internet, Artificial Intelligence and language.
d) Technological systems. Autopilot systems, robotics, integration and interoperability.

A complex system has emergent properties if it consistently presents characteristics in a macro state that are not present in the micro state. The emergent behaviour of a system may come as a surprise to the observers of the system, which may not have been predicted by looking at individual elements in isolation (Fromm 2006, Stepney et al. 2006, Johnson 2006, Ryan 2007).

Beneficial emergent properties are robustness, adaptiveness, fault-tolerance, adaptability and flexibility as well as the adoption of a product by users for applications never intended by the designers. Emergent behaviour such as the undermining of safe usage of a system and unforeseen catastrophes can also be harmful. Accidents and incidents are caused by unforeseen interactions between operators and systems that could not typically have been anticipated using current SE techniques. Other negative properties include low predictability, reliability, understandability and controllability of emergent behaviour for computational purposes (Fromm 2006, Gleizes et al. 2008).

Developing a system consisting of humans, an organisation and technical products may result in some level of emergence as a result of the flexible and unpredictable behaviour of humans under dynamic and unforeseen circumstances. Many planned, unplanned and unpredictable interactions between people, technical systems and the complex operating environment may occur. The difficulty is to allow for emergence, while maintaining control of the system to continue achieving its designed purpose. These situations lead to “wicked and messy” problems, which are discussed in the next section.

3.3.3 Wicked and Messy Problems

The complex interactions between humans, systems and the real world cause “wicked and messy” problems for decision makers to solve. Decision makers in complex situations are often faced with problems comprising a large degree of uncertainty. It may not be clear how to approach the problem and decide between alternative solutions (Pries-Heje & Baskerville 2008). Automation and related decision support tools are often not suited to such situations. Rittel & Webber (1973) defined wicked problems as having the following characteristics:

a) The problem does not have a definitive formulation and it is impossible to list all the possible solutions.

b) Wicked problems have no stopping rule, as there are no criteria to indicate that the solution has been found and successfully implemented.

c) The solution may not be a simple “true-or-false”, but rather a “good-or-bad”, as many different judgements may exist.

d) There is no immediate and ultimate test of a solution to a wicked problem, as it may affect waves of consequences over a very long time.

e) It is not possible to learn about the problem by trial and error, resulting in a “one-shot operation” as every attempted solution changes the problem.

f) Every wicked problem is unique, as it will always be possible to identify a distinguishing property.

g) Every wicked problem may be a consequence or symptom of another problem.

h) Designers of solutions to wicked problems aim to rectify or improve a situation, as opposed to research where a hypothesis may be refuted in the search for the truth.

The complexity in the problem situations arise from the dynamic nature (never stable) and multiple perceptions of reality (Checkland & Poulter 2007). A big positive as well as negative aspect is the occurrence of emergence in the system as a result of human actions. In order to solve these problems, any approach should be in line with and supported by human cognitive processes. Human actions may lead to the emergence of an effective and novel solution to wicked problems.

3.3.4 Complex Systems

Complex systems, in the context of this thesis, are large manmade systems consisting of many autonomous and individual agents, with linear and nonlinear interacting elements that cause unpredictable behaviours. Complexity may even exist in simple systems, due to interactions and feedback between elements over time. Complex systems display non-deterministic, emergent, unpredictable and unexpected (even chaotic) behaviour, as a result of nonlinear and dynamic interactions between elements and the environment caused by feedback loops with delays. Complexity can be a characteristic of the artefact's technology or the situated use of the artefact, including the context or environment (Sheard & Mostashari 2009, Janlert & Stolterman 2010, Woods 1988).

A complex system cannot be decomposed into independent and manageable elements for analysis, design and development. The structure of the complex system also cannot easily be deduced from the structure of the individual agents, as it is dependent on the interactions among the parts. The behaviour of the system may be nondeterministic, despite an apparent order, and may even exhibit chaotic behaviour under certain conditions, as a result of nonlinear dynamics. Furthermore, complex systems are seldom developed as a whole: they tend to be formed through integrating new technologies, resulting in evolution. Complex systems tend to adapt to their environment as they evolve into increasing complex systems (Sheard & Mostashari 2009, Gleizes et al. 2008, Fromm 2006, Woods 1988, Stevens 2008).

Complex systems are not easy to understand and to predict behaviour under different and dynamic situations. Suitable methods are required to analyse, design and develop modern systems to operate successfully in a complex environment. These need to address the social and cognitive demands as well as the dynamic complexity in the system (Janlert & Stolterman 2010, Reiman & Oedewald 2007, Lintern 2012, White 2009, Bahill & Gissing 1998). The type, origin and characteristics of the complexity must be considered during the design of artefacts. Complex systems can be addressed using some of the following views (Janlert & Stolterman 2010, White 2010, Fowlkes et al. 2007, Bar-Yam 2003):

a) Technical complexity. Stand-alone systems cannot meet the requirements of complex challenges in the real world anymore. The result is that more and more systems must be integrated to exchange information to enable better control, using technological advances in communications. Instead of new developments, current systems tend to be improved by inserting new technology or replacing old technology. Due to integrating these systems, coupled with exchanging information, a change in one subsystem will influence the operation of other subsystems. This gives rise to complexity, with the result of unexpected effects that may cause failures. These can be described as multiple feedback loops between the different parts, as well as emergent behaviour within the system as a whole. The results, however, can be very difficult to explain or understand (White 2010).

b) Organisational complexity. Complex systems are reliant on intra- and inter-organisational functional capabilities in order to achieve objectives. Knowledge and control are distributed in the complex system, and exist at different operational layers of elements or subsystems. The success of the overall system depends not only on the managing authority, but also on the cooperation and social interaction of others (Janlert & Stolterman 2010).

c) Human complexity. A common characteristic of systems that are difficult to analyse, design and develop is that they contain "… human beings in social roles trying to take purposeful action" (Checkland & Scholes 1990). Cross-boundary interactions between humans and machines characterise the modern world. Systems where humans play a role in making sense, making decisions and initiating actions have a tendency to get complex. The nondeterministic behaviour of people must be captured in the description of the whole system. While developing these systems, the focus must be on supporting the human with the available technology and organisation (processes). Contributors to system complexity include the dynamic and context-dependant nature of cognitive work and the dynamic nature of socio-technical work settings. Critical tasks tend to be time-limited with decisions and actions depending on feedback with delays. Complexity may lead to information, decision or communication overloads that cause confusion, stress, panic and disaster for the system user (Fowlkes et al. 2007, Bar-Yam 2003).

The accurate prediction of a system's behaviour requires a model of detailed understanding of that system. As complexity is incompressible, the model must encapsulate all of the relationships distributed all over the system. Complex systems have many simultaneous nonlinear interactions, making it impossible to keep track of the causal relationships between components. Also, as the system is open, the boundaries cannot accurately be determined. Therefore, accurate modelling of a complex system, requires a model as complex as the system itself. Since modelling aims to reduce complexity in a system, it may lead to distortion. The modeller must be cognisant of these shortcomings in the ability to model complex STSs (Cilliers 2000, Cilliers 2001, Cilliers 2005).

Most models of complex systems should be used to display general complex behaviour to support learning about the system, and not to quantitatively model specific, empirically complex systems. Models can be used to attempt to grasp the structure of complex systems (Cilliers 2001, Cilliers 2002). Therefore, by creating a descriptive and coherent model, functional and causal relationships can be derived at the level of system's behaviour. This supports an understanding of how interactions between system elements occur without a complete understanding of the complexities and nonlinearities.

As seen in the list above, cognitive and social humans are one of the main contributors to complexity in a system when they interact with the technical aspects of the system. This leads to the notion of complex STS, which is discussed in detail in the next section.

3.4 Sociotechnical Systems

The term *sociotechnical* refers to the interaction between *social* humans and *technical* systems. This is in contrast to the Taylorist-based mechanistic (scientific) management paradigm with strong hierarchical (bureaucratic) and top-down one-way coordination and control (Walker et al. 2008:480). The concept of sociotechnical systems originates from the work of Fred Emery and Eric Trist at the Tavistock Institute of Human Relations in the 1950s. During that period, the introduction of new technology to improve efficiency and productivity of organisations did not meet expectations. This led to introducing the sociotechnical approach, which focussed on the joint optimisation of the social and technical subsystems (Baxter & Sommerville 2011, Bostrom & Heinen 1977, Trist 1981).

People perform work in organisations, using technological artefacts, to achieve economic performance and job satisfaction. The technological artefacts consist of the tools, devices and techniques used by the organisation to transform inputs into outputs for economic gain. The sociotechnical approach centres on the relationship between perception and action, to create an environment for shared values that promotes collaborative decision-making (Walker et al. 2008). The social subsystem addresses the structure of the organization, encompassing the authority structures and reward system, as well as the people in the organisation with their knowledge, skills, attitudes, values and needs, as seen in Figure 14 (Bostrom & Heinen 1977).

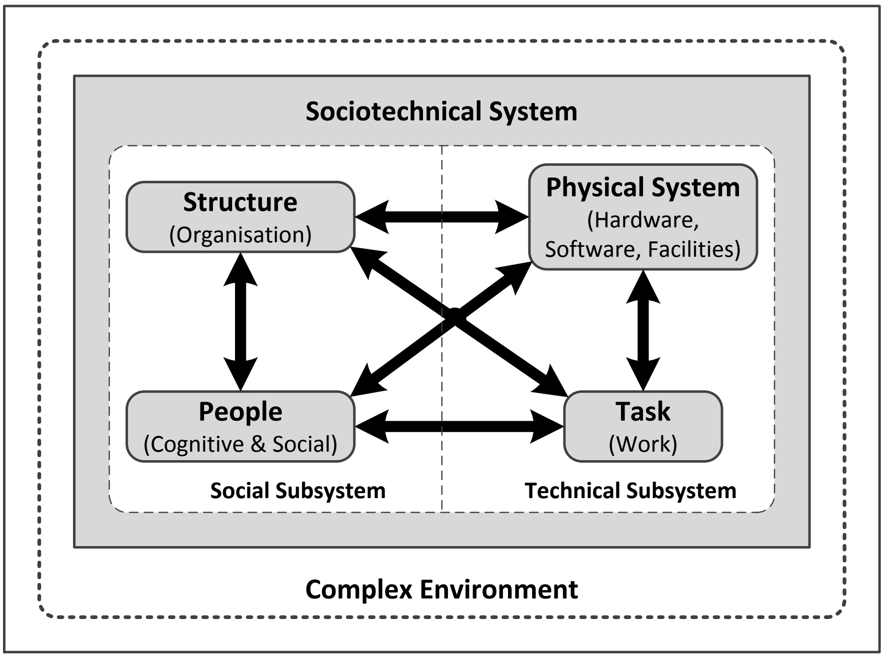

Figure 14: Sociotechnical System (Bostrom & Heinen 1977)

The STS is an open system that exists within a complex environment by which it is affected and with which it interacts. STS theory highlights the importance of social humans in the organisation, instead of relying only on technical improvements to solve complex issues.

Sociotechnical studies recognised that an organisation is a social system that can be analysed at three levels: primary work system, organisational systems and macro-social systems (Trist 1981). STS theory also developed along with the notion of open systems theory by Ludwig von Bertalanffy (1950). This includes the concepts of self-regulation and equifinality, meaning that systems somehow interact and influence one another. Jointly optimising the technical and social subsystems determines the success of the STS. Modern views on STS aim to promote knowledge sharing, learning and innovation within the organisational context, to enable collaboration and flexibility for a competitive advantage (Walker et al. 2008). The work of Trist and Bamforth (1951) highlighted the following principles of sociotechnical systems (Baxter & Sommerville 2011):

a) Responsible autonomy. Separate and interdependent small autonomous parts or groups are more effective than a strict hierarchy is, where responsibility is at the top. Teams that take responsibility for their actions within the proximity of trusted team members exhibit better cohesion and overall performance.

b) Adaptability. The elements (social and technical subsystems) of an STS pursue a goal while adapting to the external environment. Small autonomous teams are better prepared for unforeseen circumstances, and order cannot be imposed onto a complex situation. Goals can be achieved by different means and processes (equifinality).

c) Meaningfulness of tasks. As team members feel the importance of tasks, they more easily take responsibility for them. The important characteristics to consider are skill variety, task identity, task significance, autonomy and feedback.

The interaction between the social and technical aspects of an organisation may be both linear (designed cause and effect) and non-linear (unexpected and unpredictable complex relationships). When improving a work system to cope with complexity in a dynamic environment with new technology, both the social and technical factors require assessment and adjustment (Walker et al. 2008).

The term *technology* derives from the Greek words for art, skill and cunning of hand, and refers to the collection of tools (machinery) and procedures used by humans. A technology can be considered to be a material or immaterial entity (or collection of techniques) created through applying mental and physical effort in order to solve real-world problems. Engineering aims to study and design new technologies to enable humans. However, technology can have positive and negative effects on humans, society and their surroundings (Arthur 2009, Schatzberg 2006).

Changes in technology affect how the people interact because of changes in their values, cognitive structures, lifestyles and habitats (due to the new technology). These changes are dependent on the context of the work as well as on the structure of the organisation. Modern communication and knowledge management systems create new opportunities for the flow of information within organisations. The trend is moving away from one person/one task micro-management principles to teams reliant on information exchange.

An effective STS is achieved through a human focus based on shared awareness (peer-to-peer interaction), agility (autonomous groups) and self-synchronisation (synergy) (Walker et al. 2008). The physical-technical system supports the organisation through enterprise architecture, which supports the business rules or doctrine, enabling interaction between teams and individuals. People interact with the physical system and one another to distribute information and orders through a human machine interface. Assessment of the sociotechnical systems requires a simultaneous investigation into the roles and influence of all these elements, as becomes clear in the following sections.

A new technology or artefact affords new ways for humans to operate and organise in achieving a goal. This may be the result of changes in their values, cognitive structures, lifestyles and habits. It is therefore important to be formative in the development approach, as highlighted in Carrol's (Carroll & Rosson 1992) "Task-Artefact Cycle". Sociotechnical systems have become a focus for information systems development. Often information systems are used in the operation and management of enterprises, making it a complex sociotechnical system. These changes are also dependent on the context of the work and structure of the organisation (Baxter & Sommerville 2011, Carroll et al. 1991, Walker et al. 2008).

STS theory provides a useful framework of systems analysis to understand the reasons behind the poor acceptability, uptake and performance in system development (Baxter & Sommerville 2011, Bostrom & Heinen 1977). When the demand for work is unstructured and uncertain, with task interdependence, the STS approach, with its simultaneous focus on the social and technological aspects can be used in the analysis and design of complex systems. This interaction affects the successful operation or failure of an STS or organisation. People also have the flexibility and intellect to reorganise and manoeuvre to address challenges and changes in the environment (Walker et al. 2008).

3.5 Sociotechnical System Development

Introducing a new technology into an STS to be a necessary and useful tool, instead of a toy, remains a challenge. The new technology remains a means – it is not an end. STS design goes beyond interface design for human-machine interaction. Humans often have to interface socially with other humans to perform work. Both have to be addressed in complex STS modelling. The designer must discriminate between human-machine interaction and human-human interaction (social), such as in a team.

Appropriate measures for developing a new STS are required to assess the usefulness of a technology. The appropriate focus is required on better and faster decisions, judgements, effective planning and enhanced sense-making (Jenkins et al. 2011). The design of an STS can be approached from the following perspectives:

a) Human-centred perspective. Automation should support human needs and work, and not focus on the technology, per the technology-centred perspective. Technology should alleviate the workloads of humans but not increase them. Automation may be of assistance during nominal conditions but may place an extra burden on humans during complex and unforeseen circumstances. Therefore, in allocating tasks to machines, instead of to humans, one must consider these nonlinear events, especially where situation awareness is required. Function allocation should also address the cognitive control mode in context. Typical modes of cognitive control between which a human can switch according to the situational context include scrambled (panic), opportunistic, tactical and strategic (Parasuraman & Wickens 2008, Hollnagel 2012).

b) Team-oriented perspective. Automation can also be viewed from a team perspective, where the technology is a team member. A team is defined as two or more humans that inter-dependently work together towards a common goal. A major factor in teams is trust, and technology must be trusted in the same fashion as for human team members (Muir 1994, Muir & Moray 1996, Salas et al. 2008). Automation must complement humans just as they do other team members. Therefore, the design of automation should consider the team structure of the work environment, and not inhibit team communication. This can be solved through effective machine interfaces and displays. Another concern is the issue of responsibility and authority allocated to a machine as a team member.

c) Work-oriented perspective. The focus on the work the STS has to perform helps to delineate the work and tasks across the team required to achieve the objectives. The function allocation must support work in a dynamic environment, according to cognitive engineering. Work is seen as purposeful activity acting upon and in response to a dynamic environment (Rasmussen et al. 1994, Vicente 1999). This is discussed in greater detail in a subsequent section of the thesis.

3.6 Complex Sociotechnical Systems

The discussion on complex systems highlights the cross-boundary interactions between humans and machines that characterise the modern world. The contributors to system complexity include the dynamic and context-dependant nature of cognitive work and the dynamic nature of sociotechnical work settings (Fowlkes 2007, White 2010). In development, the focus must be on supporting humans with the available technology. The way that humans think, operate and interact must be brought into the context of the physical system design. Modern industrial organisations tend to be complex and dynamic STSs for the following reasons, which relate to the discussions above (Reiman & Oedewald 2007, Warne et al. 2009, Leplat 1988, Bainbridge et al. 1993, Cilliers 2001, Geels 2004):

a) Highly specialised work, often with multiple goals. Often limited time is available to complete tasks.
b) Multiple interacting parties, such as teams in complex social structures, with non-linear integration.
c) Uncertainties within the technologies employed and the environment.
d) Multiple elements in the organisation going through continuous change, as the STS is constantly changing, learning, and growing.
e) Feedback delay from decisions and the actions initiated.
f) Cascading changes, where a change to one subsystem may cause a ripple effect in other subsystems. These can even rebound back to the subsystem with the original change.
g) The STS and its subsystems constantly interacting with their environment.
h) Inflow of resources is required to maintain stability.
i) Subsystems or components of the STS have the ability to function in isolation.
j) External forces on the organisation driving the pace of innovation and technology adoption.

These complex STSs are modelled for investigation and evaluation through various methods. The description or model of the STS must capture the non-deterministic behaviour of the humans involved. The three general categories are computational intelligence, agent-based techniques and model-based systems engineering (MBSE). These focus on modelling in support of SE; therefore, the MBSE route is followed, despite the advantages of the other methodologies. MBSE is used to create models of systems in support of design. These models can explore the responses of a system being assessed, and determine the impact that proposed changes may have on that system.

3.7 Conclusion

This chapter introduces the concept of systems, and more specifically complex STSs. It is derived from the links between complexity theory and STS principles. The literature highlights the difficulty in developing complex STSs, as people, their work, organisation and technology need to be considered within a complex and dynamic environment. As a result, classical SE and system development techniques focussing on the technical aspects may not be adequate.

The next chapter discusses the problems of traditional development and SE approaches, leading to the development of a modelling methodology. It includes proposals for alternative development methodologies. The aim is to establish a new method for designing complex STSs.

4 MODELLING METHODOLOGY DEVELOPMENT

All models are wrong, some are useful.

George E.P. Box

4.1 Introduction

This chapter defines the objectives and contribution of the solution artefact. It also implements the design and develops artefact. Per the research design seen in Figure 15, this chapter forms the second and third steps in the first stage (exploratory research) of the study. The previous chapter introduced the notion of complex sociotechnical systems (STS) to extract the requirements for developing a suitable modelling methodology in support of systems engineering (SE).

The second step considers the classic SE methods currently applied during design and development of complex STSs. SE forms the basis for developing systems, including STSs. However, the classic SE processes were initially developed in the 1950s for industrial-age problems that could be isolated and decomposed. The resulting standards and processes make the development of complex STSs difficult.

This presents a gap between the characteristics of complex STSs and the capabilities of classic SE approaches or processes. The possible deficiencies of classic SE necessitate additional SE approaches and tools for successfully developing complex STSs.

Modern complex systems developments often consist of introducing new technology into existing systems, which can affect the cognitive and social humans who are part of the system. A new technology may afford new and novel uses to achieve the system’s objectives. Extensive analysis of the impact of the new technology will assist in understanding the new system's possible behaviour.

One way to improve the success of SE is to ensure that the problem to be solved is properly understood. Analysis of the problem and solution space involves capturing and modelling the knowledge and mental models of the stakeholders to support an understanding and derivation of the system’s requirements. A good description of the problem situation through a model is the first step in designing and developing a solution. These models are useful in determining through simulation the effect that the new technology will have on existing complex STSs.

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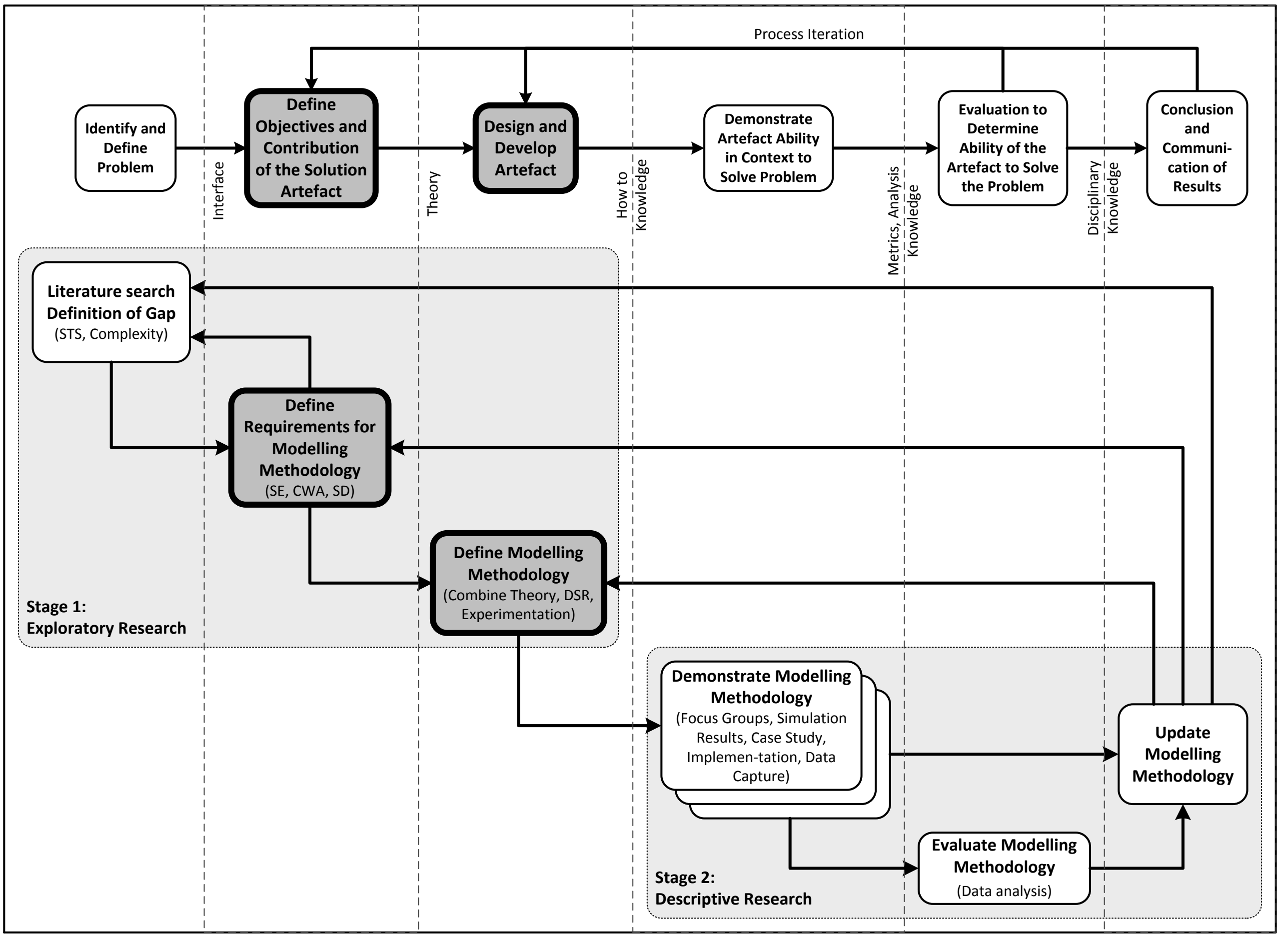


Figure 15: Chapter 4 Relation to Research Design

This chapter focuses on problem analysis and the solution design phase of theoretical SE processes to present different approaches and processes. The purpose is to identify the deficiencies in developing complex STSs that may be addressed through effective modelling and simulation in an extensive and integrated way. A modern trend in SE is to model the problem, environment and solution space. The aim of modelling is to assist in simulating, assessing and communicating concepts and understanding. Different modelling approaches are discussed before proposing the current modelling approach developed and demonstrated in this thesis.

The two main themes of interest in terms of complex STSs are the cognitive and social human role in the system as well as the effect of dynamic system interaction on decision-making. These are often neglected to some extent in classic SE processes, which tend to focus on the technical aspects of the system development (Bar-Yam 2003, Woods & Dekker 2000). Even through other factors such as availability and maturity of technology, design and supporting platforms also play a major role, this research will focus on the human factors and dynamic behaviour. The main frameworks proposed in this thesis for modelling the main sources of complexity in complex STS – humans performing work and the dynamic interaction between them and their technical artefacts – are cognitive work analysis (CWA) and system dynamics (SD).

CWA is a framework for analysing the way people perform work in an organisation while taking the environmental constraints into consideration. The environment represents the constraints of the broader context of work, which may include high stakes; dynamic interaction, ambiguous information, time limitations, and ill-defined or competing goals (Naikar 2006, Jenkins et al. 2011). The outputs of CWA are constructs or models that capture the structure of the problem. Functions provided by different technological elements are linked to the functional requirements of the system to achieve its purpose (Lintern 2012). However, CWA is limited in investigating the dynamic effect of decisions and policies on the system (Cummings 2006). The dynamic behaviour of the complex STS can be analysed using SD, which uses the structure of the system in simulation. SD looks at the effect of feedback and delays on operating the system as a result of decisions based on policies to understand the problem (Sterman 2000).

Since modelling a complex system requires these different views, a framework is required to integrate them in support of experimentation and building knowledge on the complex problem. Here the design science research (DSR) framework provides the structure for integrating the different modelling approaches. The DSR approach is the same as that used in the research design of the overall thesis, and the two applications should not be confused. These integrated modelling frameworks represent the solution artefact of this research. The next three chapters demonstrate and evaluate the utility of the developed modelling methodology.

4.2 Systems Engineering

4.2.1 Introduction

This section will discuss the relevant principles of SE to determine the utility of modelling. Typical existing SE approaches are presented and compared with the attributes of a complex STS system. The aim is to assess the deficiencies of standardised SE processes to determine the possible utility of modelling in the initial stages.

The objective of SE is to solve problems by bringing systems into being by applying systems thinking (Stensson 2010). Hitchins (2008) also defines SE as "… the art and science of creating whole solutions to complex problems …". It consists of interdisciplinary activities required to support the design and development of a useful system that creatively exploit energy, materials and information within organised systems of humans, machines and the environment. The SE process has to ensure that the stakeholders' needs are met in a cost-effective and timely manner (Blanchard & Fabrycky, 1991, Haskins 2010, Wymore 1993).

The systems approach aims to understand the part only in the context of the whole, while interacting with and adapting to the environment. This leads to systems thinking, which has evolved as the modelling of systems behaviour (Hitchins 2008). Modelling in this way goes beyond a bottom-up integration of elements where emergent properties are isolated and contained.

Behavioural modelling investigates the dynamic and non-linear interaction between different systems of interest to identify possible future outcomes. Other phases of SE include the implementation, deployment, sustainment and disposal of the system, which will not be addressed in this thesis (Oliver et al. 2009).

4.2.2 System Engineering Process

A basic SE process, as seen in Figure 16, distils the needs of stakeholders along with the characteristics of the environment to develop concepts and define requirements (US Department of Defence, 2001). The systems engineer interacts with stakeholders to capture and validate requirements. Alternative solutions are developed for trade-offs to determine the best fit to the requirements. This requires integrating many disciplines covered in the problem and solution space. Note that this SE process starts with a set of requirements for analysis, functional analysis and design synthesis, making an assumption that the stakeholders know what they want. Often, not much thought is given to an analysis of the problem requiring a solution.

Most SE processes are guided by the IEEE1220 (IEEE 2005d) and ISO/IEC 15288 (ISO/IEC 2008), which led to developing a number of different models and approaches over the years. According to these standards, the lifecycle of a system consists of the concept, development, production, utilisation, support, and retirement stages. Due to the uniqueness of every situation requiring SE, a fixed and universal approach is not always the optimal solution. Therefore, SE models and processes can only provide the required activities in reference to the system lifecycle, without prescribing details (Ramos et al. 2010).

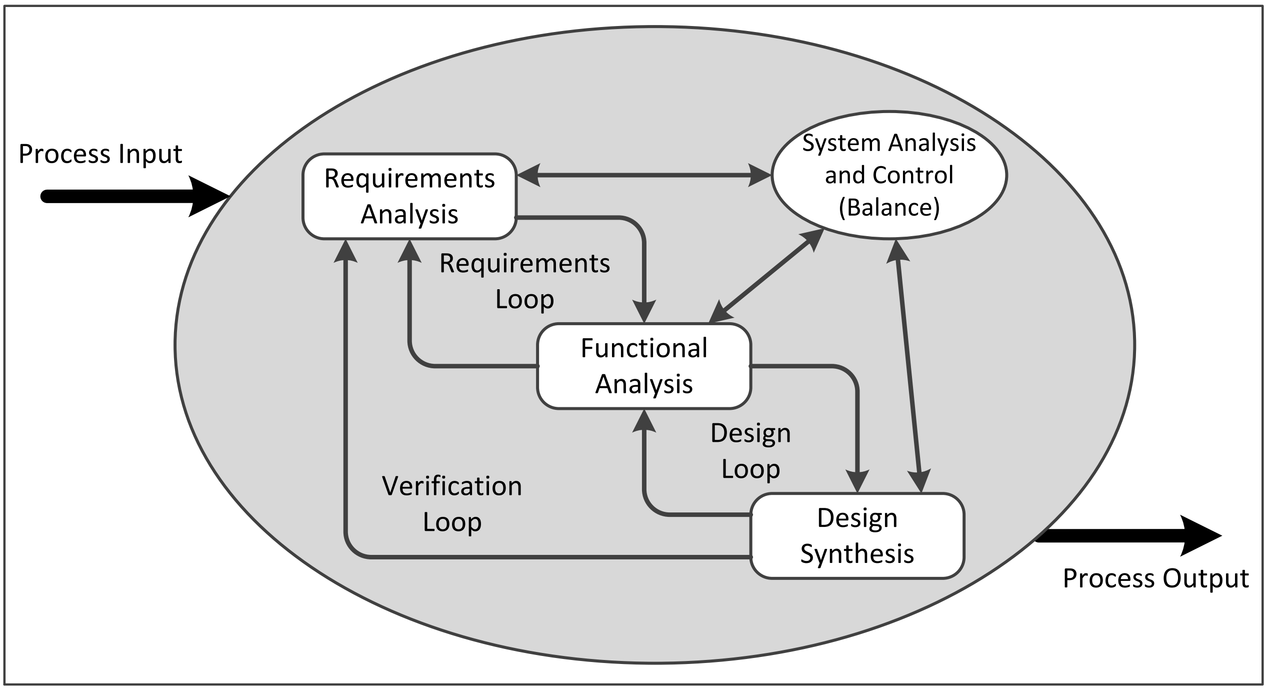
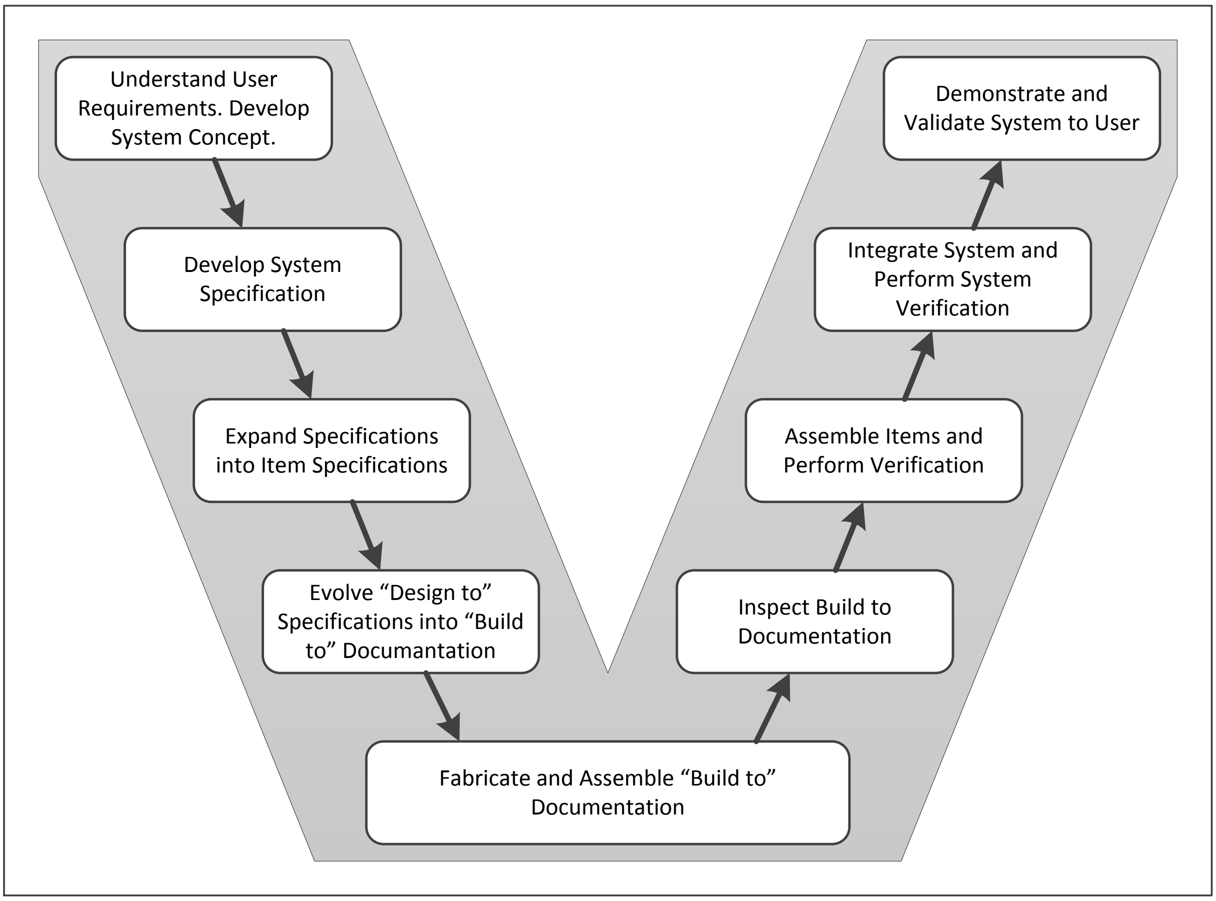


Figure 16: The Systems Engineering Process (US Department of Defence 2001)

In this thesis, the focus is on the concept stage, which assesses opportunities, explores concepts, identifies stakeholder requirements, and proposes concept solutions. In the development stage describing the requirements is refined, and the solution is created, verified and validated.

Early SE and software engineering process models were influenced by the classic Waterfall model from Royce (1970). This approach was intended to be iterative, to build on and feedback the lessons learnt in improving previous steps. However, limitations of this rigid sequential process led to developing the spiral model (Boehm 1988). Each cycle of the model improves knowledge on, and understanding of the problem and requirements through various steps of prototyping before the eventual deployment, in order to reduce the development risks related to very large and complex projects.

Forsberg & Mooz (1994) also noted that the Waterfall-type approaches prohibit initiating downstream work until the major reviews have been passed. They modified the Waterfall model into the "V" model, as seen in igure 17, which has been adopted as the current standard in SE.



igure 17: The "V" Model (Forsberg & Mooz 1994)

The structure of the "V" model enables planning and coordinating the verification and validation of the system during the different stages. The left-hand side of the "V" focuses on decomposing the problem, modelling, generating requirements and designing the solution, while the right-hand side reflects the implementation (re-composition or integration) and validation of the solution. The "V" model allows activities to start on the opposite side of the "V", to assist in verification of the requirements, design and implementation. This approach may also be executed in iterative steps, where each step of the SE process is executed in successive "Vs".

In most of the SE processes, the initial steps are used to define the problem, extract requirements and develop solution concepts. This determines the reason why a system is developed, along with a high-level description of the main functionalities – including identifying stakeholders, with their needs and expectations – validated system requirements and a concept of operations (ConOps). This may extend to exploring different alternative concepts and the baseline architecture design. The aim is to ensure that the correct system is being developed for the problem. Conversely, if the wrong solution is designed and perfectly implemented, it will be of limited use.

Extracting requirements, developing specifications and designing the solution system can be aided with models, to ensure that all stakeholders are in agreement. The ensuing steps are used to decompose, design and implement the system. Models are also applied to define, extend, refine and validate the system throughout the entire lifecycle (Ramos et al. 2010, Haskins 2010).

The focus of the research in this thesis is to provide a methodology in support of modelling complex STSs with a view to improving the technology implementation process. The next sections briefly discuss two SE approaches that rely on different types of modelling.

4.2.3 Functions-Based Systems Engineering

The objective of functions-based systems engineering is to develop a functional architecture to guide allocating functions and sub-functions to technical equipment, facilities and people. Analysing and examining system functions lead to identifying the supporting subfunctions to describe what the system will do (not how the system will do it). This iterative process eventually culminates in a completely decomposed and defined set of basic subfunctions, including the interfaces between them and the external world, in a functional architecture (Haskins 2010).

The International Council on Systems Engineering (INCOSE) Handbook defines a function as a task, action, or activity performed to achieve an outcome. This may be achieved by one or more system elements, which includes equipment (hardware), software, firmware, facilities, personnel, and procedural data (Haskins 2010). Systems engineers normally interpret "function" as an activity of a technological artefact (Lintern 2012). However, Vicente (1999) defines function as an activity-independent capability and potential to perform something if the artefact is used by humans in an

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appropriate manner. This is compared with the concept of affordance, which addresses both natural (ecological) and designed properties.

The functional analysis can only commence once all of the system requirements (functional, performance, specifications and standards), architectural concepts, ConOps and constraints have been fully identified. The typical outputs of functional analysis include the following (Haskins 2010):

a) Behaviour diagrams. These describe systems behaviour using constructs of time sequences, concurrencies, conditions, synchronisation points, state information and performance.

b) Context diagrams. This is the top-level diagram of a data flow that portrays all inputs and outputs of a system without decomposition.

c) Control and data-flow diagrams. These are box diagrams, flowcharts, input-process-output charts and state transition diagrams that provide sequences in which operations may be performed by the system. They are linked to data flows between the functions.

d) Entity relationship diagrams. The logical relationships between functions or architectural elements are depicted in these diagrams.

e) Functional-flow block diagrams. The functional flow block diagrams provide insight into the flow between the system functions.

f) Integrated definition for functional modelling. Integrated definition for functional modelling (IDEF) diagrams are process-control diagrams showing the relationships between functions by sequential input and output flows.

These outputs are in the form of various models that support simulating and analysing the behaviour of the system to characterise the functional architecture. However, the focus of this research is modelling in support of understanding the problem to initiate the functional decomposition. The constructs and conceptual system models produced by the modelling methodology in this research have to support the outputs listed above.

4.2.4 Model-based System Engineering

Model-based systems engineering (MBSE), also referred to as the object-oriented systems engineering method, is a modern approach to designing and developing systems. MBSE focuses on a top-down application of models instead of a document-based text for specifying, designing, integrating, validating, and operating a system. The MBSE employs a process to develop and increase the detail in models using a concurrent and incremental process to support communication between stakeholders (Estefan 2007, Haskins 2010). The basic process of MBSE includes the following activities, which are consistent with typical SE “V” processes (Haskins 2010):

a) Analyse Needs. This activity captures the “as-is” systems, their limitations, and potential improvement areas to support developing the “to-be” organisation. The main tools are causal analysis techniques and use cases (scenarios) to capture the mission and organisation functionality.

b) Define System Requirements. This activity defines the system requirements to support the mission requirements. The system is modelled as a black box that interacts with the external systems and users, while scenarios are modelled using activity diagrams with swim lanes. The outputs of these steps are used to derive the system's functional, interface, data, and performance requirements.

c) Define Logical Architecture. The system is decomposed and partitioned into logical elements that interact to satisfy the system requirements. The logical elements are used to capture the system's functionality.

d) Synthesise Allocated Architectures. This step describes the relationships among the physical system elements or nodes that define the distribution of resources.

e) Optimize and Evaluate Alternatives. The preferred architecture is selected through parametric models of performance, reliability, availability.

f) Validate and Verify System. The system design is verified to ensure that it satisfies the requirements, and is validated to ensure that the stakeholders' needs have been met.

MBSE utilises modelling languages such as SysML or UML to accurately capture, analyse, and specify the system with its elements, to ensure consistency among various system views. These can be used to model complex systems through diagrams of system structure, parametric, requirements, and behaviour and relationships, as seen in Figure 18. The structural diagrams represent the parts of a situation with their logical relationships. The behavioural diagrams represent the parts of a situation and their causal interactions. The requirements views specify desired and undesired structural and behavioural properties. Parametric views provide the critical engineering parameters of the system for evaluating performance, reliability and physical characteristics.

However, the purpose of this research is not to provide an alternative to MBSE, but rather to support an improved understanding of the issues and challenges associated with initiating the modelling process. Both the SE approaches discussed above are dependent on understanding the problem to be solved and the development of effective conceptual models. The aim is to address the complexity of the environment, problem and STS system. The next section focuses on the phases of system analysis and design to determine the role and requirements of modelling.

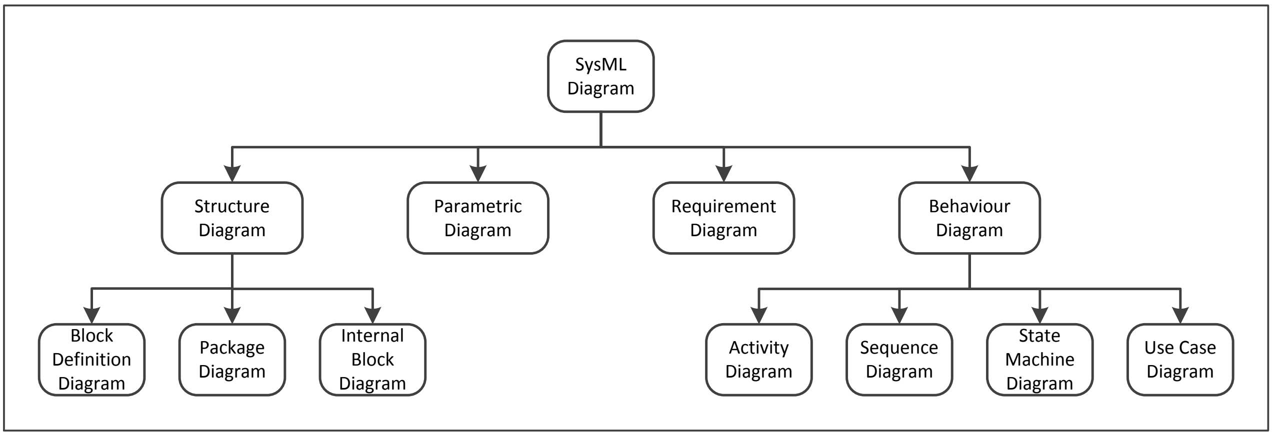

Figure 18: SysML Diagrams (Estefan 2007)

4.2.5 System Analysis and Design

Although SE includes many aspects of system development, implementation, support and management according to the systems life cycle, this research focuses on modelling the complex STS problem in support of designing a solution. Even though these two steps are often integrated, the modelling methodology aims towards analysis. Often performing analysis and modelling constitutes design in principle (Buede 2000, Haskins 2010).

Many professions such as artists, architects and any discipline of engineering utilise the term “design”. Universally, “design” is defined as creating a non-natural solution to a perceived problem (Merriam-Webster dictionary, Alexander 1964, Simon 1969). Due to an incomplete understanding of the problem (context) and limits in human processing, the design criteria cannot be absolute. As more is learned about the design space, other alternatives may become eligible. The behaviour of the artefact is constrained by both its capabilities (internal organisation) and the effects of the outer environment. The design activity has to ensure that an artefact is created through the internal organisation of components and their interaction with the environment. This is achieved by mapping the interface between the inner and outer environments, in order to implement the artefact to satisfy a set of functional requirements (Takeda et al. 1990).

Within the realm of engineering, and in particular SE, *design* means the preliminary activity required to satisfy the needs of stakeholders through a creative, iterative, decision-making process. Engineers use their understanding of science and mathematics coupled with a logical and structured approach to satisfy human needs. This process normally starts at a functional level, where goals, requirements and constraints are assessed before working towards developing specific solutions (Buede 2000, White 2009, Dym & Little 2000, Ramos et al. 2010). Figure 19 provides a typical and universal design process, derived from combining the models of White (2009) and Bahill & Gissing (1998).

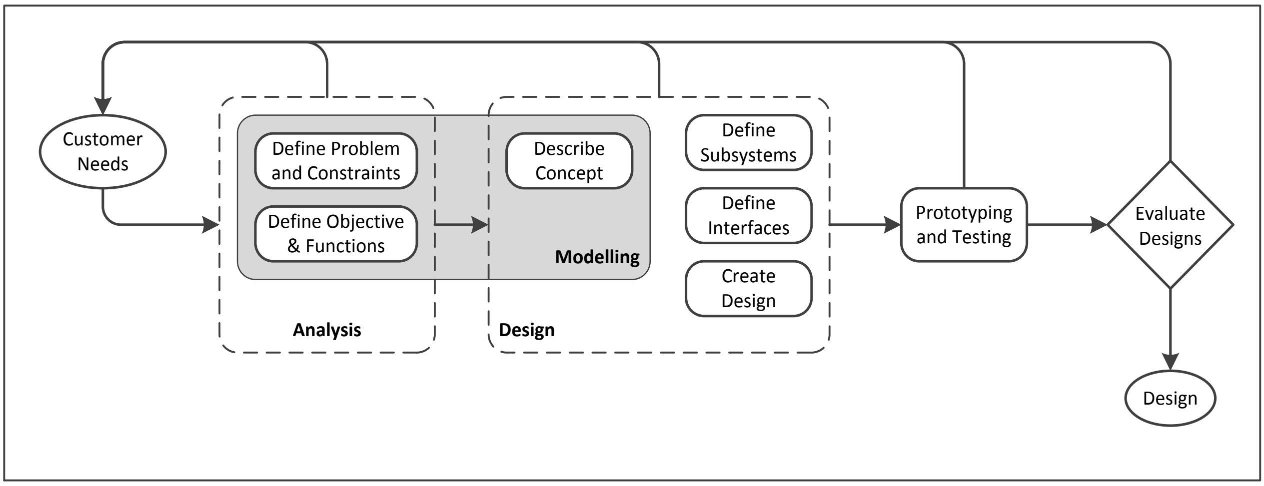

Figure 19: Typical Design Process

The input to the process is a need from a customer or stakeholder. This needs to be analysed to discover requirements, in the form of the problem and constraints definition, leading to defining the purpose, objective and high-level functions of the required solution. The problem is analysed through interacting with the stakeholders to ensure that the goals and objectives of the design are well understood (Stanton et al. 2012, Meadows 2008). As noted by Simon (1996), "… solving a problem simply means representing it so as to make the solution transparent …" Various forms of models and constructs can be used to capture and represent the information and knowledge on the problem.

Problems faced today can be ill-defined, with a wider impact, which may result in serious socioeconomic complexities and other environmental effects. Such problems may include climate change, natural hazards, healthcare, international drug trafficking, nuclear weapons, nuclear energy, waste and social injustice. Making absolute sense of a complex system is almost impossible; however, a suitable mental model to absorb and interpret information is important. The mental models of all the stakeholders must be captured in models for successful problem analysis (De Weck et al. 2011, Sterman 1994).

Various solutions and/or technologies may be available to satisfy the requirements as defined in the first phase. A synthesis of the knowledge on the problem is used to generate design options, which may satisfy the system's specifications. Due to a broad range of requirements, many adequate solutions may be available, some of which will be more suitable than others. This may be seen as points in a solution or design space. The results from a promising design synthesis are converted into detailed design system parameters and selected parameter values. This forms part of an iterative loop to establish whether the design meets or exceeds defined specifications. The optimal parameterisation of the best conceptual design is selected. However, it can be difficult to arrive at a simple selection and optimisation solution in the complex world, resulting in a multiple-objective decision under uncertainty. The chosen design and specification is assessed through manufacturing and testing a prototype (Hitchins 2008).

The generic design process in Figure 19 can be enhanced by using suitable models and other constructs to help define requirements and constraints, describe concepts, define subsystems and interfaces, develop prototypes and assist in evaluation. A systemic approach must be followed to construct systems models to guide questions during the design process. It encapsulates systems thinking in terms of boundaries, flows, relationships, feedback loops, and patterns between a system and its environment. This approach provides a way for designers to synthesise new emergent wholes instead of deconstructing them (Stanton et al. 2012, Hitchins 2008).

Complexity in problems and the environment ensures that it is not easy to apply SE processes in developing solutions. The typical difficulties experienced are discussed in the next section. The aim is to identify the requirements of the SE process to be supported by a modelling methodology.

4.2.6 Difficulty of Engineering Complex Systems

Holt & Perry (2008) list the three evils of systems engineering as complexity, communication, and understanding. System complexity depends on the number of system elements and their interaction. An improper understanding of the problem and user needs leads to inaccurate requirements and the improper application of SE. Communication problems between engineers, the development team and the stakeholders lead to interpretations of the meaning of requirements and associated models. This can be further exacerbated by poor communication between the design team and manufacturing teams.

Classic SE approaches, as developed for narrow and well-defined problems struggle with complex environments and STS. Rigidly implementing SE does not guarantee success in the design, development and implementation of systems. The demands on SE to produce systems capable of effective operation within complex environments are ever-increasing. The typical problems facing SE when solving complex problems of interest in this thesis include the following (Bar-Yam 2003, Hybertson 2009, Woods & Dekker 2000, Löwgren 1997, Stensson 2010, Sterman 2002, Nemeth 2004, Gibson et al. 2007, Walker et al. 2009, Stepney et al. 2006, Sheard & Mostashari 2009):

a) Problem Solving. The focus of SE is on “how to” develop a system to satisfy a need, after the “what to do” has been identified (Checkland & Scholes 1990). However, the complexity of the problem and the environment prevents designers and engineers from having “perfect knowledge” of the system, in order to arrive at a solution and an effective design. The basic SE processes and models are derivatives of the sequential and top-down waterfall model approaches. However, solving “wicked and messy” problems does not follow a linear sequence.

b) Myth of the Blank Slate. Nowadays, it is the exception that systems are developed from scratch. Systems tend to be developed through the piecewise replacement of subsystems with new technology. The requirements and designs are often variations of existing systems or solutions. Integrating new and old systems designed according to different sets of requirements increases complexity. Elements within the different systems may be designed from different technological baselines, for different problems, and are in different parts of their life cycles.

c) Myth of Requirements Driven. Traditional large, long-term and expensive projects rely on detailed requirement specifications, extracted from the stakeholders. This assumes that the stakeholders actually know in detail what they want and need. Due to complexity, the system requirements tend to be vague, fluid and conflicting. Projects frequently exceed budgets because of the customers' gradually evolving insights into the shortcomings of the initial *elicitation* of requirements.

d) Decomposition of the System. It is assumed that a system can be reduced to the sum of its parts without losing functionality at a higher level. The details of one part of the system can be designed independently from other parts of the system. However, modern information technology and STS can exhibit emergent effects. System capabilities can become non-traceable to any single cause.

e) Addressing Humans. An inherent shortcoming of most SE approaches is that the human functionality and cognitive contributions are not adequately addressed. The human element is often seen as being outside of the system under development. Typical models used in classic SE fail to capture the dynamic and complex nature of the social elements in the system due to their often counterintuitive nature. The human operator is often left to adapt to the system's functionality to conducting hidden work.

f) System Integration. Stand-alone systems can often not meet the requirements of complex challenges in the real world. As a result, more systems must be integrated for better control and information exchange, leading to complex systems where a change in one subsystem will influence the operation of other subsystems. The resulting emergent properties may not be obvious when analysing the individual elements in isolation.

Note that this list is not comprehensive and only focuses on the aspects related to complex STS. The issues listed here highlight the need for a fresh look at analysis, design and development of systems. The ability to adapt to changing environments and handling of complex situations needs to be designed into the system. The remainder of the chapter provides a discussion of alternative approaches and enhancements for system development. These include possible complex SE techniques and the dedicated use of models.

4.2.7 Engineering of Complex Systems

Alternative approaches to classic SE, with the focus on addressing complex problems, have been thrown together under the banner of complex SE. As with SE, complex SE is about solving complex problems (Kuras 2006). Complex SE flowed out of attempts to fix the inherent problems and weaknesses of classic SE in coping with complex systems, through the introduction of complexity science. A crucial initial step is to recognise when complex SE is required in solving a problem, instead of forcing a classic SE approach.

The main difference between classic SE and complex SE is that the former focuses on the order in systems by identifying a problem for solving, which is achieved by creating a design and implementation (Sheard & Mostashari 2009). Complex SE, on the other hand, investigates the evolutionary behaviour in existing systems and tries to affect certain characteristics to produce more desired results. While SE focuses on detail in functionality and the subsequent implementation, complex SE focuses on the coherence of the whole system without direct and immediate attention to the detail.

Complex SE requires a focus wider than only the technical aspects of a system. The following is a list of the main guiding principles for complex SE from the literature (Sheard & Mostashari 2009, Kuras 2006, Fromm 2006, Johnson 2006, Bar-Yam 2003, Fowlkes 2007, Stevens 2008, Militello 2009, Hybertson 2009, White 2010, Rouse 2007, Walker et al. 2009):

a) Complex systems may evolve instead of being designed from scratch when reducing the complexity of design is impossible. Complex systems may evolve into the required form from vague, flexible and unstable requirements. Evolution assumes that many different systems exist at the same time and that changes occur in parallel. The system must be designed to adapt to rapid changes, while ensuring robustness and safety. The system will change the environment; therefore it has to change (evolve) along with the environment. The result is that complex SE can continue developing a solution without a detailed knowledge of these relationships.

b) The design of the system must ensure that multiple possibilities are retained. The technical equipment must co-evolve with its human users in the whole system. This requires a transition in focus from what the equipment is to what the equipment can actually do. An implementation of new technology must be assisted by analysing the tasks to be completed. Human adaptation may cause the changes to fail or result in new opportunities. The technical system should comprise simple, flexible, transparent and open system elements to provide humans with flexibility and self-synchronisation in the STS, in order to perform complex, real-life, effects-based tasks. Adaptability and the high tempo of changes have to be catered for in the initial design of the system, as users learn new requirements while using the system.

c) Social and human factors are important and should be analysed in conjunction with the technical aspects. Complex SE focuses on the human behaviour in a complex world, which includes human performance, mental models and social networks. These functions are not always deterministic, as required by an SE process, as different humans have different cognitive capabilities, skills and experience (Macleod 1996). In information-age systems users can do many different tasks with the same technical system and reach the same end-states from different initial conditions as well as by applying different processes.

d) Systems are developed across traditional boundaries of organisation, discipline and function. Integration is enabled through information technologies, requiring a trans-disciplinary ontology with a supported taxonomy.

e) A multi-scale analysis is also required when dealing with complex systems. This includes the context in which the system is to be engineered, developed, acquired and operated. The scientific method should be the basis for starting to define a successful approach to complex systems.

f) The elements that cause complexity to guide the design of the system should be identified in order to manage and utilise them. Local actions that can influence the system on a global level should also be identified. Complexity should not be limited or ignored, but rather exploited to improve the adaptability of the solution. Domain knowledge is the source of stability and is captured in the general models/knowledge space of the model.

g) A thorough understanding of the relationship between the system as a whole and its parts should be developed. This should include the possible emergent properties, to ensure an effective and efficient design. The focus should be on the coherence of the whole (what it can do) system without direct and immediate attention to the detail (what it is). The current SE methodologies attempt to control the functions and quality in order to provide a solution to a perceived problem. Emergence may not be controllable but can support a better understanding of the problem space as well the implications of possible solutions. There must be a balance between allowing the system to be robust and adaptable through emergence while ensuring it stays fit for the high-level requirement. Describing systems that exhibit emergent behaviour completely in a bottom-up approach with simple models is virtually impossible (Johnson 2006, Ryan 2007).

h) Development of complex STS should consider the effect of the organisational environment on the system. Different organisation structures may have varying effects on the culture prevailing in the system.

One of the main themes in complex SE is assisting the system engineers in understanding the problems and complexity in the system and the environment. One way to assist this effort is by using models instead of text-based descriptions of the system and requirements. Models can provide a visual representation of complex structures and processes, which can be readily analysed and interpreted. As seen in the list above, many of the issues can be addressed through effective modelling early on in the SE process. Effective modelling can be a powerful tool in the SE effort, as is discussed in the next section.

An important step is the transition from analysis to synthesis (design). Up to now, analysis of STS has not always led to designs of new systems. The reason for this is the difficulty in predicting the relationships between people, technology and organisational context (Baxter & Sommerville 2011). A solution for this is to develop and assess prototypes of the proposed solution system within real-world contexts. The prototype should consist of basic and simple elements integrated to support humans solving complex problems. Rapid prototyping and knowledge engineering can be used to develop systems, which include command and control (C2) (Cooley & McKneely 2012).

Prototyping is a methodology that uses the model of a system to design, implement, test and install the final solution system. In some instances the prototype can become the final solution. A prototype enables iterative system development as opposed to the serial process of more traditional approaches. The advantages of applying a prototyping methodology are to build relationships with the users, reduce the development cost, reduce development time and ensure that the right solution is implemented (Lantz 1985).

An important aspect of prototyping is developing and applying models. Even if a model is not a true reflection of the environment, problem or solution system, it reflects the current understanding. Experimenting with the model and testing assumptions further improves understanding the problem and what is required as a solution. Since the analysis phase of the development process results in constructs and other related models, it provides a good foundation for prototyping.

4.3 Modelling in System Engineering

4.3.1 Modelling

“How can I tell what I think ‘til I see what I say?”

E.M. Forster (Nemeth 2004)

4.3.1.1 Models

A model is defined as an explicit and incomplete representation or idealised abstraction of reality, or a selected part thereof, to aid its description and understanding. Humans use models on a daily basis to simplify and understand reality. Examples of model uses include capturing requirements and domain knowledge, thinking about the system design, representing usable work products, manage (organize, find, examine, filter, manipulate, and edit) information about large systems and exploring several solutions. (Ramos et al. 2012, Kant 1950). A model is generated for a purpose and describes the essential nature, characteristics or pattern of a process or thing without being the thing itself. A model requires a language to guide representing reality (Oliver et al. 1997, Haskins 2010, Oliver et al. 2009).

Abstracting reality results in avoiding distraction and detail, which may not be relevant to a particular model, despite being important. This enables smaller amounts of related information to be gathered, processed, organised and analysed in building models. If the problem is complex, more information can be captured through focusing on an aspect of the model while maintaining the context of the larger model. The success of a model is determined by its reliability, completeness, accuracy, power to convince, ease of use, compatibility, and extendibility (Hull et al. 2005, Buede 2000, Ramos et al. 2012, Polack et al. 2008). The three main types of models are the following (Buede 2000, Hughes 1997, Rothenberg 1989, Polack et al. 2008, Haskins 2010):

a) Definitive. A definitive model defines the required characteristics of a system to assist design through inputs, outputs, functions and resources at an appropriate level of abstraction. It is more typical of conventional engineering to support constructing an artificial system; it requires a rich language to assist interpretation and representation.

b) Normative. Normative or exploration models guide decision-making about the system by addressing how people ought to think about it. Exploration is the process of searching and discovery for the purpose of the system. Models used for exploration are validated within a range, and are tested for their generality within that range. They are effectively interpolating between observations to predict outside of the known and observed.

c) Descriptive. These models are commonly used in science and engineering to capture the observed high-level behaviour of the system in a specific situation. They are used to clarify the context, content, structure, and behaviour of the problem. The explained behaviour leads to discovering causalities in the system, which must increase the understanding of the audience.

This thesis focuses on descriptive models to abstract reality, simplify complexity, consider constraints and synthesise results (Stanton et al. 2012, Haskins 2010).

4.3.1.2 Modelling and Simulation

Modelling is the act of creating models, from their conceptualisation, using a standard, rigorous, structured methodology (DoD 1997, Maria 1997). This leads to the notion of modelling and simulation (M&S), which uses models to develop data in order to obtain insight into a system's behaviour as a basis for making decisions. M&S is the additive process of conceptualising, developing, and if necessary, testing the model, followed by exercising the model to study its behaviour. M&S is useful in addressing complex problems (Harrison et al. 2007). Models can be used to gain control over reality in support of decisions about the world. Modern modelling approaches, such as functional models, originated after the 1950s (Weilkiens 2008, Ramos et al. 2010). The uses of modelling and simulation include the following (Maria 1997):

a) Build a better understanding of the system through testing hypotheses.
b) Time can be compressed to observe certain phenomena over long periods.
c) Time can be expanded to observe a complex phenomenon in detail.
d) Learn about a real system without disrupting it.
e) Create new or unknown situations on which only weak information is available.
f) Identify prominent variables in the system that have influence on the system's behaviour.
g) Identify multiple performance metrics for the system.

However, M&S does have limits. It is impossible to capture every reality with models and simulation, as the utility of the model will diminish. Abstraction also requires making assumptions, which may cause incorrect solutions, and are not always stated explicitly by the modellers, increasing the risk of the incorrect application. Creating and executing models of complex systems can be expensive, demanding large amounts of resources and time. The requirement for modelling and simulation in new product development is to reduce the cost of prototyping. Validating the model requires collecting proper data to ensure that reality is accurately represented. Decisions based on models are only as good as their validation (Lucas & McGunnigle 2003, Davis 2004).

4.3.1.3 Modelling and Simulation Process

M&S is an iterative process to develop, use and update models. The model is constructed through schematics and network diagrams of the system to indicate how entities flow through the system. Simulations may address system functions or the detailed structure through identified scenarios. The general steps in applying modelling and simulation are typically as follows (Haskins 2010, Maria 1997):

a) Identify and formulate the problem to be modelled.
b) Select the appropriate type of model.
c) Collect and process observed system information.
d) Design the model to meet its general criteria through fundamental analysis of the system. This requires identifying the relevant system characteristics, measurable parameters as well as the scope and content of data needed to arrive at a decision to be supported by the model.
e) Validate the model through an appropriate method that is determined to be adequate by the stakeholders.
f) Design an experiment with the model.

g) Gather data for input into the model in order to generate the required outputs.

h) Perform simulations with the model.

i) Evaluate the data to provide an answer to the original question.

j) Evolve the model if required. Review the modelling and simulating process throughout all the iterations. Answers may lead to a better understanding and new questions, which will require changes to the model.

4.3.1.4 Model Validity

The validity of the model is critical and must be determined before use (Maria 1997). It can refer to conceptual, operational or data validity, which are observed and measured under controlled conditions (Buede 2000, Polack et al. 2008, Oliver et al. 1997). Conceptual validity addresses the qualitative model's representation, theories employed and assumptions made to determine if the model's structure is appropriate. Operational validity focuses on the model's quantitative output and must represent the real world. Lastly, data validity determines if the inputs are correct. The model's performance under known conditions is compared with the performance of the real system. Also, system experts can examine the model to determine their confidence in it (Maria 1997).

Since this thesis aims to develop a modelling methodology for complex STS in support of SE, the next section will investigate how models are applied in SE.

4.3.2 Modelling in Systems Engineering

4.3.2.1 The Role of Models in Systems Engineering

The purpose of modelling is to gain insight into complex systems and to support answering questions on the system to be designed or problem to be solved. A model describes the system through abstracting reality, simplifying complexity, considering constraints and synthesising results (Stanton et al. 2012, Hitchins 2008). SE is based on systems thinking with modelling being the basis of systems theory. A mental model can be viewed as humans' interpretation of a system via their senses. Complex systems must be abstracted and modelled at a high level to develop an architecture. Models provide cost-effective tools to generate data for analysis. The model of the system describes how the system will change internal states due to external inputs. Architecting requires technical knowledge and creativity to establish a framework of models for system development, and assists in trade-offs and design decisions (Maier & Rechtin 2000, Ramos *et al* 2010, Buede 2000).

In SE, conceptual models describe and represent selected aspects of the structure, behaviour, operation and characteristics associated with a system and its operational environment, enabling systems and interfacing with other systems. These models represent the system design, and are used to communicate ideas to other stakeholders. Models are used to create, specify, communicate and test a shared vision through finding, examining, filtering, manipulating, and editing information about systems. These are required to support improved system development decisions through clarifying requirements. In turn, this requires multiple views for theoretical or empirical understanding, calculations and predictions concerning the system, without necessarily mimicking the system. The different views of the system may be organised in an architecture, to structure the model. Modelling can be used throughout the system's lifecycle (Buede 2000, Hybertson 2009, Polack et al. 2008, Ramos et al. 2012, Maria 1997, Haskins 2010).

The model should be similar to, or a close approximation of the system it represents incorporating most of its salient features. The model must achieve a balance between realism and simplicity, to enable understanding and simulation (Maria 1997). Models are utilised to experiment with knowledge on the problem and to develop an understanding of the implications of different solutions. Experiments evaluate candidate architecture options for optimisation. These can be used to confirm anticipated system behaviours and to justify requirements. Richardson (2000) points out that the value of complexity science and thinking lies not so much in the model but in the modelling process and the supporting culture. Making absolute sense of a complex system is practically impossible, but a suitable mental model to absorb and interpret information is important (Sterman 1994). SE provides different approaches to modelling systems; they are the following (Melão & Pidd 2000):

a) Machine Metaphor. The system is seen as a deterministic machine consisting of a static structure that can transform selected inputs into required outputs for a purpose. The system elements have interpreted linear interactions with humans and humans mechanistically convert inputs into outputs. Examples of such modes include IDEF0 and UML sequence, activity, state machine and use case models (Bennett et al. 2005). The limitations of this approach are seeing the system as static with linear interactions and human beings as mechanisms, despite having basic needs, and seeking ways to satisfy them.

b) Organic Metaphor. The machine metaphor is extended with an ability to monitor the environment and adapt to changes. This is achieved by identifying a system boundary to identify external influences and environmental stimuli. A typical implementation is through discrete event modelling and similar simulation approaches. However, the ability to adapt dynamically due to internal factors is not addressed.

c) Feedback Loop Metaphor. Despite the system having a static structure, it has a boundary for inputs and resources and can handle non-linear interactions between parts through mathematical models and feedback loops. These are achieved through causal loops, and stock and flow approaches according to the SD approach. Still, the influence of social and cognitive humans is not addressed adequately.

d) Socio-Technical Metaphor. The socio-technical metaphor encourages the analysis of human needs to determine the effect thereof on the system. This metaphor recognises that human beings have needs and interests. Different modelling approaches address the fitness of humans for the task or to participate in groups, as well as the implications of politics and the general working culture. The success of this approach depends on amount of information on human beings and the groups they form being available.

When considering the discussion on the problems experienced in SE in the previous section, this thesis focuses on integrating the feedback loop and socio-technical metaphors to enhance the modelling of complex STSs. Improved understanding of these aspects should support the development of complex STSs.

4.3.2.2 Types of Models in System Engineering

The initial models in the SE process are primitive ones that are elaborated and translated in later stages. Different models are used to represent different views on the system. The modelling of complex systems requires an incremental approach, without being immersed within the most complex and demanding implementation (Maani & Maharaj 2004, Haskins 2010, Buss & Sánchez 2005). Various categories of models exist in the literature. These can be summarised into the following common set of model classes (Buede 2000, Przemieniecki 2000, Dieter 1983, Ferguson 2006, Polack et al. 2008, Haskins 2010, Ramos et al. 2010):

a) Physical Model. A physical or iconic model is a visual representation of reality, rather than of behaviours. These models indicate what real things look like, such as prototypes, structural test model, maps, and 3D scale models.

b) Quantitative Models. These are descriptive mathematical models that provide numerical or statistical answers, and can be analytical, simulation or judgemental models. They are analogue in nature, and aim to provide insight on behaviour while not necessarily being similar to the real entity of interest. They help scientists to explore variables contributing to observed behaviour.

c) Qualitative Models. Symbolic models are mostly used nowadays to provide symbolic, textual or graphic solutions for agreement among individuals. They abstract the important quantifiable components of a physical system. Diagrams tend to be descriptive models and can be in the form of connectivity, structural or state machine diagrams. The most common examples of qualitative models are:

    i) Functional Modelling. A functional flow block diagrams illustrates the sequence of a system's functional flow through a functional decomposition approach.

   - ii) Structural modelling. Describes the hierarchy of a system and its elements.
   - iii) Process Modelling. The IDEF series represents activities or processes to model the functional perspective of a system, the data flow and the system control.
   - iv) Object-Oriented Modelling. This graphical language approach, based on UML and SysML, supports the specification, analysis, design, and verification of complex systems.

d) Mental Models. Mental models are cognitive representations or abstractions of thought, which are required by engineers in conversation on the quantitative, qualitative or physical model. They are affected by the characteristics of the human thought process, such as memory limit, linearity of thought, and using subjective information. They are often implicit and intangible, making them difficult to formalise and communicate. However, every effort must be made to capture accurately the mental models of all the stakeholders.

4.3.3 Complex Sociotechnical System Modelling Requirements

4.3.3.1 General

This section summarises and discusses the modelling methodology requirements for a complex STS. The STS framework from Figure 14 (Bostrom & Heinen 1977) is used to identify the different aspects to be modelled. These inputs are used to select a suitable approach from the literature as well as adapting to it, if required.

The modelling of complex STS is difficult, as the models have to present the structure and behaviour of human work in the system. Behaviour is caused by dynamic interaction between the system elements and the environment. A suitable modelling approach must be able to capture the mental models of stakeholders. Models can be more useful than text-based SE documents to develop system concepts and requirements. Models support experimentation with knowledge on the problem, and develop an understanding of the implications of different solutions. They can guide identifying the elements that cause complexity, in order to guide the design of the system in managing and utilising them. Knowledge of the problem and suitability of the solution is gained through experimentation. Experimentation must be planned and executed using a well-defined conceptual model (Alberts & Hayes 2006).

Simulations based on mental models of the system under consideration and the environment are useful to understand the effect of certain influences and factors. The simulations should be supported by scientific reasoning and should enhance social interaction within groups operating in the complex environment. The modelling methodology must be capable of describing the complex STS structure to aid in identifying arising threats and emerging opportunities for a system being distributed across organisational, social, cultural and legal boundaries. It must also support the qualitative, or even quantitative, analysis of a large system (Baxter & Sommerville 2011, Walker et al. 2008, Jenkins et al. 2011).

Modelling has become a specialised scientific endeavour that is largely disconnected from social processes, while it holds the potential to shape society through its outputs. Functional and structural models to investigate the complex dynamic behaviour of complex STSs require a specialist or “expert modeller” (Fararo & Butts 1999, Herrmann & Loser 1999). However, this limits the ownership and confidence of the client in the models created. Therefore, the modeller should ensure that the system stakeholders are involved from the start, and should apply methods that support engagement and debate (Yearworth & Cornell 2012).

Ockerman et al. (2005) highlight the importance of utilising subject matter experts (SMEs) throughout the process of modelling STSs, as their operational experience and domain knowledge are used to identify cognitive processes and requirements as well as to assist in design evaluations. Scenarios are used to assess the effects and goals of a cognitive in context. They can also be used during interviews to elicit knowledge from operational stakeholders (Elm 2008).

Lintern (2008) defines a cognitive system as a complex STS, being part of a thinking information system. It has a form of intelligence embedded by the coordinated collaboration between distributed human operators. Humans are included in the cognitive system because humans can reason, while machines cannot. Furthermore, two humans in coordination can reason much better than one in isolation. The actions and abilities of humans are guided by the ability of the available physical element (tools) to support operation by them within the constraints of the operating environment in attaining the purpose of the system. Human factors and design ergonomics are starting to focus on the cognitive and social aspects of human operators.

4.3.3.2 Environmental Constraints

The analysis and design process should address the constraints of complex work domain and operating environments on the STS. These constraints affect attainment of the systems purpose. Changes in the environment and work context may also influence the constraints on the STS. The influence of environmental constraints and context on work must be understood, to ensure that the effect of changes can be understood. This includes the context in which the system is to be engineered, developed, acquired and operated (Lintern 2012).

4.3.3.3 Human-Machine Interaction

Developing and improving information-based STSs need to allow cognitive humans and logical machines to complement and support one another. The human is not just a passive user of the (cognitive) system; the human is inside and part of the system. People should be seen as problem solvers instead of mere users. Humans need to be designed into the system as contributors, to complement the technical elements and to be assessed inside the system during its operation.

Implementing new technology must be aided by analysing the tasks to be completed. As a result, humans remain central to operating complex systems (Woods & Roth 1988). The roles humans play in and with systems can be one or more of the following (Nemeth 2004, Woods & Roth 1988):

a) Decision Maker. Humans consider alternatives and select a course of action by estimating the possible outcomes, based on the skills-rules-knowledge model from Rasmussen et al. (1994).

b) Monitor. The monitoring role can be vigilant (detecting infrequent or unpredictable information) or supervisory (monitoring a complex system controller). This is required to identify a problem to be solved.

c) Information Processor. Despite humans being slow information processors, they can handle a diverse range of inputs. In general, information processing functions are allocated for automation where possible.

d) Closed Loop Controller. An operator can function as an adaptive controller to moderate operating other components.

e) Encode and Store Information. By encoding information, humans have the ability to store and retrieve it.

f) Discriminator and Pattern Recogniser. Humans are adept at locating and recognising patterns.

g) Ingenious Problem Solver. Humans can bring various skills to bear on a problem to devise novel and ingenious solutions. This is possible through achieving insight into the problem situation and the possible solutions available, or combinations thereof.

The increasingly complex work domain, requires an effective sense-making and decision-making tools to help solve real-world problems (Elm et al. 2003, Lintern 2012).The effectiveness of the human machine interface ensures effective interoperability between man and machine to augmenting human cognitive activities to solve complex problems in a complex world. Vicente (1999) identified that situation awareness, or sense-making, is a prerequisite for decision-making. The modern communication technology and the interconnectivity of systems ensure that more information is available, resulting in an increase in the difficulty of making sense of complex situations.

Classic SE focuses on a techno-centric design strategy and automation of systems, and not so much on the humans to meet the demands of the complex work domains or environment (Nelson & Stolterman, 2003). This approach is mostly applied for STSs, with the technological functions of the system being designed and developed requiring the human operators to adapt. Up to now there has been a motivation for increased automation to negate variability in the system and the possibility of human error (Bonaceto & Burns 2006). More automation in an attempt to design human error out of the system will make it inflexible and unable to cope with complex or unforeseen conditions (Bonaceto & Burns 2006). More often than not, the human operator is the most adaptable part of the system. Humans are more capable than machines of coping with unforeseen circumstances, provided they have the experience and information available to support sense-making (Norman 1993).

As information-age, technical equipment relies on open systems and information exchanges. The correct interfaces are as important as the correct inner workings of the technical equipment. Even though boundaries exist, the elements and tasks can share functionality. Therefore, using work and task principles to define activities ensures that all functions can be identified and allocated (Walker et al. 2009).

Graphically rich ecological displays are required to support the natural cognitive strategies of humans to reduce interaction complexity. Ecological displays represent information on domain constraints in a way that is compatible with human perceptual and cognitive capabilities through configurable graphics. They have to support an adaptive response to both routine and unanticipated situations. Information needs to be presented to the decision maker in line with natural cognitive patterns and processes for direct perception. This is crucial with today’s complex systems, where humans use machines to assist in situation assessment, decision-making and system control. This is achieved through analysing the cognitive and collaborative demands to be embedded in a design, and implementing and evaluating the structure and work environments (Ockerman 2005, Woods & Roth 1988).

Cognitive humans and logical machines must be allowed to complement and support one another to solve real-world complex “wicked and messy” problems with the relevant tools. Machines are logical and consistent, while humans can detect and interpret patters. Humans are very good at perception and have the ability to be creative. They are not substitutes for each other. The combination is more powerful than either is alone (Norman 1993). However, the coordination of functional requirements and cognitive processes must be combined into a coordinated system. The design of an STS requires some strategy of function allocation (Bonaceto & Burns 2006, Lintern 2012, Ockerman et al. 2005, Elm et al. 2003).

4.3.3.4 Human-Machine-Organisation Interaction

How the human will apply the system in the work domain has to be considered in conjunction with the technical aspects from the start of the development process, in the analysis phase. This includes the complex relationships between the humans (social and cognitive behaviour), business processes (organisation) and technical means in unison. Systems are developed across traditional boundaries of organisation, discipline and function. Integration is enabled through information and communication technologies. Effective design should result in coordinated collaboration between distributed human operators for distributed sense-making and decision-making. If the purpose of the system is not fulfilled by people in the organisation, the system is a failure, despite having a technically sound design. The design has to consider the complex relationships among the humans, business processes and the organisation. New technology should continue supporting the current way of doing things as well as encourage new ways and methodologies (Norman 1993, Goguen 1999, Walker et al. 2009, Herrmann & Loser 1999).

4.3.3.5 Bottom-Up and Top-Down Approach

A thorough understanding is required of the relationship between the system as a whole and its parts, as well as the possible emergent properties, to ensure an effective and efficient design. Since multiple possibilities must be kept open during the design of the system to ensure flexibility, utilisation in different ways needs to be accommodated. When constraints and limitations are added to the system, its complexity will increase, and they should therefore be limited to the absolute minimum. Top-down processes alone for designing complex STSs will not suffice, as early design choices may have unintended consequences at lower levels. A bottom-up approach based on subsumption may limit this effect (Walker et al. 2009, Johnson 2006, Ryan 2007).

Complex systems and emergence should where possible be analysed through a top-down and bottom-up approach (De Wolf et al. 2006). In the top-down cycle, the high-level requirements can be analysed and delineated. The operational context and expected scenarios are defined from the initial high-level requirements to derive the required roles, tasks and functions of the system. These will provide the parameters for the simulation and synthesis during the bottom-up cycle (Oosthuizen et al. 2011).

4.3.3.6 Addressing Complexity in the System and Environment

From the law of requisite variety, designers should attempt fitting in with the external complexity by increasing internal complexity. However, the sociotechnical perspective proposes simplifying equipment complexity to enable humans in the STS to perform real-life and complex tasks (Walker et al. 2009). Therefore, complex STSs require subsumption and transparent, ubiquitous, open systems and flexible technology to enable self-synchronisation. The designer should recognise and differentiate elements that are volatile versus stable, then utilise the stable to anchor and guide the volatile. Domain knowledge is the source of stability and is captured in the models. Local actions that can influence the system on a global level are to be identified. Complexity should not be limited or ignored, but rather exploited to improve the adaptability of the solution.

4.3.3.7 Summary of Modelling Requirements

A summary of the foregoing discussion is provided in Table 4. These requirements are used to develop and evaluate a modelling methodology to support development of complex STSs.

Table 4: Complex Sociotechnical System Modelling Requirements

No	Complex STS Modelling Requirement
1	Present the structure and behaviour of human work in the system.
2	Capture the mental models and domain knowledge of stakeholders and SMEs.
3	Support experimentation with knowledge on the problem.
4	Guide identifying the elements that cause complexity to support the design. This includes the constraints of complex work domain and operating environments.
5	Support the qualitative and quantitative analysis of a large system.
6	Use scenarios to assess the effects and goals of a cognitive work in context. This includes considering situation awareness, sense-making and decision-making in the system.
7	Consider open systems and information exchanges.
8	Address the complex relationships between the humans (social and cognitive behaviour), business processes (organisation) and technical means, in unison.
9	Using work and task principles to define activities to ensure that all functions can be identified and allocated.
10	Understand the relationship between the system as a whole and its parts, as well as the possible emergent properties to ensure an effective and efficient design. This requires a top-down and a bottom-up approach.

4.3.3.8 Modelling Approaches

A design approach for complex STS has to consider the human, organisational and the technical aspects. The design method must develop an understanding of how these elements affect the work performed through modelling and analysis. Baxter & Sommerville (2011:4) proposed a list of possible STS design approaches:

a) Soft Systems Methodology. The soft systems methodology (SSM) from Checkland (1981) combines action research and systems engineering, but not the social sciences explicitly. The focus is on understanding the problem by considering roles, responsibilities and the concerns of stakeholders.

b) Cognitive Work Analysis. The CWA from Rasmussen (1994) and Vicente (1991) provides a formative approach for complex STSs to analyse the work performed.

c) Sociotechnical Method. The sociotechnical method (Waterson et al. 2002) focuses on function allocation to design work systems, and identifies the work distribution between humans and machines.

d) Ethnographic Analysis. An ethnographic analysis investigates the situated nature of the work. It identifies the workarounds taking place because of the physical environment.

e) Contextual Design. A contextual design incorporates the user's requirements on how to perform work to design interfaces for the information system.

f) Cognitive System Engineering. This is also referred to as “cognitive engineering” to enable developing a joint cognitive system (Hollnagel 2012). Analysts use observation to identify patterns in the workplace, in order to understand the sources of expertise and failure. This analysis of the organisation supports system design.

g) Human-centred Design. This is a standardised process to base design on understanding the users of a system and their environment, with a focus on the context.

h) System Dynamics. SD models the effect of feedback and delays on the dynamic behaviour of the system due to decisions based on policies, in order to understand the problem (Sterman 2000).

Baxter and Sommerville (2011) compared this list of approaches with the requirements of the analysis and design of sociotechnical systems in Table 5. The remainder of this chapter focuses on the most promising approaches from the table. Armed with the knowledge of modelling and how it can be applied in SE, the next section delves into the requirements of such a methodology. This is done to guide the development of this thesis’s modelling methodology.

Table 5: Comparison of STS Modelling and Design Approaches adapted from Baxter and Sommerville (2011)

Principle	General	Analysis	Design	Evaluation
CWA		✓✓		
Sociotechnical method		✓	✓	
Ethnographical workplace analysis		✓	✓	
Contextual design	✓	✓✓	✓	
Cognitive SE	✓	✓✓	✓	✓
Human-centred design	✓	✓	✓	✓
SSM	✓	✓		
SD	✓	✓✓		

4.4 Developing of a Modelling Methodology for Complex Sociotechnical Systems

4.4.1 Introduction

The task here is to convert all the literature and requirements discussed up to this point into a modelling methodology suited for complex STS, the artefact of this research. Baxter and Sommerville (2011) suggested that STS engineering approaches should be integrated into existing

SE and software engineering life-cycle processes. However, it is difficult to achieve results in focused sociotechnical designs because of the inconsistent terminology, levels of abstraction, conflicting value systems, analysis without synthesis and the lack of multidisciplinary approaches (Baxter & Sommerville 2011).

The analysis and design of complex STSs needs to be reviewed to take into consideration how the technology is used, with adequate attention paid to human work and interaction (Walker et al. 2009). The softer issues such as cognition, and social and dynamic interaction then tend to become neglected. This necessitates the need to investigate different approaches to STS that operate in complex environments. Implementing new technology and continually using the same tasks, processes and structures do not utilise all the new possibilities that new technology affords. New ways of operating must be investigated and developed to achieve the purpose of the sociotechnical system. STS tends to be complex and nonlinear, making it impossible to predict accurately behaviour that can be quantitatively measured.

Due to the nature of complex systems, a single approach may not be sufficient; therefore, an adequate framework may be required to integrate multiple methodologies. Multi-methodologies are also used to provide a bridge between grounded theory and SD modelling, through a process of qualitative data analysis (Yearworth & White 2013, Mingers 2003). This section first proposes a framework, before discussing the modelling methodologies to be included.

CWA has been described by many authors as a suitable way to analyse complex STSs (Jenkins et al. 2009, Naikar et al. 2006, Vicente 1999, Pejtersen & Rasmussen 2004, Stanton & McIlroy 2012, Sanderson et al. 1999). Similarly, SD is motivated as an approach for modelling and simulating dynamic behaviour in social systems (Carhart & Yearworth 2010, Forrester 1994, Wolstenholme 1990, Georgantzas & Katsamakas 2008, Lofdahl 2006, Papachristos 2011, Sterman 2000, Meadows 2008). Therefore, CWA is chosen as a starting point for developing a modelling methodology before continuing to the application of SD.

4.4.2 Modelling Framework

The two main frameworks to be considered for the modelling methodology are the “scientific method” and DSR. The scientific method consists of repeated cycles of observing phenomena, deriving a hypothesis to make predictions under certain conditions and testing. This in turn will lead to more observations to change or improve the hypothesis, in order to make further predictions to be tested. After a number of these cycles, the hypothesis should converge into a theory that holds for all stated and tested conditions. The power of this method lies in maintaining tight control over the cycles. The emergence of global behaviour from local interactions in the assessment provides useful inputs to the characteristics of the sociotechnical system. The assessments should also focus on humans being part of the solution. This methodology can be applied when investigating the behaviour of the systems, through simulation and observing emergence. Success in applying the scientific method is determined by how the experiments are planned and by the quality of the models (Fromm 2006).

However, the success of the scientific method depends on an accurate model and a controlled environment for experimentation, which are not always possible in complex and dynamic systems. Modelling provides an analytical process to develop understanding and generate predictions in support of policy decisions. It does not necessarily only support generating hypotheses to be tested during experimentation (Yearworth 2010).

Since the DSR framework has been used to develop information systems, its utility is considered instead. Therefore, the DSR approach is also used for the artefact of this research, the modelling methodology. The DSR is a framework that is also used for information system research and development, to address complex problems through creating artefacts for a human purpose with the required relevance and rigour (Hevner et al. 2004, Venable, 2006).

The two basic knowledge-building activities in DSR are designing (constructing) a novel and useful technological artefact for a specific purpose and evaluating it to determine the level of success, as discussed in Chapter 2. Artefacts are developed as part of a sequential problem-solving process. Design artefacts can be constructs, models, methods or instantiations. This is contrasted with behavioural science, which tries to understand the current state and behaviour of the world. Applying accumulated knowledge to real-world problems leads to new knowledge that is applied to design new solutions (March & Smith 1995, Hevner 2007, Pries-Heje & Baskerville 2008, Baskerville & Wood-Harper 1996, Peffers et al. 2007, Kuechler & Vaishnavi 2008).

Despite being a research framework, DSR can support development of complex STSs by focusing on designing and testing artefacts. This basic framework for the modelling methodology is subsequently populated with CWA and SD in the next two sections to address the characteristics identified in complex STSs.

4.4.3 Soft Systems Methodology

Soft systems methodology (SSM) is an organised inquiry aimed at addressing complex, messy and ill-structured problems. This is a method of inquiry into the requirements of the system by comparing the models (required future state) with current system states at different levels. SSM is contrasted with (hard) SE, which suffices for well-defined and -structured problems. SSM, unlike the standardised SE processes, takes cognisance of world views. SSM uses models of purposeful activity relevant to the problem situation, without relying on the models to describe the situation. These models are used to explore the situation through structured debate, even though they are not accurate (Checkland & Scholes 1990, Checkland & Poulter 2007).

The complexity in the problem situations arises from the dynamic nature (never stable) and multiple perceptions of reality. A human's experiences in the world give rise to concepts to describe and address it. One way is "systems thinking", which describes the world as a whole. SSM provides systemic processes of enquiry using systems models. An analysis should consist of a client, a problem solver and a problem owner (Checkland & Scholes 1990).

The SSM includes differentiation between logical analysis and other softer analyses, as seen in Figure 20. Firstly, the problem situation must be identified and described in terms of the real world. Systems thinking is applied on this available information and on perceptions to thrash out the root definitions that are relevant to the system performing its actual task and purpose. These are used to develop conceptual models of understanding.

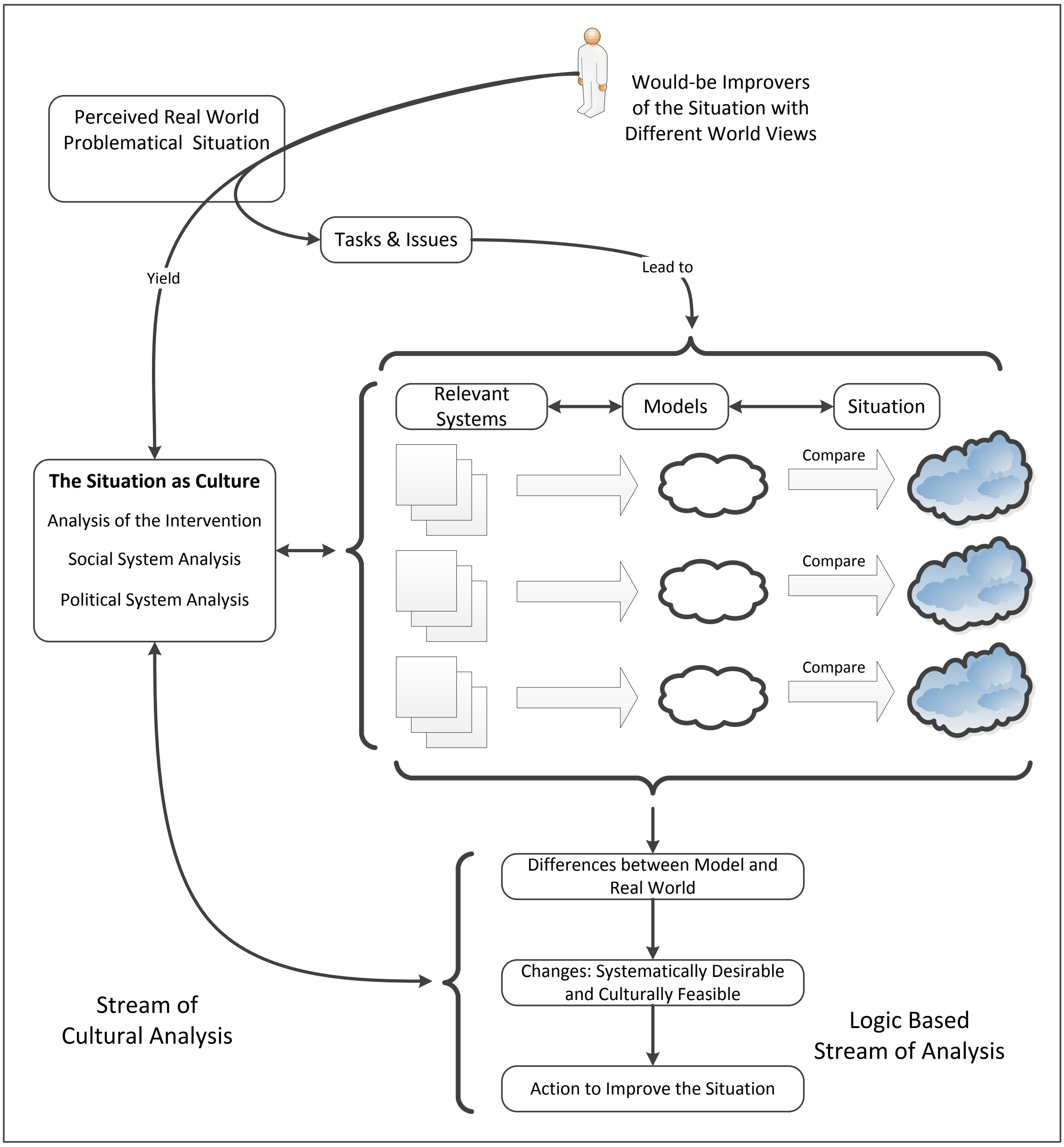

Figure 20: Soft Systems Methodology (Checkland & Scholes 1990)

The developed models are used by assessment practitioners as vehicles for supporting interaction with members of the STS, in order to compare their understanding and definitions with the real world. This then guides identifying the changes required to improve the current real-world situation in order to achieve a desired future state. Defendable (not necessarily validated) transformation models are used to structure enquiries in the problem situation (Checkland & Scholes 1990). The main steps of the SSM methodology are the following (Checkland & Scholes 1990):

a) Logic Stream Enquiry. A system is required to convert an input (some entity) into an output (the entity in a transformed state), using a transformation process.

b) Cultural Stream Enquiry. One characteristic of SSM is the use of rich pictures to describe the underlying definitions. A cultural and political analysis adds to an understanding of the problem, by determining human interactions and how power is expressed in the environment of the problem situation. A social system analysis based on roles, norms and values follows to shed more light on the problem situation, as the social analysis is never complete or static.

The aim of the enquiries is not necessarily to improve the models to more closely resemble reality, but rather to find an accommodation between the different interests in the situation. This will indicate the actions required to improve the problem situation (Checkland & Scholes 1990). An approach such as this is more useful to understand the environmental issues in existing systems and to identify what should be done to rectify the problem.

4.4.4 Cognitive Work Analysis

4.4.4.1 Background

Work is defined as an activity aimed at accomplishing something useful with a purpose, values and success criteria. It consists of a combination of cognitive and physical elements. Human work has also become more cognitive and less physical through, for example, the evolution of smartphones, cloud computing, and enterprise resource planning technologies. This highlights the need for cognitive analysis and modelling of the work environment as part of the SE process, to ensure that the cognitive strengths of the human are leveraged. CWA provides a comprehensive modelling framework of analysis to uncover requirements, constraints, and implied (hidden) affordances in the work environment (Lintern 2012, Stoner et al. 2006).

The system must enable human actors to perform their work effectively, with the required technology and supporting organisational structures. CWA is an approach for developing formative (how work can be done) designs for decision support systems. It is contrasted with normative models (how the system should behave) and descriptive models (how the system is actually behaving) (Vicente 1999). CWA also considers the ecological constraints that may shape executing tasks, as well as the cognitive approaches of the users of the system (Bennett et al. 2008).

CWA has been applied in systems analysis, modelling, design and evaluation, and the development of human performance measures in large-scale socio-technical and complex systems such as C2, aviation, health care and road transport (Jenkins et al. 2009). The products of CWA also define the required information content and applicable context of where it is used within a cognitive system. The theoretical roots of CWA are in systems thinking, adaptive control systems and ecological psychology. Flexible design is required to support people executing the work, while adapting to unforeseen and changing environmental conditions (Bennett et al. 2008, Lintern 2008, Lintern 2009, Naikar et al. 2006, Naikar et al. 2005, Vicente 1999).

CWA recognises the inability of system design based on assumptions about pre-planned work procedures and stable work demands. Design has to be flexible to adapt to unforeseen and changing conditions (Naikar et al. 2005, Bennett & Flach 2011). The objectives, work requirements, and resources of a complex STS, which constrain operator behaviour, must define the boundaries of acceptable performance. Inside the boundaries, operators may still have many degrees of freedom and solution possibilities. This can be achieved through different sequences of tasks and complex STS behaviours; it may result in closed-loop, adaptive systems (Van Westrenen 2011).

CWA is supported through ethnographic descriptions or analyses of cognitive work. This enables assessing and generating constructs, which consist of situation awareness and mental simulation. The system must enable human actors to perform their work effectively, with the required technology and supporting organisational structures. The advantages of CWA include the following (Naikar et al. 2005, Jenkins et al. 2011):

a) Recognition that complex STSs are dynamic as a result of technological changes, the computerisation of work and integration between different systems.
b) A focus on domain and environmental constraints, to allow for a variety of work patterns in order to solve unexpected problems and situations, resulting in flexible systems.
c) Support of the formative development of “cognitive affordances”, which are devices that intuitively fit in with how human cognitive processes are performed.

The CWA process starts with a focus on understanding the ecological elements, before relating it to the cognitive capabilities of the humans to enable flexibility that, which helps to reduce the cost of development (Vicente 1999, Bennett et al. 2008). CWA must go beyond allocating tasks to machines or people, to whoever fits the requirements best. It addresses designing human capabilities to operate the whole system (Lintern 2012). The ecological constraints still allow for a variety of work patterns to solve unexpected problems and situations resulting in a flexible decision support. Products of CWA define the required information content as well as the applicable context where it is used within a cognitive system (Bennett et al. 2008, Lintern 2008, Naikar et al. 2006, Vicente 1999, Jenkins et al. 2009). The five phases of CWA that cover different aspects of work, which are discussed in more detail in the next sections, are work domain analysis (WDA), control tasks analysis, strategies analysis, worker competency analysis, social organisation and cooperation analysis.

4.4.4.2 Work Domain Analysis

WDA provides the foundation for understanding the functional structure of the STS and the environmental effects on work, to elicit and present information on the system from existing documentation and expert users. The WDA determines what can be accomplished in a system without exceeding the capabilities of the system. This analysis uses an abstraction decomposition space to model the work domain, and not the system, by identifying the goals and purposes of the cognitive system in providing a reasoning space about the environment. The modeller requires an understanding of the functional structure of the enterprise under consideration (Jenkins et al. 2011).

The WDA defines the problem and solution space, independent of specific instantiations. In the abstraction dimension, a top-down (global) view of human operators trying to achieve the purposes of the system is integrated with a bottom-up view of available physical resources (Naikar et al. 2005). The means-ends relationship between the physical resources and functionality needs to be highlighted to guide possible problem-solving strategies as well as how individual components affect the overall system purpose. The “means” indicate how a task or function is achieved, while the “end” is the function or task. Within the abstraction levels, the elements can be viewed in different states of decomposition, as required by the level of analysis. Modelling identifies categories of constraints, and is not task- or event-driven, but leaves space for events that may or may not be anticipated. This is useful where technical systems, the environment and people interact dynamically, which may result in many possible instantiations with multiple options for action to fulfil the purpose of a system (Naikar et al. 2006, Vicente 1999, Jenkins et al. 2011).

The WDA is useful where technical systems, the environment and people interact dynamically, resulting in many possible instantiations (many-to-many relationships) (Naikar et al. 2005, Vicente 1999). While the physical constraints (laws of nature) tend to be causal, the intentional constraints on the organisational objectives (conventions, values, formal or informal rules of conduct and operator intentions) may be more complex (Naikar et al. 2005).

The top three levels of the hierarchy address the domain and are independent of the technology used in the system. The bottom two levels consist of the physical objects and the functions they perform in the system (Jenkins et al. 2011). Each level independently provides a complete description of the work. Many-to-many relationships indicate the multiple options for action to fulfil the purpose of a system, combined with the multiple functions utilising the same of physical objects. This also leads to a magnitude of intended or unintended side effects from decisions and actions. The means-to-ends relationships are useful in assessing the propagation of effects, from decisions or actions, throughout the system, to fulfilment of the intended purpose (Naikar et al. 2005). The levels of the abstraction decomposition space are the following:

a) System Purpose. This provides the reason why this specific cognitive system is being developed.

b) Values and Priorities. The reasoning process requires performance measures, principles, standards, or qualities, to be maintained while executing the process.

c) Knowledge, Insight and Semantics. This level provides the domain or general functions required to execute the work in satisfaction of the system purpose. These functions must be performed independently of the physical elements utilised, and can be used to generate scenarios for using the system.

d) Facts, Ideas and Opinions. The physical functions are implemented through activating or using the physical objects. Physical functions are related to functional requirements in the SE process.

e) Source Objects. These are the physical elements present in the work domain available to perform the work.

4.4.4.3 Control Tasks Analysis

In a complex STS, a goal may be accomplished in different ways through a set of activities. This step is useful in identifying the different combinations of work tasks performed under specific conditions, to structure more efficient and proficient ways to do work. These activities consist of a set of work situations and work functions that depend on different decisions or control tasks. The control task analysis focuses on the work requirements and constraints limiting achievement of the goals and purposes identified in the WDA. It identifies the relevant information and relationships in solving specific situations. The contextual activity matrix from Naikar (2006) and the decision ladder from Rasmussen (1994) are used to represent the work situations, problems, states of knowledge, information processing, and their interconnections.

4.4.4.4 Strategies

The cognitive processes identified in the decision ladder are further analysed to determine the strategies for how the tasks are executed, especially by experts. Multiple patterns of activities are available to complete a task, which are determined by contextual factors. System resilience depends on the human employing different cognitive control modes to adapt to changing situational contexts. The typical strategies to be employed include a snap decision, searching for recommendations or searching to infer the most suitable solution from structural principles. The knowledge of how and why workers may choose between different strategies is useful in designing a cognitive system. The output of the cognitive strategies analysis is a detailed description of potential strategies and their application that are used to execute the cognitive processes in an information flow map (Vicente 1999, Lintern 2008).

4.4.4.5 Worker Competency

Worker competency analysis links the cognitive constraints and preferences of humans and provides a method to system designs. This analysis enables allocation functions based on the current human capabilities to achieve the work. To assist in problem solving, humans form a mental model of their environment as part of understanding the situation. This is achieved through a mix of sensory-motor responses, actions based on experience and basic rules, as well as an internal representation of underlying characteristics (Elm et al. 2003). These can be mapped to Rasmussen's (Rasmussen et al. 1994) skill-based, rule-based and knowledge-based decision-making strategies used in controlling a system.

4.4.4.6 Social Organisation and Cooperation

The aim is to design effective organisations or structures with the required technologies that support communication demands. The interaction and roles of diverse distributed human and technical functions in the complex STS must also be analysed. A social transaction occurs when some element, such as information, is transferred between agents. The social organisation and cooperation analysis focus on the content and form of interactions.

The coordination, responsibilities and roles of the different entities, as well as the information exchanged needs to be listed. This includes considering the ability and requirement for formal and self-organisation of the STS. Within the cognitive domain, interaction exists between peers, as well as between management and workers. Processes and technologies are required to support these informational interactions. This collaboration (lateral) and coordination (vertical) can be characterised in terms of the transactions performed (Vicente 1999, Lintern 2008).

4.4.4.7 Summary

CWA seeks to identify hidden, complex relationships among goals, functions, information required, work environment, and agents in support of modelling complex STSs. The WDA models the required functions in a work domain. The strategy analysis models different function allocations, in the form of strategies, to execute the work. Coordination and structuring of the organisation is derived from the social organisation and cooperation analysis. Worker competency analysis guides identifying human capabilities and limitations. This complements the SE process through being able to move from a high-level conceptual view of purpose, intent and goals to a detailed view of functionality and capability.

CWA also supports existing architectural frameworks, such as the UK Ministry of Defence architecture framework (MoDAF), with the constructs representing many of the standard views (Bruseberg, 2008). However, very little information is available on the whole five-phase CWA application. Most projects, similar to the approach taken in this thesis, focus on the initial phases of WDA and control task analysis. The main constraints inhibiting a complete CWA are time, funding limitations and a lack of tools for the latter phases (Sanderson et al. 1999, Cummings 2006).

The CWA framework requires a documentary analysis of the operational environment, supported by SMEs, with their operational experience and domain knowledge, to identify cognitive processes and requirements as well as to assist with design evaluations (Ockerman 2005). This includes aspects such as doctrine, operational procedures and responsibilities. Scenarios are used to elicit the effects and goals of an STS in context during interviews from operational stakeholders. The inputs from SMEs are critical in developing realistic and comprehensive scenarios (Cummings 2006).

This insight is used to identify measures of effectiveness (MoE) specific to the STS as well as to provide high-level system requirements. These measure how well a system performs its higher-level functions within a given operational environment. Defining the MOEs for complex STS is a difficult task, as systems are difficult to isolate from the environment (Sproles 2001). They are often integrated within a higher-order system to support a mission. CWA and other behavioural or “soft” sciences provide methods to derive useful and representative MOEs. Determining MoE requires an identification of system properties in a top-down approach and an analysis of human cognitive aspects (Sproles 2002, Malerud et al. 2000, Bruseberg 2008).

Despite its apparent advantages, CWA does not support developing a complete understanding of the complex STS system and its operating environment through an adequate dynamic system model. The models are qualitative and static, based on assumptions without proper validation. The CWA constructs do not support cause-and-effect relationship analysis due to unanticipated and intentional events as well as the effect of time work. CWA also tends to be used for analysing existing systems instead of designing revolutionary and novel systems, motivating the need for additional tools. It is difficult to derive low-level requirements that could not have been achieved with standard SE processes. However, CWA phases can be useful to elicit knowledge from users and domain experts (Cummings 2006).

4.4.5 System Dynamics

4.4.5.1 Background

The concept of SD was developed during the 1950s and 1960s at the Sloan School of Management at MIT to investigate the effect of feedback in social systems through systems thinking (Forrester 1968, Wolstenholme 1990). The different modes of behaviour as a result of high-order nonlinear systems were related to complex problems in management and economic decision-making. SD is one way of applying systems thinking in the analysis of problems, and supports other management science problem-solving methods (Forrester 1994, Wolstenholme 1990).

SD presents a method that combines the qualitative top-down modelling approach of complex STS with quantitative simulation, where the aggregated behaviour is modelled directly. SD studies system behaviour over time in relation to real-world scenarios to understand the underlying structures in support of decision rules, policies or strategies development. SD emphasises the multi-loop, multistate, nonlinear character of feedback in complex real-world systems (Sterman 2000, Meadows 2008, Wolstenholme 1990).

The foundation of SD is that understanding the holistic dynamic behaviour of the system through the interaction between elements will lead to successful implementation, not predicting the future behaviour of a system. Therefore, the validity of a model is not reliant on how realistic the driving scenarios are, but on whether the system responds with a behaviour represented by realistic patterns (Wolstenholme 1990). This approach can be useful in identifying the counterintuitive behaviour of the system resulting from time and policies. People cannot perform intuitive scientific thinking about the problems in systems, as mental simulation with mental models is incomplete and without parameters, functional forms, external inputs and initial conditions (Meadows 2008, Wolstenholme 1990).

Feedback in a system is one of the main causes of the complexity. The complexity within the components has a smaller contribution than the interactions among them. Dynamic complexity may exist in simple systems, with low combinatorial complexity, due to interactions between the agents or components over time. This can be related to the elements (people, organisation, technical system) of an STS. The delays in making decisions and converting them into action compound the effect of dynamic complexity and slow down the learning loops, leading to possible oscillation in the system. This makes controlled experiments difficult and expensive (Sterman 2000, Meadows 2008).

System structure is the source of system behaviour, and consists of interlocking stocks, flows, and feedback loops. SD employs causal loop diagrams (CLD) as well as stock and flow diagrams (SFD) to present the process and information structure of the system for discussion between stakeholders (Sterman 2000, Meadows 2008). Behaviour observed over a long time leads to dynamic patterns of system behaviour that support learning about the underlying structure and other latent behaviours (Sterman 2000).

SD has been used to model very large complex STSs in terms of the volume and timing of information. This can help to gain an understanding of the social and technical interaction in a dynamic environment (Lofdahl 2006, Fiddaman 2002). SD supports understanding the complexities and challenges in information systems, with insights into development, implementation and flexible infrastructures. SD simulation examines the aggregate emergent and dynamic effects of embedded mechanisms in processes, technology and resources in complex STSs.

4.4.5.2 System Dynamics Process

SD utilises diagrams to present the understanding of the process structure and information structure of the system, to guide discussion between stakeholders (Wolstenholme 1990). The models and simulations need not be perfect, but have to support the stakeholders in understanding the behaviour of their system under different conditions and governing policies. Sterman (2000) proposed the following iterative process for performing SD modelling and analysis:

a) Problem Articulation and Boundary Definition. The modelling process must not focus only on the system, and requires a clear purpose to address the problem. The model must focus on the factors deemed relevant for the problem and must be detailed enough to be useful, as it simplifies reality.

b) Formulation of Dynamic Hypothesis. The dynamic hypothesis provides a theory on the problematic behaviour in the system, to explain the dynamics in terms of the feedback and stock and flow structures. This is a working theory to be updated and improved as the problem is better understood. The boundary and causal structure of the model can be described and communicated by the following constructs and models:

   i) Model Boundary Chart. The model boundary chart summarises the scope of the model and assumptions made through listing endogenous and exogenous variables. These are the sources and sinks of material, people, money or information that have infinite capacity and never constrain the flows.

   ii) Subsystem Diagram. Subsystem diagrams show the overall architecture of the model, including the major subsystems, with interfaces and flows.

   iii) Causal Loop Diagrams. CLDs show the causal influences between variables to identify the feedback structure of the dynamic system. Positive feedback causes self-reinforcing or amplification to generate growth within the system, while negative feedback is self-correcting and opposes change, to be self-limiting in the support of balance (equilibrium) within the system. Systems may contain multiples of feedback loops, where delays cause inertia in the system, leading to dynamics and oscillations.

   iv) Stock and Flow Diagrams. SFDs show the structures that represent the physical processes, delays and stocks related to the complex dynamic behaviour in the system over time. Feedback is the result of a causal connection between the stock and the flow, which is important in understanding the behaviour of the system. It applies decision rules that are dependent on the stock levels to influence the flows.

  v) Policy Structure Diagram. These diagrams focus on the information cues identified that guide decision rules.

c) Formulating a Simulation Model. The simulation model is developed from the information gathered in the previous steps. This process helps to identify weak assumptions and concepts as well as to resolve contradictions before testing is started.

d) Testing. Testing is used to compare the simulated behaviour of the model with the actual behaviour of the system under investigation. This is to ensure that variables compare to useful concepts in the real world and that equations are checked for dimensional consistency. The sensitivity of the model's behaviour and possible solutions are assessed within the same set of uncertain assumptions.

e) Policy Design and Evaluation. Once the model is proven with existing data, it can be used to develop solutions to the problems.

The functions or purposes of an information system are difficult to derive. Often, they become apparent only through observing a system's behaviour. Some form of simulation is required to assist people to assess the effect of feedback loops and to understand the mental models (Sterman 2000, Meadows 2008).

4.4.5.3 Modes of Dynamic Behaviour

The behaviour of a system is defined as its behaviour over time in terms of growth, decline, oscillation, randomness and evolution. Behaviour results from the structure of the system and can be analysed through a series of events (Meadows 2008). There may be many positive and negative feedback loops present in a system, with a specific type being dominant, to guide discussions and investigations. The “order” of a system (or loop) is determined by the number state variables or stock it contains. A first order model contains only one stock and cannot oscillate, even if they are non-linear. The relative strengths of the feedback loops may change as populations change, possibly as a result of the carrying capacity of the environment (Sterman 2000).

A delay is the average length of time that the output of a process lags the input. Delays in control systems are the time it takes to record (measure) information and to report it. It also takes time to assess the information and make decisions. A material delay is caused by the physical flow of material through the system. The different delays are pipeline (a constant transportation delay), first-order material delay (mixing and varying processing times), higher-order delays (combination of the previous two) (Sterman 2000).

It is also important to consider nonlinearities, as they make understanding the behaviour of a system difficult. They may cause changes in the relative strengths of feedback loops to radically change between modes of system behaviour (Meadows 2008). Certain system archetypes can be identified from studying SD behaviour. These are important to systemic thinking and communicating the possible side effects of system changes to people (Wolstenholme 2003). Sterman (2000) and Meadows (2008) provide the following archetypical modes of behaviour present in systems with feedback loops, as seen in Figure 21:

a) Exponential Growth. The cause of exponential growth is positive, or self-reinforcing, feedback. This can be seen in compound interest and population growths. The results of positive feedback are growth, amplified deviations and reinforced change. This leads to exponential growth or dramatic collapses over time.

b) Oscillation. Oscillation may occur within a system, with delays in the feedback loops that cause under- and overshooting in the system state, due to corrective action. This tends to be the most common mode, and is represented in damped oscillation, limit cycles and chaos.

c) S-shaped Growth with Overshoot. The overshoot in S growth is the result of delays in the feedback loops, causing an oscillation around the carrying capacity.

d) Goal-Seeking. Negative feedback loops bring the state of the system in line with the desired goal or state, and lead to balance, equilibrium or stasis. The aim is to counteract disturbances or influences on the system that may steer the state of the system away from the goal. The system compares the current state to the desired state and takes corrective action to bring the system in line with the goal, through negative feedback.

e) Overshoot and Collapse. The S-shaped growth can collapse if the carrying capacity is decreased (eroded or consumed) as a result of the population growth. After the initial growth, the state of the system declines, followed by the population.

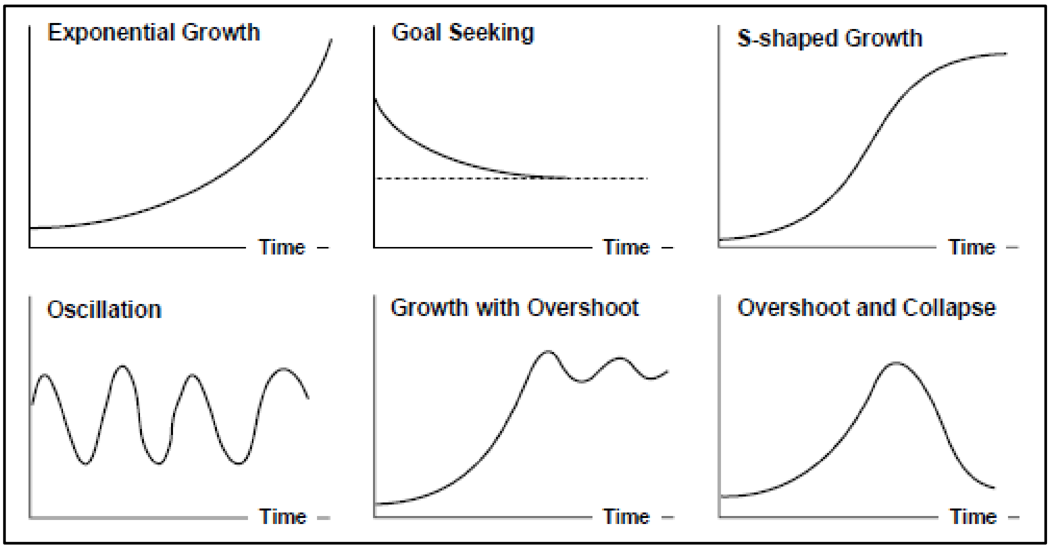

Figure 21: Modes of Dynamic Behaviour (Wolstenholme 2003)

f) S-shaped Growth. The S-shaped curve presents initial exponential growth followed by goal-seeking to an equilibrium level. This is a result of the carrying capacity of the system and its environment. Determining the carrying capacity of the environment is subtle and complex, as it is influenced by the characteristics and evolution of the system it supports. S-shaped growth exists if the nonlinear positive and negative feedback loops do not have significant delays and the carrying capacity must be fixed.

g) Stasis or Equilibrium. The behaviour of the system my exhibit some form of consistency (meaningful time horizon) to keep the state may remain constant despite environmental disturbances. This is caused by slow dynamics due to strong negative feedbacks.

h) Randomness. Unexplained variation in the behaviour of the system indicates a lack of understanding of the mechanics guiding it. This needs to be monitored until the system is understood and the "random" behaviour is quantified.

i) Chaos. Chaotic oscillations that have irregular fluctuations do not repeat, even though the systems dynamics can be deterministic due to endogenous behaviour. In nonlinear systems the chaotic pattern is bounded to a certain region or state space, and is sensitive to initial states.

4.4.5.4 Causal Loop Diagrams

According to Sterman (2000), a CLD is used to represent the feedback structure of the dynamic system through capturing a hypothesis on its dynamics and causes. The input to the CLD is the elicited and recorded mental models of individuals and teams in the systems. CLDs consist of variables in the system being connected by arrows to show the causal influences and relationships.

A positive link between two variables indicates that if the cause increases, the effect will increase to above the level where it would have been. This also means that if the cause decreases, the effect will also decrease to below the level where it would have been. A negative link between two variables indicates that if the cause increases, the effect will decrease to below the level where it would have been. This also means that if the cause decreases, the effect will increase to above the level where it would have been (Sterman 2000).

The polarity of the feedback loop is determined by tracing the effect of a small change in a variable as it propagates through the loop. If the original change is reinforced, the loop is positive. If the original change is opposed, the loop is negative. This is independent of the number of other variables in the loop or where the assessment is started (Sterman 2000). Feedback loops can only affect future behaviour, as there are inherent delays in information gathering, processing, decision-taking and implementation. These prevent the instantaneous effect of corrective action. It is

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important to identify the delays in each loop, as they are critical in creating inertia and dynamics (Sterman 2000, Meadows 2008).

4.4.5.5 Stocks and Flows

SFDs are required to show the structures that represent the physical processes, delays and stocks that are related to the dynamic behaviour in the system. The dynamics of stocks and flows are investigated over time to understand the complex behaviour of a system. Time is continuous in the SFD, whereas events may occur at any time, and changes occur continuously. This can happen at any granularity of time (Sterman 2000).

Stocks are accumulations of resources through integrals of inflow and outflow. They are things of importance in the system that can be counted, seen, felt, or measured. Stocks change over time through flows of elements through the system, and serve as the inertia and memory of the system. Stocks also cause delays in the system, as often there is a difference between the inflow and outflow of resources. They cannot be drained instantaneously, due to the limitations of maximum available flow rates. Even if flows could change instantaneously, stocks cannot. This causes time lags or delays in the system. Stocks indicate the state of the system, due to the history of changing flows to support decisions (Sterman 2000, Meadows 2008).

Stock is measured as the quantity of resources. Flows are the rates or derivatives of the net changes in stock. Flow is measured as the same unit as the stock per time period. Dynamic equilibrium is achieved when the flows in and out of the system are the same and the stock remains constant (Sterman 2000, Meadows 2008). The boundary of the system under consideration is represented by clouds (sources and sinks). Clouds in the structural diagrams are the sources and sinks of stocks. This is defined with the boundaries of the system under consideration to support the problem being investigated. If they are too large, it may make the system impossible to assess (Meadows 2008).

The SFD discriminates between the flow of stock through the network and the information in the feedback loops. The content of the stock and flow network is conserved. Stocks only change through the rate of flow in the system. The flow is defined as its instantaneous value at any moment, or the instantaneous rate of change of the stock. Changes in stock affect the flows through feedback loops. They can allow stocks to maintain a level, grow or decline. Feedback is the result of a causal connection between the stock and the flow. It applies decision rules that are dependent on the stock levels to influence the flows. Stabilising or balancing loops allows for the maintenance of an acceptable level (equilibrium) of stocks, by opposing the direction of change in the system. However, feedback can fail due to delays in information or incomplete and hard-to-interpret information (Meadows 2008, Sterman 2000).

4.4.5.6 Decision-Making

Decision rules are the policies and protocols the decision makers apply to assess and interpret (process) the available information, to produce decisions. Therefore, not the decisions, but rather the guiding policies must be modelled. The inputs to the decision-making process are various types of information. The five fundamentals of decision-making are the following (Sterman 2000):

a) The information available and time of availability to the decision makers limits the decision rules (Baker Criterion).
b) Decision rules need to be in line with managerial practice.
c) The difference between desired and actual conditions must be determined. This should be in line with the physical constraints on the ability to achieve the desired outcomes.
d) The decision rules should be able to withstand extreme conditions.
e) Equilibrium is not a given and may – or may not – emerge from the interaction between the elements of the system.

Decisions are often made without considering delays, side effects, feedbacks and nonlinearities. These must still be consistent with the mental models that underlie the specific decision rule. Decisions may vary from automatic to serious deliberation on social, mental and emotional inputs. The rationality of human decision-making is bounded as humans can be overwhelmed by the complexity of the system and the environment, despite having cognitive capabilities. Bounded rationality implies that decisions are made with the current information available and a short-term view of the implications. The causes of this are limitations in knowledge, attention, selective perceptions (emotional interference), cognitive capability and the time available (Sterman 2000, Meadows 2008).

4.4.5.7 Validation

A general method of model validation is to determine whether its output corresponds with historical statistical data. SD considers future scenarios with different policies that may not have historical data, making validation more complex. Here validation may be based on the confidence the stakeholders have in the model, determined by its general structure and behaviour (Wolstenholme 1990). When introducing new technology in a system, one cannot rely on historical case studies and associated data for analysis, as this results in too much change in the complex system (Papachristos 2011). The methodology for analysis must look at different ways of understanding the future implications of the new technology.

4.4.5.8 Summary

SD modelling takes place at the aggregate level of the system, and not explicitly by considering individual entities inside the system. Therefore, model parameters consist of averages or aggregates of large homogeneous populations. Systems consisting of highly heterogeneous populations are more difficult to model. SD is more suited to a system of systems analysis where the parameters can be aggregated per constituent system. Aggregated systems are population dynamics, ecosystems, and macro traffic problems. Systems with lower abstraction, more details and higher diversity may be better supported through agent based modelling and dynamic systems (Borshchev & Filippov 2004). As with any modelling approach, both CLD and SFD are abstractions, with a balance between simplicity for the sake of communication concepts and completeness to achieve validity (Wolstenholme 2003).

Traditionally the impact of new technology on an organisation tended to be evaluated at either a too-high (general) or too-low (detailed and complex) level. A high-level evaluation of the technology is often static, focussing only on the contribution of the technology, and not on benefits to the overall performance of the organisation. The technical-level assessments are singular and often domain-orientated, with tools not necessarily designed for this purpose. However, SD presents a balanced intermediate-level assessment that considers the application of the technology in evaluating its global impact. The aim is to develop insights and learning on the systemic impact of the new technology on the larger organisation (Wolstenholme 2003). Wolstenholme (2003) proposed a three-stage methodology that consists of the following steps:

a) Model the Domain of Application. The first step is to develop the required SD model, as described in this section, of the domain where the technology is to be applied without the new technology. The modelling process, that captures the knowledge and mental models of people in the work domain, should assist in understanding the problem and identifying performance measures.

b) Technology Assessment. The model is subsequently applied as a testbed to assess the impact of the new technology, by superimposing its perceived impact onto the model. The model provides a simulator to explore the interactions of assumptions and to learn about the new technology.

c) Technology Accommodation in the Domain. The third stage is based on implementing a new technology, often requiring changes in procedures and policies to utilise its full potential. Changes could address re-engineering processes, information paths and policies, eliminating delays or increasing or reducing capacities, and identifying high-leverage intervention points.

This approach provides the ability to assess a technology in terms of the interaction with and its effect on the dynamic behaviour of the larger system. This should highlight some counterintuitive benefits or problems of the new technology, as opposed to a static cost-benefit analysis. The models and simulation results facilitate a shared thinking and 'what-if' analysis about the technology, between the different stakeholders. Most of all, management may be able to understand the overall perceived merits of a new technology before costly commitments (Wolstenholme 2003).

Also, SD can be used to investigate the difference between a short-term and long-term decision focus, the difference between local decisions and global impact. SD is a continuous simulation method to model systems by assessing their behaviour due to relationships between variables with smooth increments of time, as opposed to them being controlled by events. This approach assists in making high-level decisions on a problem. SE process models seldom consider the idiosyncratic and non-deterministic aspects of human situation assessment and decision-making (White & Owens 2011).

4.4.6 Modelling Methodology for Complex Sociotechnical Systems

4.4.6.1 Comparison of Frameworks

The literature research in the previous sections highlights some characteristics and key concepts pertaining to complex STSs and their proposed modelling frameworks. The advantages and disadvantages of SD and CWA are provided in Table 6.

Table 6: Advantages and Disadvantages of Cognitive Work Analysis and System Dynamics

Modelling Approach	Advantages	Disadvantages
Cognitive Work Analysis	• Based on systems thinking. • Capture social and cognitive demands, including values. • Formative design of constraints, boundaries of acceptable performance. • Ecological elements and context of dynamic work and environment. • Identify elements and interaction that may lead to complex behaviour. • Functional structure, bottom-up, top-down, elicit and present information. • Elicit knowledge from users and domain experts.	• Inadequate dynamic modelling. • Models are qualitative and static, based on assumptions without proper validation. • Constructs do not support cause-and-effect relationship of unanticipated and intentional events as well as the effect of time work. • Analyse existing systems instead of designing revolutionary and novel systems. • It is difficult to derive low-level requirements that could not have been achieved with standard SE processes.
System Dynamics	• Based on systems thinking. • Capture the decision rules and process structure. • Incorporate nonlinear and dynamic feedback with delays. • Analyse complex dynamic with simulation. • Address holistic dynamic behaviour.	• Systems consisting of highly heterogeneous populations are more difficult to model. • Models are abstractions, with a balance between simplicity for the sake of communication concepts. • Difficult to understand situation in the complex system to develop models.

In Table 7 the characteristics of CWA and SD are compared with the demands on modelling of complex STS from Table 4. This comparison indicates that a framework employing both CWA and SD can address most, if not all the modelling characteristics of complex STS. CWA address the work system operating within real-world constraints, while SD focuses on the system's behaviour within the context of decision rules and policies. It is clear that CWA does not adequately address the dynamic behaviour and interaction among subsystems, while SD does not cater for the impact of technologies on human work. SD tends to focus on the macro-level behaviour of the system, while CWA addresses the lower-level functions and the role of technology. The aspects addressed by SSM are also covered by combinations of CWA and SD. Although not explicitly present in the methodology and table, the principles of SSM are still applied.

Table 7: Comparing the Modelling Framework to Complex STS Modelling Requirements

No	Complex STS Modelling Requirement	Focus Group	DSR	CWA	SD	SSM
1	Present the structure and behaviour of human work in the system.			✓	✓	
2	Capture the mental models and domain knowledge of stakeholders and SMEs.	✓				✓
3	Support experimentation with knowledge on the problem.		✓		✓	
4	Identifying the elements that cause complexity, including the constraints of work domain and environment.				✓	✓
5	Support the qualitative and quantitative analysis of a large system.		✓		✓	
6	Use scenarios to assess the effects and goals of a cognitive work in context.			✓		✓
7	Consider open systems and information exchanges.			✓	✓	✓
8	Address the complex relationships between the humans and technical means, in unison.			✓		✓
9	Using work and task principles to define activities to ensure that all functions can be identified and allocated.			✓		
10	Understand emergent properties through the relationship between the system as a whole and its parts (top-down and a bottom-up approach).			✓	✓	✓

4.4.6.2 Complex Sociotechnical System Modelling

The development of complex STS depends on knowledge on the problem and the effect of solution artefacts to enable successful implementation though SE processes. This is achieved through modelling of the problem and solution systems, and testing them through experimentation. Modelling must capture humans and the work they perform with the technical system, within the context of a complex environment.

The resulting emergent properties can be used to assist in developing STS solutions. The modelling methodology presented in Figure 22 is developed by integrating CWA and SD in the relevant phases of the DSR framework. These two methods support discovery of the problem and formulation of the hypothesis. The characteristics of the two methodologies were matched with the characteristics of the different phases of DSR. Each step in the modelling methodology is subsequently discussed in more detail.

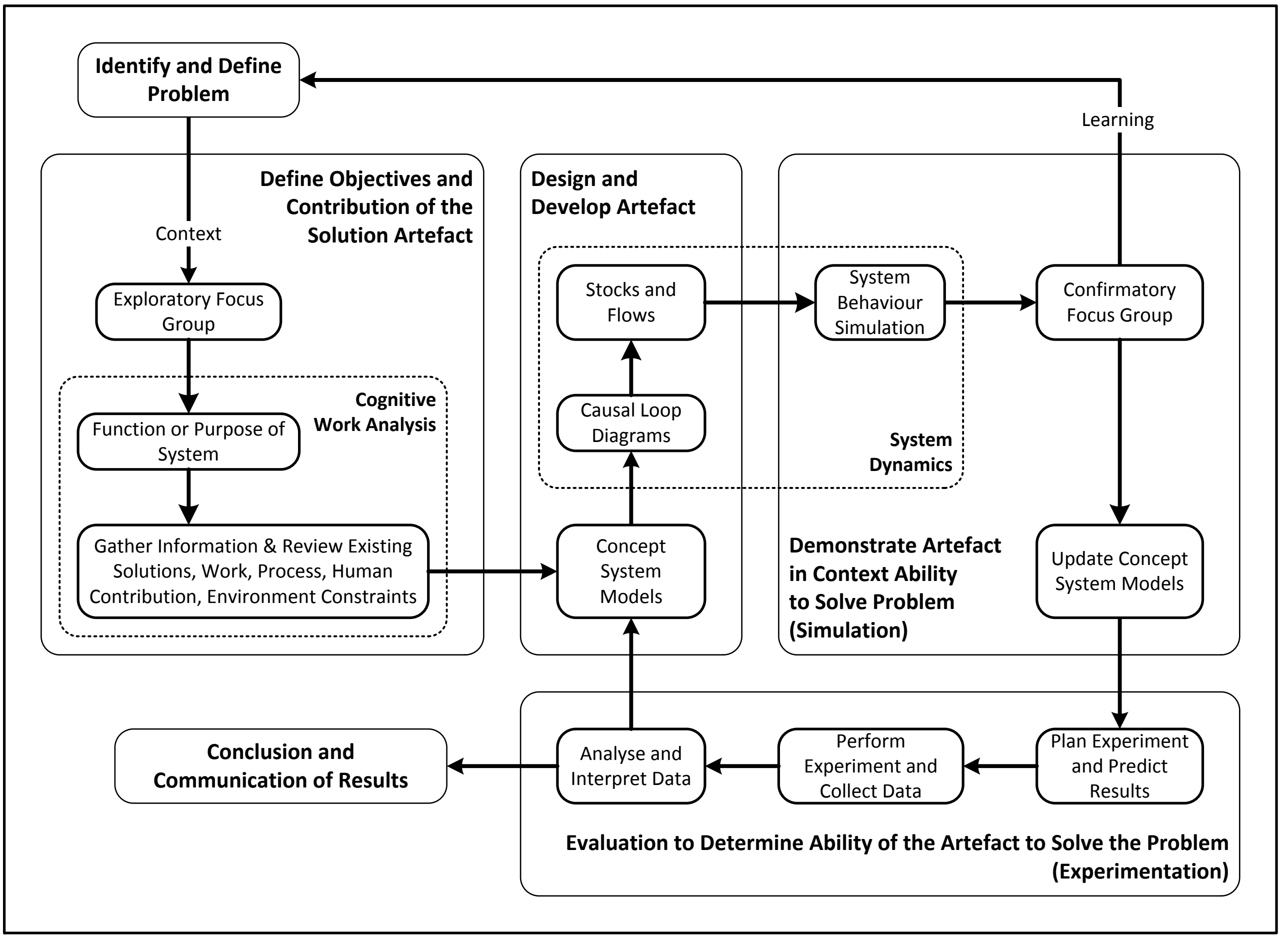

Figure 22: Modelling Methodology

4.4.6.3 Identify and Define the Problem

SE aims to solve a problem, which is identified and defined in the first phase of the modelling methodology. This provides the reason and requirements for modelling the complex STS. The cause may be the availability of new technology to improve a system (technology push) or changes in the environment, or other constraints that inhibit the effective functioning of a system (technology pull).

4.4.6.4 Define Objectives

The second step in the DSR framework is to gather knowledge on the problem and the environmental restrictions, to define the objectives, requirements and context of the solution artefact. This can take the form of an “operational question” to provide the focus for analysis and the direction for modelling. The CWA framework is used to present the current understanding, based on available information on the system and operational requirements within the context of the problem. Often documentation and the supporting literature do not provide all the answers, and SMEs need to provide their opinions and experience.

Focus groups are useful in making explicit the complex relationships among the different levels of the abstraction hierarchy. Modelling cannot be performed in isolation from the complex STS stakeholders, as they require confidence in the model in order to buy in to it. These interactions are useful in identifying causal relationships and filtering out false information. During an exploratory focus group discussion among colleagues, semantic relationships among these levels tended to emerge (Pejtersen & Rasmussen 2004, Carhart & Yearworth 2010).

The output of the CWA is a set of constructs about the understanding of the sociotechnical system and the environmental influences. It describes how people use the system to achieve its purpose (formative) as well as how they adapt to changes in using it. These elements are crucial in planning assessments of the real system or prototypes, by identifying MoEs. The output of the CWA is coupled to the development and choice of assessment tools, methods and metrics.

4.4.6.5 Design and Develop Artefact

The next step is to design and develop the solution artefact, which in this methodology is a model of the complex STS to assess the problem situation and solution artefact. Creativity is applied with knowledge of the relevant theory to provide a solution aligned with the problem's requirements. The act of designing is also important, as new knowledge is gained from the environment and techniques are applied. Existing and generic models of the complex STS are enhanced with information and knowledge captured in the CWA framework, to focus on the defined problem. CWA identifies high-level MoEs, and SD assists in quantifying them. Since SD in this approach does not focus on human processes, the inputs of the CWA are crucial in modelling the problem. The outputs of this combined modelling approach support generating a hypothesis for planning experiments and guiding the analysis of recorded data (Rasmussen 1997, Howie et al. 2000, Cook & Rasmussen 2005).

The CWA constructs are used to develop boundary chart and subsystem diagram models in the form of the functional (behaviour) and physical structure models of the system. These models support constructing CLD and SFD. The information from the CWA assists SD modelling by linking the endogenous (internal) and exogenous (environmental) constraints, through the abstraction levels of the WDA. The means-to-ends relationships also provide a starting point for CLD. The decision rules applicable to the STS can also be derived from the WDA and supporting decision ladders, with the environmental constraints and objectives of the system. The SD modelling approach requires these inputs and user participation to prevent black-box modelling (Sterman 2000).

4.4.6.6 Demonstrate Artefact

The utility of the model is demonstrated in the next step of the DSR framework through SD simulation, before time and resources are committed for an evaluation. This is a little different from the actual DSR, as this step is seen as the experiment, and the next step the evaluation of the recorded data. In this modelling methodology, the next step is the experiment as well as the evaluation of the recorded data.

Simulation adds value to modelling and makes it possible to address complex problems. As STSs are complex, many of the behaviours and characteristics are not always observable or explicitly available from the stakeholders. Here simulation can guide the empirical work, explore complex system behaviours, examine possible consequences of assumptions and demonstrate hypothesis outcomes. This provides theoretical rigour and promotes scientific progress (Harrison et al. 2007, Carhart & Yearworth 2010).

SD simulation is used to analyse and understand the dynamics of the complex STS through simulating the effect of different technologies on the delays in feedback loops. Results of the simulation are assessed through a confirmatory focus group, which also assists in updating models and identifying variables, to guide the planning of experiments. The purpose of SD is not to predict how successful the system is, but to understand the effect of certain causes in support of assessing and understanding possible system behaviour.

The objective of this step is to develop an understanding and initial assessment of the system with the impact of the new technology. SD modelling is used to identify the different mode archetypes, to support an understanding of the underlying structure of the system and the existing feedback loops. The idea is to learn about the system and not to go to unnecessary trouble to validate each model, but to identify the leverage points of the system. Since the focus of this thesis is on complex

STS where humans have to make sense of information in support of decisions, such as C2 systems, the SD investigates the flow of information through the system.

4.4.6.7 Evaluate and Validate Artefact

The final part of the methodology focuses on experimenting with and assessing the artefact. The evaluation consists of experimentation using a case study or other accepted research methods. The aim is to gain knowledge and experience in applying the artefact to solve a problem. The outcomes are compared with the objectives of the perceived problem state and solution values, using quantitative and qualitative analysis techniques. Here, new knowledge and understanding on the problem and system can again lead to improved models for assessment. This is an iterative process until the models and prototypes are adequately matured to enable implementing the final solution (Peffers et al. 2007).

The MOEs must be adequately addressed in the experiments so that the outcomes of the experiments resolve the problems in existing systems or support capturing requirements for future systems. Experiments require valid and credible results to be of value for decision makers. Validity relies on the ability to apply the potential cause that leads to observing a related effect. There must be no plausible alternative explanation for the effect other than the applied cause. Developing a solid hypothesis also improves the success of the experiment. This requires clearly identifying the cause (new technology in this case) of an effect (system behaviour) and supporting it with the relevant MoE (Kass 2005).

Once an acceptable result is achieved, the outcomes can be communicated to the relevant stakeholders to initiate the SE process of implementing the solution. Implementing a solution may change the problem environment and related constraints, which may affect what solution is required. The advantage of the DSR framework for this modelling methodology is that the complex STS model will continually be improved.

4.5 Conclusion

This chapter discussed the issues of analysis and development of complex STSs using SE. It highlights the problems of classic SE and development methods to propose a different approach that effectively addresses the human role and dynamic aspects of the system. The role and contribution of effectively modelling the cognitive and dynamic interactions in complex STS are highlighted.

The modelling methodology needs to capture the human contribution to the system's success as well as the dynamic interaction due to the effect of environmental constraints and operating the system. The theoretical discussions culminated in an analysis and design approach for complex STSs, consisting of CWA and SD built into a DSR framework. This is the artefact of the research design to solve the perceived problem of modelling complex STS.

In terms of the research methodology and design for the thesis, this methodology has to be demonstrated in a suitable case study, to achieve research rigour. The next three chapters apply and test the modelling methodology for modelling a technology for complex STSs. These will focus on operating management systems such as C2 for military operations, anti-poaching operations and residential neighbourhood watches.

5 DEMONSTRATING THE MODELLING METHODOLOGY FOR NEW TECHNOLOGY IN BORDER SAFEGUARDING COMMAND AND CONTROL

> *In these troubled, uncertain times, we don't need more command and control; we need better means to engage everyone's intelligence in solving challenges and crises as they arise.*
>
> Margaret J. Wheatley

5.1 Introduction

This chapter establishes rigour in the research process by demonstrating the artefact's ability – as developed throughout this thesis – in context to solve a real problem. This chapter forms the first step in the second stage (descriptive research), as seen in the research design in Figure 23. The first stage established the modelling methodology through a deductive literature search and reasoning, while this stage demonstrates its ability to model complex sociotechnical systems (STS) in support of systems engineering (SE).

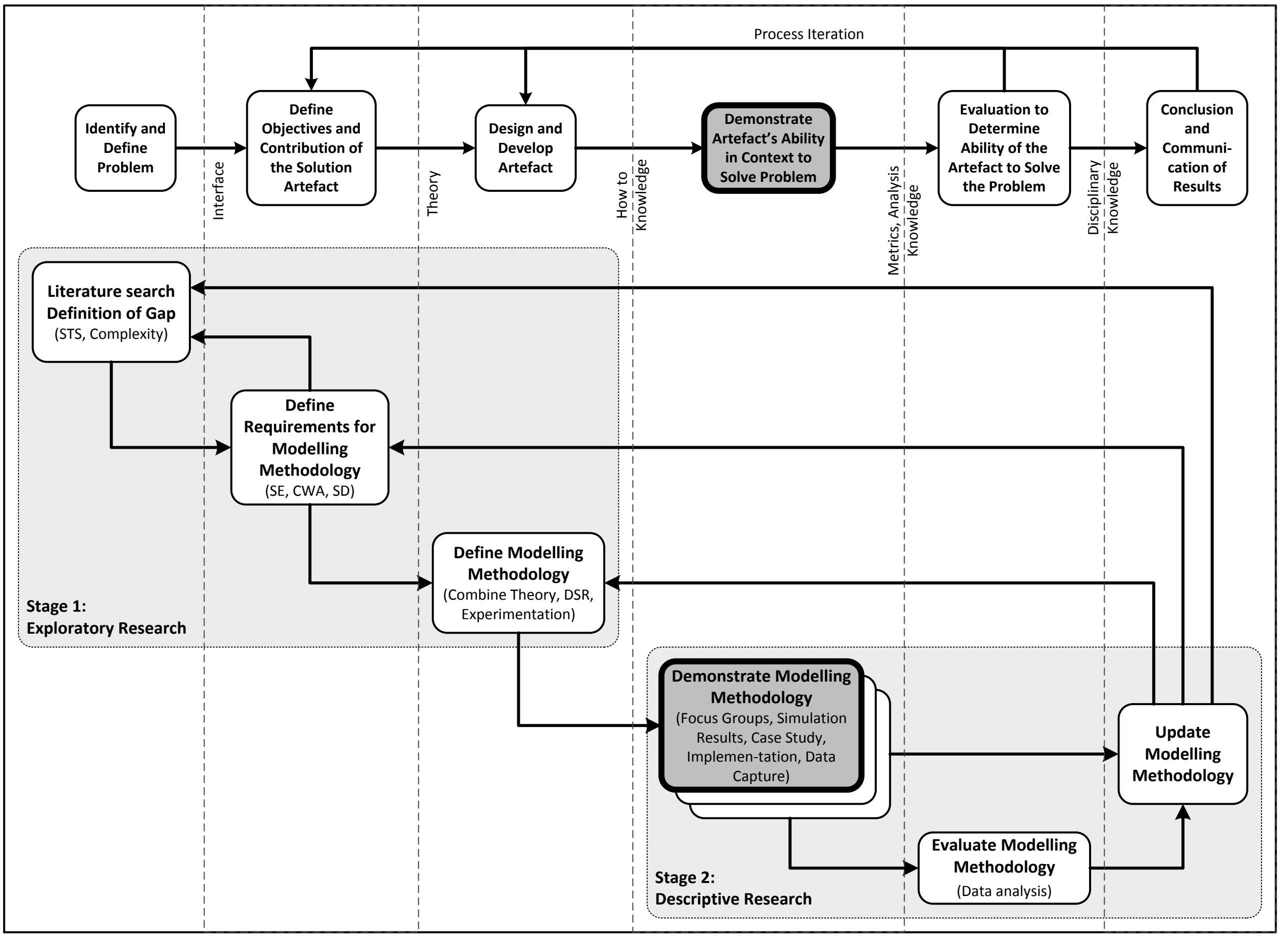

Figure 23: Chapter 5 Relation to Research Design

Many STSs are enhanced or developed by introducing new technology, which consists of technical or other artefacts. This is implemented with an SE process, which tends to be standardised and rigid, with a focus on the technical aspects. Before introducing a new technology, through SE, into a complex STS, the effect thereof on the whole system must be assessed and clearly understood. Effective modelling of the problem situation that addresses system and environmental constraints on human work, as well as dynamic interaction should support an improved understanding of the problem situation.

The modelling methodology is demonstrated in this study through modelling the effect of a new technology on a command and control (C2) system for border safeguarding operations. C2 is a good example of a complex STS, and forms the test case for the artefact developed during this research (Walker et al. 2009). This chapter firstly introduces the role and function of C2 in military operations, highlighting the complexities experienced in the modern combat environment. The discussion centres on the functions of sense-making (situation awareness) and decision-making required in C2.

This demonstration culminates in a generic model for a C2 system to support system dynamic (SD) simulations for assessing the effect of new technology on the operation and effectiveness of a system. The outputs of the simulation are validated through a confirmatory focus group consisting of subject matter experts (SME). This can lead to understanding the expected behaviour of the system with new technology. This model also supports developing future C2 systems. The specific test case focuses on introducing a web-based collaboration technology for border safeguarding C2.

5.2 Command and Control

5.2.1 Warfare

Clausewitz (1976) summarised war as the “clash of wills” and “nothing but a duel on a large scale …. an act to compel our enemy to do our will”. War is an adversarial activity between two forces where neither is inert or waiting to play along with the plan of the other. Both sides constantly seek the initiative to foil the plans and objectives of the other at a political, strategic, operational or tactical level (Smith 2007). The political situation between two adversaries provides the contextual boundaries of conflict (Beyerchen 1992).

From the time of Sun Tzu, and later Clausewitz, warfare has been understood as being complex and laden with uncertainty with terms such as “fog of war”, “centre of gravity” and “friction”. Wars are different, as they are determined by the context and initial conditions (Cil & Mala 2010, Beyerchen 1992). For a state, many things may be at stake, such as national prestige, resources and preserving freedom. This leads to the famous second definition of war as “merely the continuation of policy (politics) by other means” (Clausewitz 1976, Czerwinski 2008).

Modern warfare tends to take the form of conflict among the people. It does not culminate with a single major battle, but is rather a series of events aimed at delivering a desired political result. The way military force is applied must be in line with the required foreseen political outcome. Battles occur in the streets and houses of cities, where the enemy is among, possibly supported by, or disguised as the people. The sides in a conflict tend to be non-state and may even comprise multinational groupings. The required outcomes of conflicts are changing from hard military objectives to establishing favourable conditions for a desired political condition. Therefore, strategies are becoming increasingly complex, as it is difficult to conclude an open-ended and timeless conflict (Smith 2007).

War is characterised by the feedback loops between violence and power. As a result every military act may have both intended and unintended military and political consequences. These actions may include every building destroyed; road used; soldier killed or captured; innocent civilian killed, assaulted or captured; and violation of custom in the heat of the conflict. These make the successful conduct of a military operation extremely difficult and even inherently complex (Smith 2007).

Ilachinski (1996) describes land combat as a complex adaptive system because of the interaction between forces, composed of a large number of nonlinear elements with feedback loops. Nonlinear interaction is caused by enemy actions, chance, sense-making and decision-making processes. Long-range order can be observed, despite the appearance of "chaotic" local action. Combat forces also continually innovate and adapt to survive in a hostile and changing environment.

Border safeguarding presents a challenging mission for military forces, as they have to safeguard an extended border with limited resources, while cooperating with external (non-military) state departments. Here an effective C2 system can be a force multiplier through supporting effective decision-making on the commitment of limited resources to border incidents.

5.2.2 Command and Control Principles

Commanders of military operations are faced with complexity, uncertainty and novelty in everyday situations. Military success depends on the responsiveness and opportunism of commanders and their forces. In order to achieve success, intelligence and information are required (Schmitt 2006, Smith 2007). As commanders cannot foresee every eventuality of an operation during the planning phase, they require a C2 system, which is adaptable to the plan that is executed. Information technology must support commanders in understanding situations in the contexts of environments, to enable separating belligerents from the people, in order to apply the required force. It needs to support the bringing to bear of complex weapons with complex capabilities within complex situations in order to achieve complex objectives (Smith 2007).

The purpose of C2 is to bring all available information and assets to bear on an objective through converging efforts to ensure the desired effects within a military context. A successful C2 system can act as a force multiplier that applies limited resources more effectively. It is a knowledge system that converts data into information to build knowledge in support of sense-making and decision-making. C2 is problem-solving within a military context to provide focus and convergence of effort. Decision-making requires a continuous assessment of the environment, capabilities of assets and the risks involved. On its own, C2 cannot ensure a successful mission, as there are many other factors also having an influence. However, it is a necessary requirement for the successful operation (Alberts & Hayes 2006, Van Creveld 1985, Brehmer 2007, Brehmer 2005).

The C2 system designs courses of action and controls their execution in order to achieve military or other goals. Commanders have to determine the best course of action to achieve the desired results, as well as lead those under their command. Control is the process of determining the relationship between desired and real results, and the taking of any necessary authorised steps to correct deviations from the desired plan of action. This is achieved by directing and coordinating actions to ensure that the appropriate resource is available at the right place, at the right time, with an appropriate mission. C2 can be related to a knowledge system (Alberts & Hayes 2006, Van Creveld 1985, Brehmer 2007, Brehmer 2005).

One way to investigate C2 is to make a split between planning (command) and execution (control). The “command” of C2 is concerned with the planning of an advantageous encounter with the adversary, which is compared with being an “art”. As it is almost impossible to predict the behaviour of the adversary, “control” is required to steer the outcome of the conflict in a favourable direction, which is compared with being a “science”. Commanders throughout history have been aware of this, as seen from the famous dictum of Moltke (1800-1891) (Daniel 1993) that “No plan survives contact with the enemy.” Thereafter, it depends on the responsiveness and opportunism of commanders and their forces (Brehmer & Thunholm 2011).

5.2.3 Models of Command and Control

C2 is an iterative and cyclic process that continually requires updates to decisions for adapting to a changing situation. One of the most widely used C2 models is the “observe-orientate-decide-act” (OODA) loop developed by Boyd (1987) (Grant 2005). A simplified and adapted version of the OODA loop is provided in Figure 24 to guide the theoretical discussion on C2. Boyd noted that it is the objective to operate inside the enemy’s OODA loop, performing the OODA functions faster and forcing it to react to your actions. One must be faster than the enemy is, and attack it where it does not expect it, to create confusion in its environment. Despite being widely accepted and used, the OODA loop is flawed as a comprehensive C2 model and is often criticised.

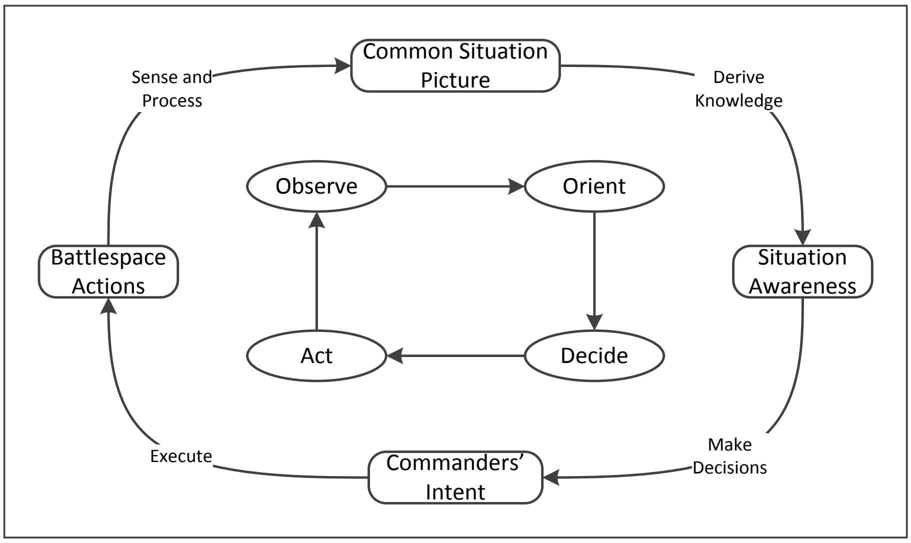

Figure 24: Simplified OODA Loop

Grant and Kooter (2005) identified that OODA is reactive, and does not incorporate commanders' intentions, planning or exit criteria. In addition, the OODA loop does not address the inherent delays in the C2 and execution system. However, the OODA loop was originally intended as a model for winning and losing, to guide the development of strategy and tactics, not specifically for implementing and developing C2 systems. However, the OODA loop is a good basic model to guide developing and implementing C2 doctrine.

Brehmer (2005) expanded the OODA loop with cybernetic C2 model inputs and manoeuvre warfare concepts, to form the dynamic OODA (DOODA) loop, as provided in Figure 25. It includes the elements of the mission and command concept (commander intent). There also exists an exit condition when the mission objectives have been achieved.

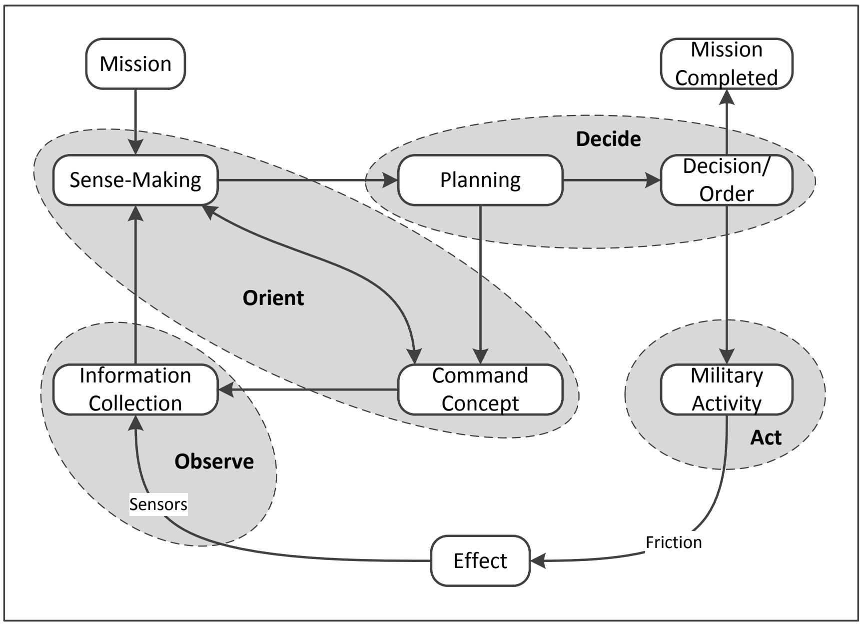

Figure 25: Dynamic OODA Loop Adapted from Brehmer (2005)

The DOODA loop is a useful enhancement, as it highlights the processes of sense-making in relation to the mission's objectives, the command concept and the available information. Effective C2 systems maintain control in the process of implementing the objective or commander's intent. This process includes collecting data, making sense of the information, performing planning, making a decision on a favourable course of action, and issuing orders for action.

An important aspect of C2 is the effect of delays in every step of the process (Brehmer & Thunholm 2011). By the time commanders send their orders for action, the information, and even the planned solutions, may already be out of date. This makes it even more difficult to implement an effective solution to the perceived problem. The process of decision-making, in an environment with inherent risks and delays, results in a complex dynamic system. Management of this complex dynamic system requires careful modelling to understand all the implications (Sterman 1994).

5.2.4 Command and Control System

C2 is executed within a system that is integrated within the larger military system. The C2 system consists of equipment and people (commanders and subordinates) organised in a structure to execute a task, through applying standardised methods (Brehmer 2010). Brehmer (2007) notes that C2 cannot be the automated function of a “C2 machine”, as it is impossible to identify all possible permutations and combinations to develop an algorithm. C2 will always require human interpretation to make sense of complex situations. This increases the complexity in operation for the C2 system, making it impossible to predict correctly the outcome of every situation, as people often interpret information differently.

When analysing and/or designing a C2 system, it is useful to consider all three levels of design: purpose, function and form (Brehmer 2007). Understanding the purpose, what it is that is required to achieve, as well as how, and to what extent the system achieves its purpose in a given case is the key to understanding C2. These observations support the general design perspective that C2 belongs to “the sciences of the artificial” (Brehmer 2010, Simon 1996). The “form” of the C2 system consists of the organisation, methods, procedures and support systems. As C2 happens throughout the military system, with its numerous participants, it also has a cognitive and social side that requires support from the “form” element. C2 is a function of the military system to produce effects through the direction and coordination or resources. When developing a C2 system, these become the purpose of the C2 system. Therefore, the C2 system requires the functions of data collecting, sense-making and planning to support directing and coordinating the military system (Brehmer 2007).

The main elements of a C2 system are provided in Figure 26. The commander is the key factor in successfully applying force in a military mission, with the authority and the accountability to make decisions regarding the solution or plan of implementation. He or she determines the structure and application of the force and resources available. He or she requires cognitive and social abilities, through experience and training, to interpret a situation and utilise creativity to develop a solution (Smith 2007, Jensen & Brehmer 2005).

Sensors are deployed in the environment to collect data. They may consist of radars, optical sensors and intelligence sources, with varying degrees of accuracy, granularity and context of the data. The effectors execute orders received through the C2 system. Feedback on the progress and execution of orders is also a form of sensor that feeds data into the system. The communication subsystem is the transport medium for data from the sensors to the command centre, as well as for orders to the effectors from the command centre.

A cognitive support system integrates data from all the sensors into a situation awareness picture. This includes some analysis to enhance the value of the information in support of making sense of the situation, as well as decision-making on which action to take. Normally the interface between the commander and the C2 system is through a human machine interface. The design of the human machine interface has to support the mental model and cognitive processes of commanders, to ensure quick and efficient decision-making. The quality of sense-making and decision-making is determined by the degree of shared awareness, social climate and interaction between the staff and the organisation of the work.

The output of a C2 system is a plan implemented through distributing orders. The plan should be based on the sense-making of current information and the context of the operation. The plan must define the required outcomes and assign the authority, responsibility and resources to achieve it.

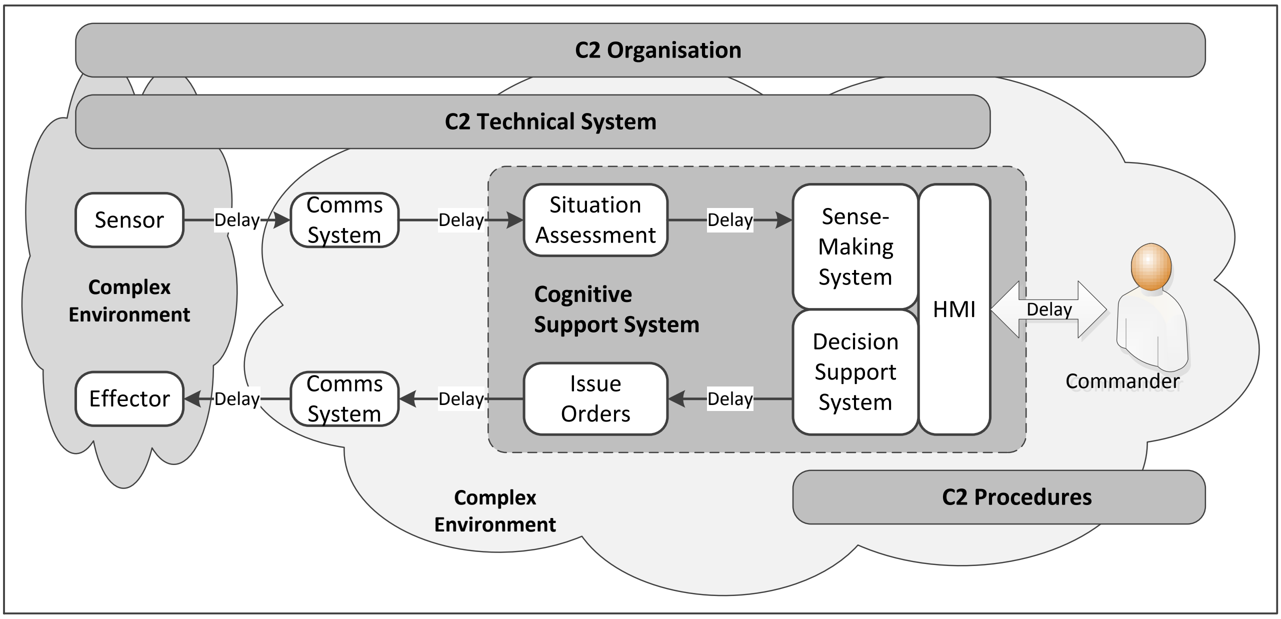

Figure 26: Command and Control System

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5.2.5 Sense-making and Decision-making

The C2 system has to support making sense of complex situations and managing the risks during the execution of an operation (Ntuen 2006). In order to control the operation and plan future actions, commanders are required to anticipate future events. This is achieved through gaining and maintaining control of the situation through feed-forward and feedback control. Commanders require awareness of what is happening and what has happened through aspects of human cognition such as reasoning, pattern recognition, intuition, judgement, experience in comparing facts and differentiating between information that does or does not make sense. (Bennet & Bennet 2008).

The C2 system supports operators by presenting the information they require for sense-making and decision-making. The method of presentation must be aligned with their mental models to support natural cognitive processes for decision-making. The problem must be transparent through presenting the information required for the decisions, instead of raw data, to reduce the human cognitive effort. Having information alone, even almost complete and perfect information, is not sufficient for quality planning in military operations. Making sense of that information and the processes and procedures supporting it is what makes the difference. The human must be allowed to follow different problem-solving strategies, ranging from instinctive reaction through to elaborate reasoning on problem fundamentals. A decision-support system must enable the processing and display of large volumes of data to support understanding the situation (Janlert & Stolterman 2010, Elm et al. 2003, Simon 1996, Jensen & Brehmer 2005, Leedom et al. 2007).

Endsley (2000, 2003) defines situation awareness as “the perception of elements in the environment within a volume of time and space, comprehension of their meaning and projection of their status into the near future”, as seen in Figure 27. In warfare, a shared and common situation awareness is required for effective decision-making. Building and keeping effective situation awareness is difficult, and requires great effort to update and interpret information in a rapidly changing environment.

Commanders make decisions in a changing environment, while the impact of the decisions also changes the environment. Decisions are guesses about the future (Bennet & Bennet 2008). Brehmer (2011) describes this as dynamic decision-making, which consists of a series of interdependent decisions in real time on an ever-changing problem. This is similar to the wicked problems discussed in Chapter 3.

Human decision-making is largely an intuitive process affected by the ability of the decision maker to assess the situation and to perform mental-based simulation on the probability of success of a candidate solution. The natural tendency is not to optimise a solution of the problem, but rather to implement the first satisfactory option (Klein 2008).

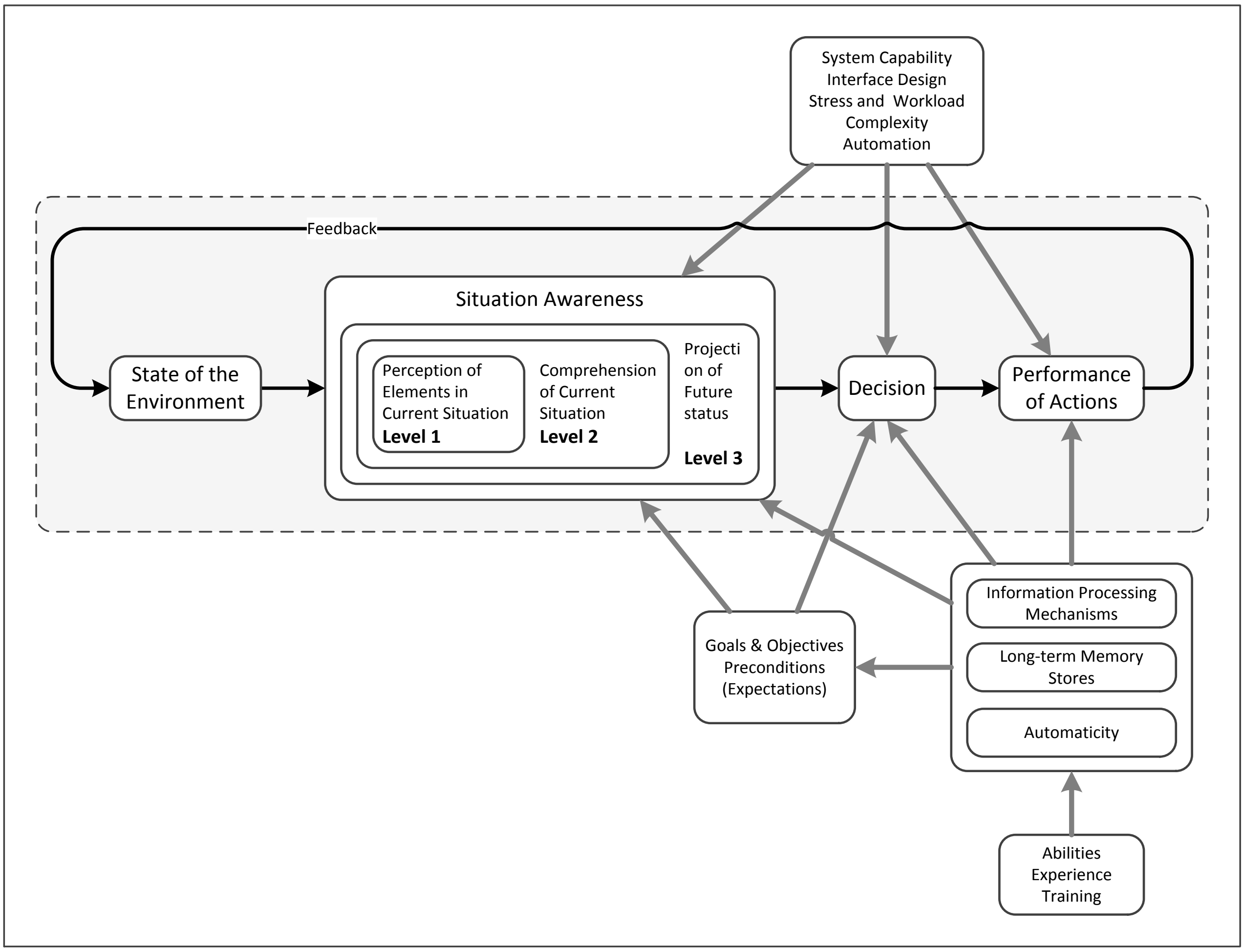


Figure 27: Situation Awareness Model (Endsley 2003)

As humans are part of the cognitive system that performs sense-making and decision-making, their contribution must be included in modelling the effect of a new technology. Decision makers must be able to monitor the effect of their actions, to modify their situational understanding, if required. The interface must also provide information on the context of the problem. An analysis of complex situations requires the commander to think at different levels of abstraction and to identify the links between the different levels (Klein 1989).

5.2.6 Command and Control as a Complex Sociotechnical System

C2 is an example of a complex STS as it is composed of personnel commanders and subordinates, organisational structures (authority and responsibility), work procedures (doctrine) and technical equipment (communications and decision support) operating in a complex environment of warfare (Walker et al. 2009, Brehmer 2010). The modern trend is towards network-centric warfare, which requires new organisational structures supported with new technical systems. A major contributor is modern communication technology that provides wider connectivity for data exchange.

The C2 system must have the capability to assimilate all the available information, while harnessing the cognitive and social capabilities of decision makers to control military operations. This places new demands on commanders to make sense of complex situations with decision-support tools. The escalation of the human's role increases the complexity in operation for the C2 system, as human behaviour is context- and task-dependant. Different decision makers may have different levels of objectives, responsibility, chains of command, decision cycles, timelines and methods of decision-making. The C2 system must support the operators in addressing complex situations (Alberts & Nissen 2009, Smith 2007).

War and combat present an environment with complex problems caused by chance, initial conditions, contextual complexity, nonlinear interaction, decentralised control, collective dynamics, self-organisation and adaptation (Beyerchen 1992, Ilachinski 1996). According to Ashby's Law of Requisite Variety, to control combat as a system, the variety of states within combat itself must be similar to the controller of the combat system (Moffat 2003). Therefore, the C2 system also requires complex capabilities.

In addition to the complexity associated with systems integration and compatibility with other systems, C2 systems are coping with the environmental constraints and performing problem-solving for unprecedented work. However, emergent characteristics in the C2 system, because of complexity, must not be prevented, as they may be required for agility in order to cope in the evolving modern military environment. The process of decision-making, in an environment with inherent time pressure, risks and delays, results in a complex dynamic system. C2 systems require agility to cope with changes in the situation or environment through responsiveness, versatility, flexibility, resilience, innovativeness and adaptability (Alberts 2011).

C2 system development projects seldom build brand new systems, but tend to be technological upgrades that need to be tested and analysed to gain knowledge of the requirements and performance gaps. Due to the inherent complexity in the development of C2 systems a number of issues and challenges can be encountered. Therefore, C2 system analysis should consider all elements and artefacts in the system, in unison. However, human performance is complex, context-dependant and difficult to specify. C2 systems have to support the different decision makers in the C2 hierarchy throughout the entire decision-making cycle (Hallberg et al. 2010, Cooley & McKneely 2012). The theoretical discussion of C2 in this section is summarised in Table 8 and compared with the characteristics of complex STS (Alberts & Nissen 2009, Alberts 2011, Vicente 1999).

Table 8: Comparing Command and Control to a Sociotechnical System

Complex Sociotechnical System	Command and Control
Technology (Tools, devices, techniques)	C2 systems utilise automation and mediated interaction in the form of communication, computerised presentation and decision-support systems as an interface for commanders to analyse accumulated information. The ability of workers to solve complex problems are greatly affected by the ability of the interfaces to provide stimuli associated with natural cognitive thinking patterns.
Human Influence (Social humans with knowledge, skills, attitudes, values, needs)	Individuals and/or teams, consisting of commanders and subordinates with different characteristics and capabilities, interact with one another within a C2 system, each with their own ideas, motives and objectives.
Work (Task interdependence, unstructured, uncertain)	C2 concepts for sense-making, decision-making and control determine how work is performed. This is affected by risk, time pressure and uncertainty. Different tasks require different timescales and levels of activity.
Organisation (Authority structures)	Multiple and interdependent chains of command exist in a hierarchy requiring a shared situation awareness with the objectives of the participants not being aligned.
Environmental Interactions (Situated cognition)	The environment may vary, including terrain, weather, adversaries, own forces, politics, culture and information sources, to provide the context and initial conditions.
Information (Knowledge system)	Data sensed and reported by various entities is converted into information to support situation awareness, understanding and decision-making.
Complex System Behaviour (Unpredictable, dynamic, non-deterministic, emergent)	C2 systems are dynamic due to the control and adaptation of plans and actions with time lags. Interaction between different elements or subsystems within a C2 system makes prediction of outcomes of an action difficult. Available information may be incomplete and uncertain. Participants react differently when scared, hungry, thirsty and dirty, within the operational environment.
Agility (responsiveness, versatility, flexibility, resilience)	Commanders have to deal in combat scenarios with unanticipated events, by improvising, to adapt in order to implement contingencies for a successful mission.

5.2.7 Collaboration Technology

5.2.7.1 Overview

The collaboration technology to be introduced into a C2 system to demonstrate the modelling methodology as part of this research is a technology demonstrator called Cmore. The name refers to various C2 acronyms and capabilities. The goal of Cmore is to enhance situation awareness, decision support and achieve information superiority. The basic inputs, outputs, enablers and controls of the Cmore system are provided in Figure 28. A graphical representation of the system is provided in Figure 29.

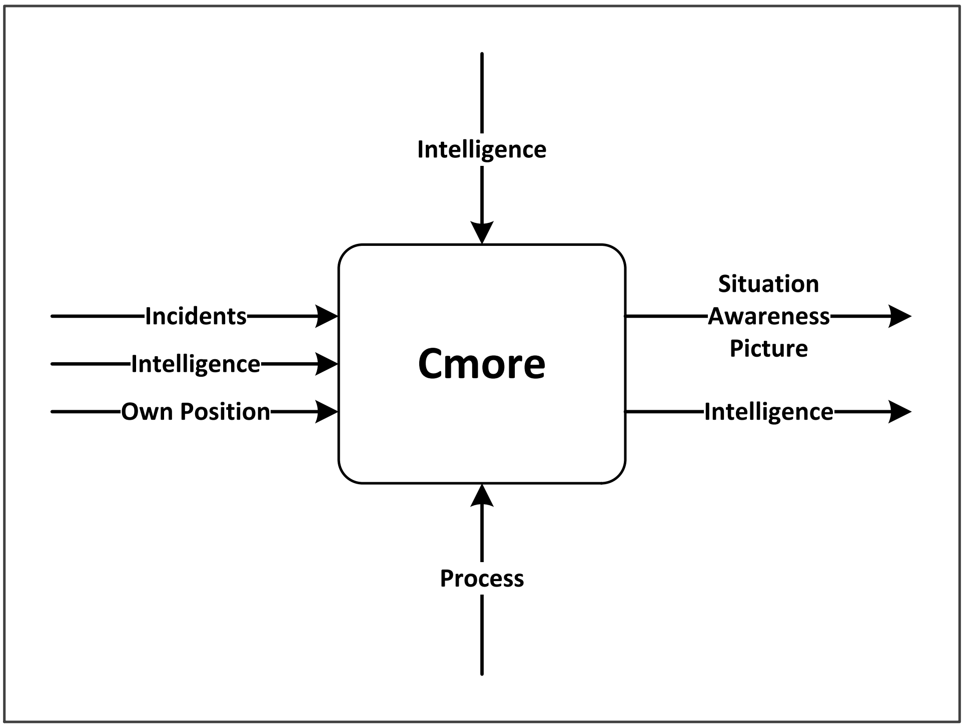


Figure 28: Basic Cmore System

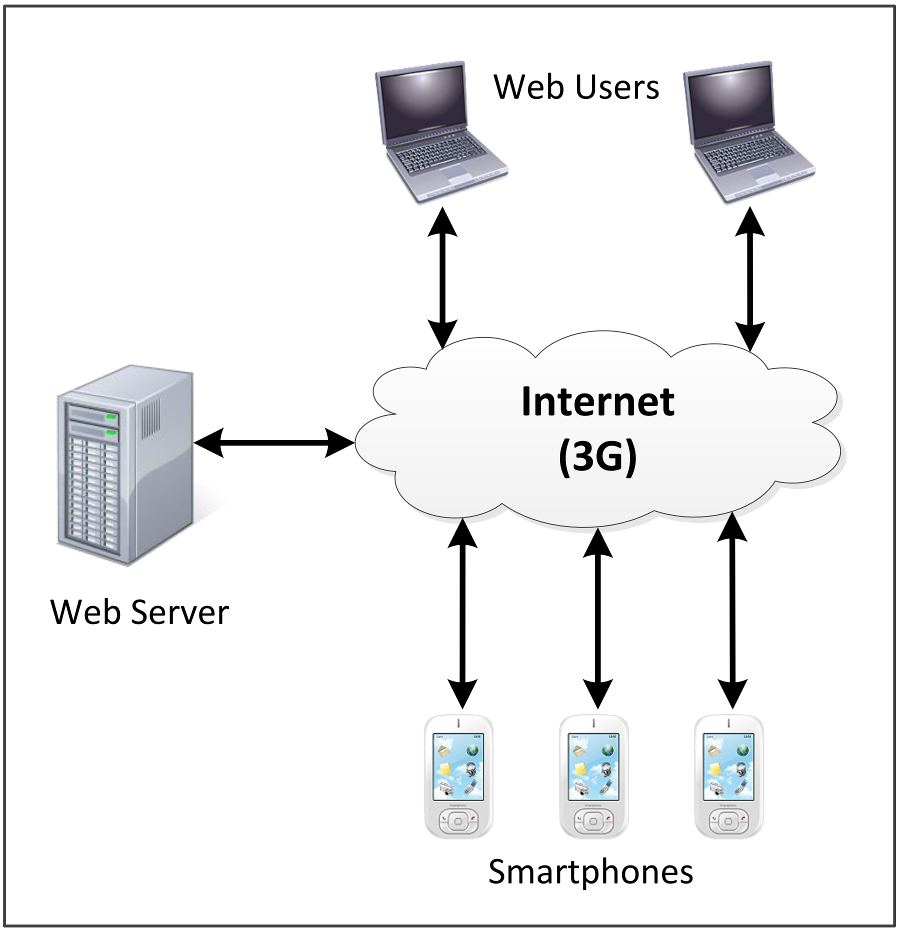


Figure 29: Cmore System Overview

Collaboration implies working with others to do a task and to achieve shared goals through a recursive process. This is achieved by sharing knowledge, learning and building consensus. Diverse knowledge, expertise, and experience enable full exploitation of information. Collaboration and information sharing improve the quality of information and shared situation awareness. The shared awareness enables self-synchronization (Alberts 2007, Alberts 2011).

Cmore uses any network, such as the Internet, for its communications backbone in a web-based architecture, consisting of a structured query language (SQL)-based server to provide support for geospatial data, full-text searching and analytical processing. Google's Chrome browser supports the client-side platform for viewing information and interacting with the system. The user interface has been designed for easy collaboration, sharing and understanding of information. Cmore mobile clients are standard commercial Android smartphones that interact with the server through Google Cloud Messaging.

The Cmore portal is the front-end of the Cmore system, which connects the operator to all other Cmore clients and sensors. Although Cmore can operate on any network, it is typically accessed over the Internet. For this reason, it is important to encrypt sensitive data. Cmore utilises a custom authentication provider that ensures each individual is authenticated. Data-level authorisation is provided with group structures in the Cmore collaboration model.

The system is able to create organisations and sub-organisations, each with their own users. Messages are visible down the hierarchy of an organisation, which means that the top-level node sees everything beneath it. Users can be assigned specific roles within the context of an organisation or operation.

5.2.7.2 Core Cmore Capabilities

The basic Cmore capabilities relevant to the C2 system and functions, to be supported in this research implementation, are:

a) Blue Force Tracking. Cmore provides real-time tracking of all operatives in the field through the global positioning system (GPS) inside smartphones. This application reports the GPS position to the command centre if an Internet connection is available. This gives the control centre the ability to locate all of the assets.

b) Incident Capture. Cmore captures incidents in the field through the smartphone cameras. These images are uploaded immediately to the command centre or as soon as an Internet connection is available. Pictures are also geo-tagged and time-stamped. Patrollers can contextualise the picture with a short message before sending it to the Cmore server. Live video can be streamed from the device on request from the command centre.

c) Chat and Coordination. A group chat feature allows the exchange of messages within the context of an operation or group. Participants have the ability to join remote planning sessions. Notifications and history of messages can also be accessed for tracing the unfolding of situations.

d) Workflow. The technology can be applied to support military units in cooperating with police and other departments to apprehend criminals and collect (preserve) evidence for prosecution.

e) Situation Awareness Picture. A map display with the available geolocated information will assist commanders with situation awareness, understanding, decision-making and planning. The typical display elements consist of the following elements: maps (Google), satellite images, incidents, risk areas and BFT.

f) Information Analysis. The recorded information can be analysed to detect patterns of patrolling, incidents and crime, to highlight problem areas. Typical tools in Cmore include heat maps of incident counts, filtering, clustering and instant global search.

5.2.7.3 Cmore Interface

Cmore follows the recent trend in web-based applications that has seen a shift from the traditional website, where a user interacts with the information they require by navigating via hyperlinks and buttons, towards a single-page application. This means that all information is displayed on a single page that organises the information in different functional panels.

This allows the user initially to view a high-level overall picture of the available information and then to drill-down to specific details only if they wish to do so, as seen in Figure 30. These views provide the following information and capabilities:

a) Main Centre Panel. Map display (including satellite) with annotations of blue forces, incidents and other important information.

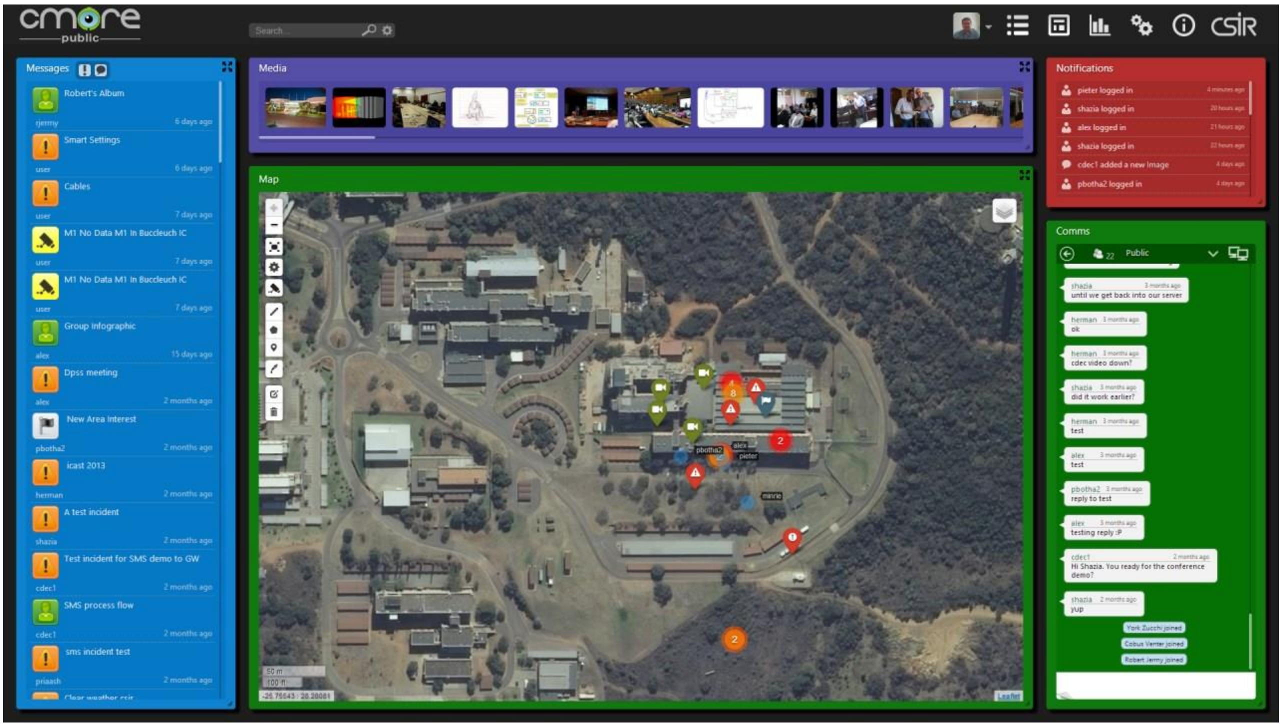
b) Left-Hand Panel. Messages, resources and incidents, with the ability to view previous sessions.

c) Centre-top Panel. Multimedia consisting of images and videos.

d) Right-hand-top Panel. System notifications and text chats in group sessions (conferences) or one-on-one appear here. Chat notifications help to alert users on required actions.

The map display also provides for a visualisation of coverage, areas of interest, options and clustering (annotation on map). This can be supported with an instant global search, incident count and heat-map visualisation, as seen in Figure 31. Cmore mobile is a trimmed-down version of the Cmore portal, and requires the smart device to have an active Internet or any other network connection so that it can connect to the Cmore web server. The Cmore mobile capability is used by friendly mobile forces, other participating departments or even the public to capture information in support of the C2 process.

This section presents the new technology to be introduced in the complex STS. The next section models and analyses the contribution of the new technology in the complex sociotechnical system of border safeguarding.



Robert's Album — rjemy — 6 days ago
Smart Settings — user — 6 days ago
Cables — user — 7 days ago
M1 No Data M1 In Buccleuch IC — user — 7 days ago
M1 No Data M1 In Buccleuch IC — user — 7 days ago
Group Infographic — alex — 15 days ago
Dpss meeting — alex — 2 months ago
New Area Interest — pbotha2 — 2 months ago
icast 2013 — herman — 2 months ago
A test incident — shazia — 2 months ago
Test incident for SMS demo to GW — cdec1 — 2 months ago
SMS process flow — cdec1 — 2 months ago
sms incident test — priaash — 2 months ago

pieter logged in — 4 minutes ago
shazia logged in — 20 hours ago
alex logged in — 21 hours ago
shazia logged in — 22 hours ago
cdec1 added a new Image — 4 days ago
pbotha2 logged in — 4 days ago

shazia — 3 months ago — until we get back into our server
herman — 3 months ago — ok
herman — 3 months ago — cdec video down?
shazia — 3 months ago — did it work earlier?
herman — 3 months ago — test
alex — 3 months ago — test
pbotha2 — 3 months ago — reply to test
alex — 3 months ago — testing reply :P
cdec1 — 2 months ago — Hi Shazia. You ready for the conference demo?
shazia — 2 months ago — yup
York Zucchi joined
Cobus Venter joined
Robert Jermy joined

Figure 30: Main Screen with Satellite View

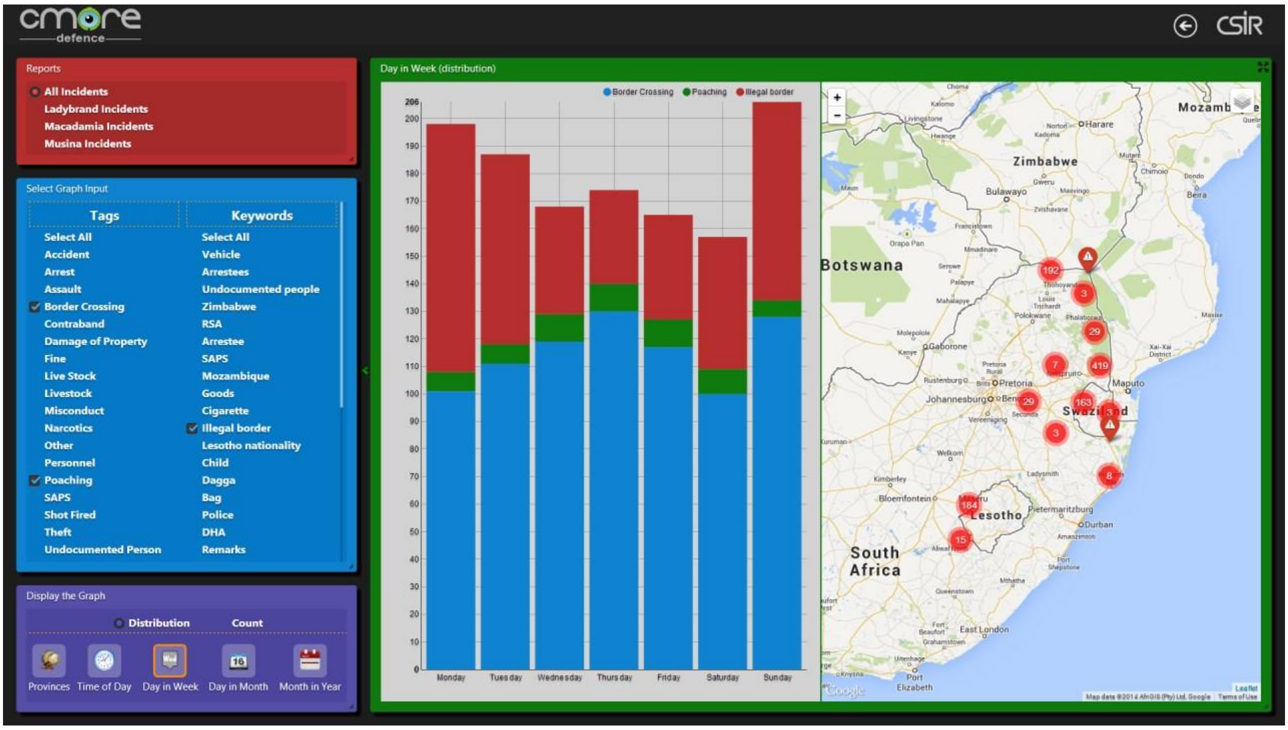


Figure 31: Information Analysis

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5.3 Modelling of Command and Control for Border Safeguarding

5.3.1 Methodology

The modelling methodology, as developed in Chapter 4, is used to model and evaluate the effect and contribution of the new web-based collaboration technology, Cmore, for C2 during border safeguarding operations. This research demonstration will stop at the confirmatory focus group, as indicated by the dotted ellipse in Figure 32. The aim is to demonstrate the ability of the methodology to model a problem situation in support of understanding the implications of a new technology on a complex STS. The confirmatory focus group output is used to determine the utility of the modelling methodology.

The technological capabilities of Cmore described in the previous section may assist in enhancing C2 for border safeguarding. The degree of the contribution and application of Cmore in the complex STS still needs to be understood. This is achieved through applying the modelling methodology developed in this research. It is important to remember that the artefact developed through this methodology is a model of the contribution of the technology in the complex STS. The detailed execution of the modelling methodology is described in the subsequent sections.

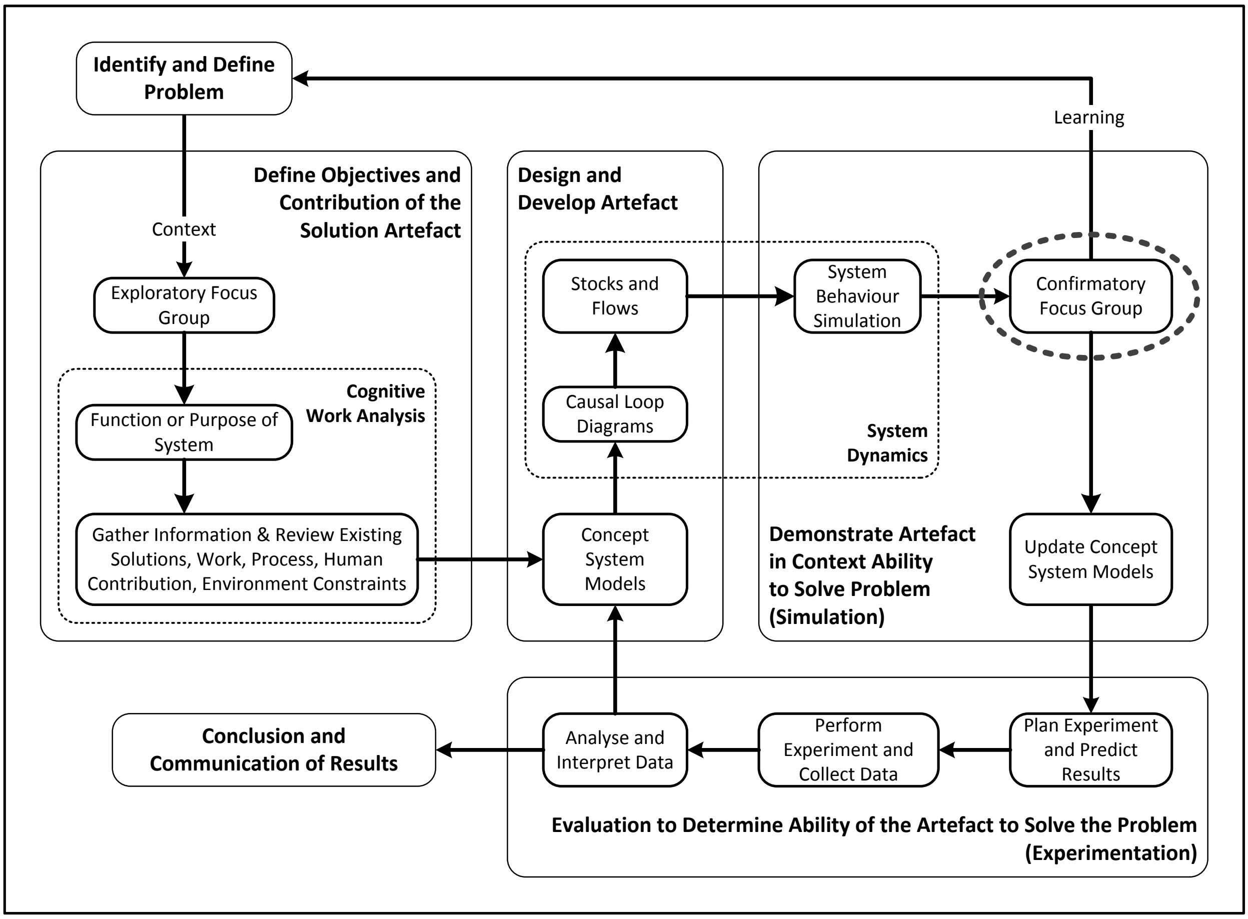

Figure 32: Modelling Methodology for Command and Control

5.3.2 Identify and Define the Problem

Researchers have proposed new communication and situation awareness display technology, based on smartphones and web services, to enhance C2 collaboration for border safeguarding operations. This research case study examines the effect of this new technology on a C2 system for border safeguarding.

Border safeguarding entails controlling and enforcing state authority on national borders, to curb cross-border crime such as illegal immigration, rustling of livestock, poaching, and smuggling (Naudé 2011). The main functions of the C2 system for border safeguarding are the following:

a) Gather information and intelligence from sensors or interaction with local communities.
b) Manage resources to ensure availability when required.
c) Take action when required, which include passive measures such as confusing, diverting, avoiding detection or distraction.
d) Plan courses of action for prioritised tasks.
e) Liaise with other departments and entities involved in border safeguarding operations.
f) Preserve forensic artefacts for prosecution.

This is a case of “technology push”, which involves new technology that has the capacity to enhance the performance of an existing complex STS (being the border control system) and where not all the system deficiencies are known. The new technology provides more information to the C2 system that can support situation awareness, sense-making, understanding, planning, decision-making, and coordination to improve a mission's success. However, existing intelligence analysis methods and tools may not be adequate any more. Therefore, the advantage of the new technology may create new problems.

The impact of these issues needs to be understood when initiating an SE-based project for a C2 system implementation. Therefore, the problem to be addressed in this demonstration of the modelling approach is to understand the contribution of the new technology to situation awareness as well as the factors (variables) influencing its success. This may lead to additional requirements for information analysis tools in the system. Identifying this problem is part of the research problem, as experienced in this context.

5.3.3 Define Objective and Contribution of the Solution Artefact

5.3.3.1 Focus Group

A focus group with C2 subject matter experts (SMEs), consisting of designers, developers and users of C2 systems, was conducted to gather information on the requirements of a C2 system. The questions addressed in the focus group to identify the priorities and inputs to the modelling process are the following:

a) What is the purpose of C2 in border safeguarding? (Also, look at the different levels.)

b) Which of the main functions executed during C2 in border safeguarding can be supported through technology? (Situation assessment, sense-making, decision-making, planning, tasking, control, etc. Is the list complete?)

c) Which of the functions are more important than others?

d) Which variables influence or constrain the success of the C2 system the most? (Information, resources, situation awareness, accuracy, time delays, etc.)

e) Which functions in the C2 system are affected by the identified variables?

f) What are the shortcomings in C2 that can be addressed by technology?

g) Where can a new technology such as Cmore contribute to the effectiveness of the C2 system? (Typical capabilities in Cmore are sensing, information distribution, information management, information display, information analysis, planning tools, order distribution in reference to the variables and functions discussed.)

h) How will the technology influence the way people do the work in the system?

i) What is the effect of the technology on the timeline of events?

j) What will the effect be of extra information captured by Cmore? (Better understanding or information overload.)

A summary of the focus group planning, composition, output and analysis is provided in Appendix B.1. This information is used to support modelling the impact of the new technology in the complex STS.

5.3.3.2 Cognitive Work Analysis

The C2 system for border safeguarding operations, as captured in an abstraction decomposition hierarchy (ADH) through a WDA, is shown in Figure 33. The aim is to capture the real issues of performing work with a C2 in border safeguarding operations that is to be supported with the new technology. The information gained from the focus group and literature was used to populate the ADS. An initial ADH was constructed from literature to support the focus group discussion. This framework was used to sort the transcripts into themes (ADH layers) and to identify important concepts and their relationships, as seen by the highlighted phrases in Appendix B.1.

In Figure 33 the yellow blocks indicate the physical and functional elements that the current technology supports. The blue-coloured blocks show how the new technology can increase or enhance the functionality. The blocks with no colour indicate an uncertainty of being supported by either technology.

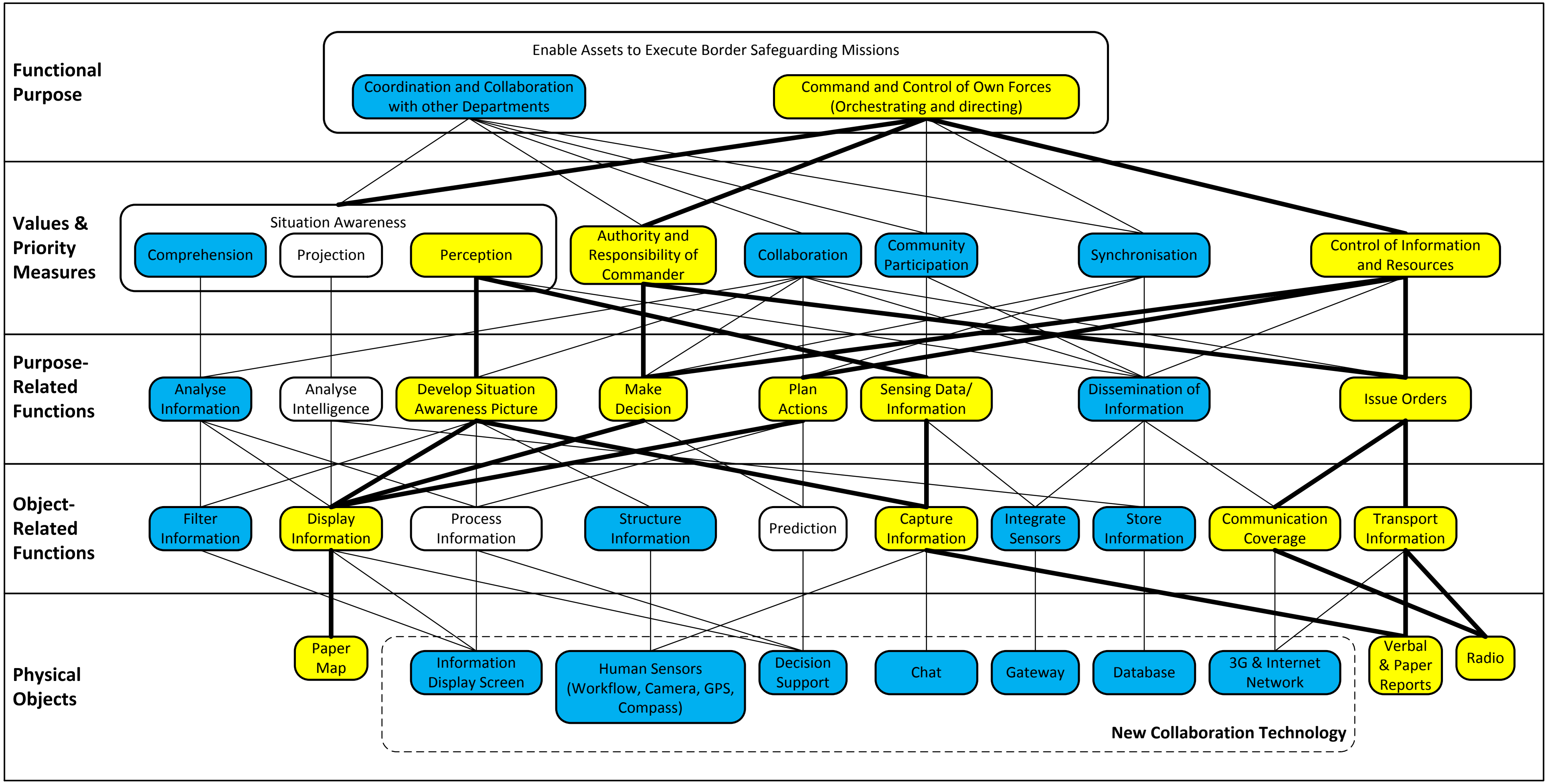

Figure 33: Work Domain Analysis for Border Safeguarding with New Technology

The ADH does not present perfect and complete information about the C2 system but supports investigation into certain aspects in relation to the context of the mission. The framework assists in understanding the system to derive the possible technological influences on the functions and purpose of the system within the environmental constraints. This is useful in constructing system models for further analysis of the problem and the whole system. From the ADH in Figure 33, the following typical inputs to a C2 model can be derived:

a) Current system does not have automated information processing tools.

b) Reported information only supports development of situation awareness picture.

c) A database will support the information display as well as information processing, which both support intelligence analysis.

d) Decision support tools, including intelligence analysis, are required to process information for the situation awareness display, sense-making, intelligence analysis, decision-making and planning of actions.

e) Intelligence is required to understand the current situation and to make decisions that support an economy of force and surprise in the pursuit of executing border safeguarding missions.

f) Other variables or constraints to be considered when implementing new technology include involving community participation, collaboration and synchronisation between different participants, addressing issues with the authority of the commanders, and controlling available resources.

Information from other departments may not be in the same structured format as military entities. This necessitates structuring unstructured information to increase its utility.

Many other outputs can be derived from the ADH, but the list above is what is required to investigate the identified problem of understanding the contribution of the new technology to situation awareness, as well as the factors (variables) influencing its success. The aim is to understand the requirement for intelligence analysis tools in the system. Some of the functions may be present without the technology but tend to be very limited and manual paper-based processes. Current C2-supporting tools include paper-based reporting and display systems with voice communications over radios. Normally, only a fraction of the possible information available is recorded, explaining the current lack of Intelligence analysis tools.

5.3.4 Design and Develop Artefact

5.3.4.1 Command and Control System Model

The solution artefact of the modelling methodology is captured in the form of functional (procedural) and structural system models. The generic functional C2 model (DOODA) from

Figure 25 is converted to a high-level functional system model in Figure 34, with inputs from the CWA in Figure 33.

This is the same as the model boundary and subsystems diagram (overall architecture of the model) from Sterman (2000), which will at a subsequent stage be required for SD modelling. The contribution of the new technology is the collaboration and coordination of capabilities. The diagram identifies the following links between functions and system elements:

a) Commander's Intent. The functions of developing the commander's intent serve as the main input to the C2 process. These determine the critical information elements required for decision-making and guide the intelligence analysis process.

b) Information Collection. Within this case study, information is collected by human sensors with hand held mobile devices through interaction with civilians in the environment. This has the ability to capture photos and videos as well as adding context in the form of text notifications. This includes reporting of the positions of own force assets.

c) Sense-making. The new technology displays information and provides tools to analyse (process) intelligence in support of understanding the situation. This is used to identify and prioritise incidents in the environment to be addressed.

d) Intelligence Analysis. Despite not pertinently being shown in the DOODA model, the intelligence analysis is required to process all the additional information in support of sense-making, decision-making and planning. This supports the process of joint intelligence preparation of the operational environment (JIPOE), which supports commanders in planning and developing and selecting options.

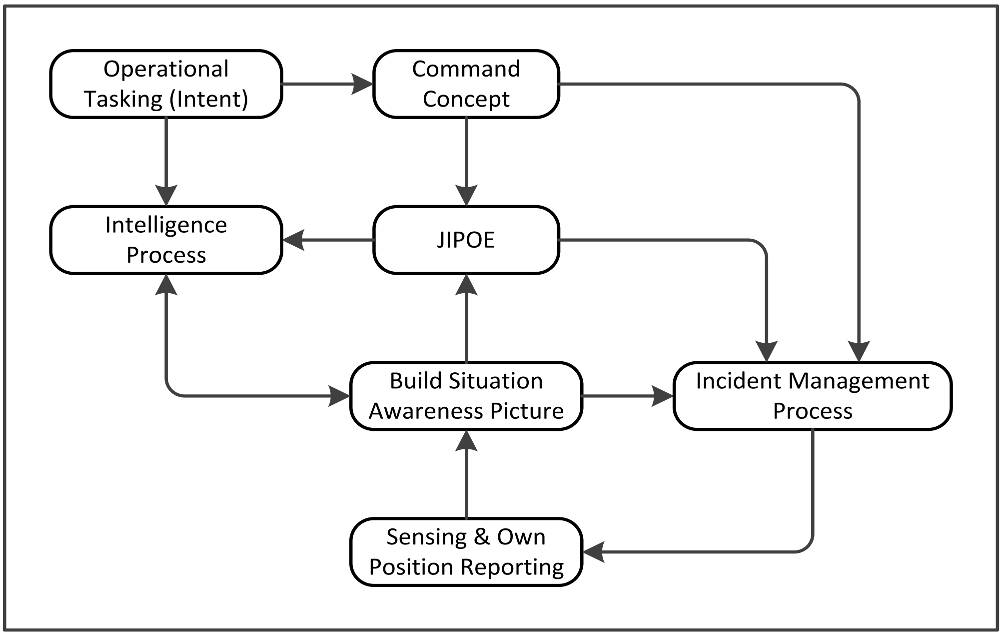

Figure 34: Functional Model for Border Command and Control

e) Incident Management. Since border safeguarding is not a purely military operation with close interaction with other departments, the function of incident management includes the activities of planning and selecting options. Planning relies on understanding the situation, and on the intent and state of available resources. This is converted to orders and is distributed to the relevant resources for the required action.

The main functions of Figure 34 are expanded into a number of sub-functions, identified in the ADH in Figure 33, to derive the interactions between different elements, as seen in Figure 35. These functions are executed by commanders and their staffs in the system. They need to be supported by processes and technology. The same colour scheme is used as in Figure 33, where yellow depicts the current capability, and blue the contribution of the new technology.

Next, the object-related functions of the ADH are combined into another functional model, as seen in Figure 36. These are the functions to be performed by the technology in support of human work. This gives an indication of the integration and information flow between the different subsystems. Information from the CWA is used to adapt the functional model to the specific requirements of the C2 system with the technology introduced.

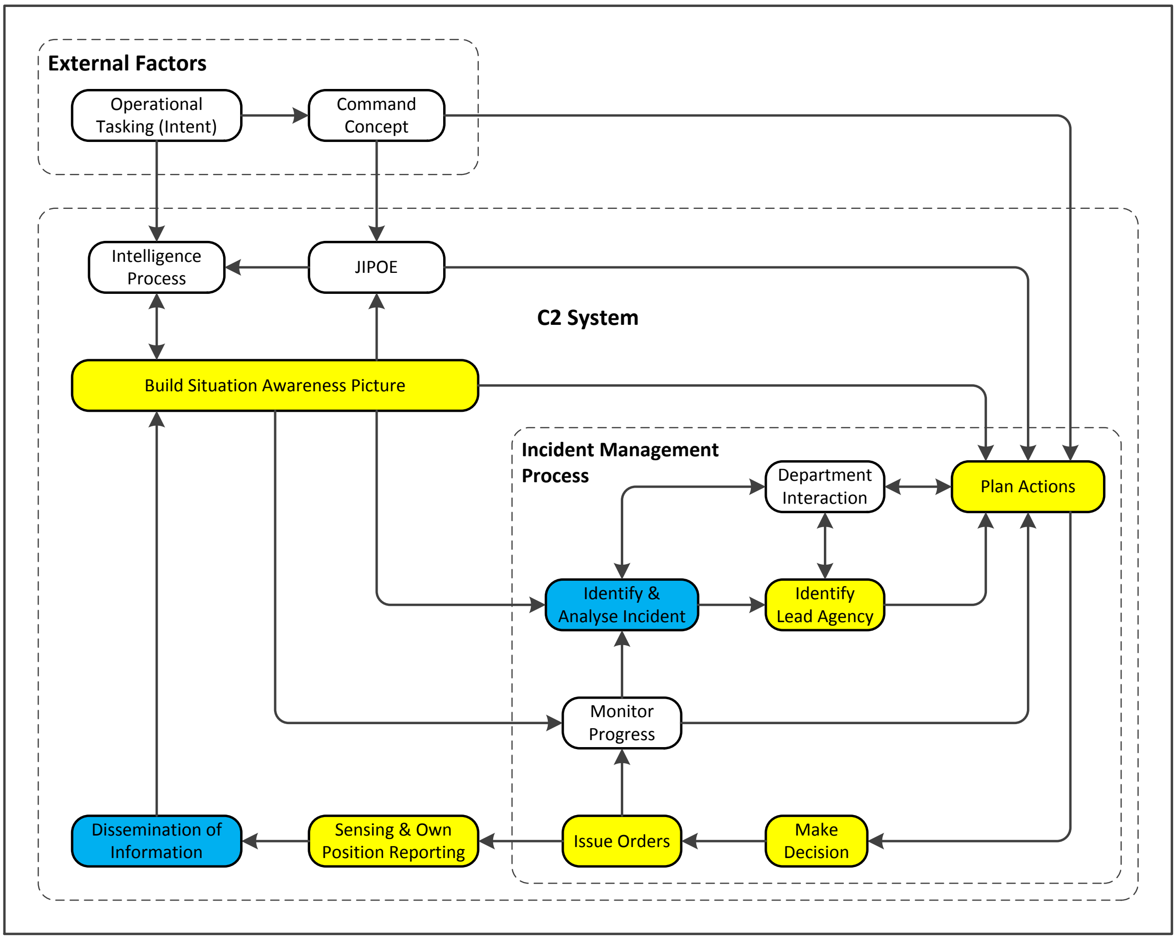

Figure 35: Detailed Command and Control Purpose-related Functions for Border Safeguarding with New Technology

5.3.4.2 Causal Loop Diagram

5.3.4.2.1 Process

The dynamic hypothesis for SD modelling in this demonstration is that the proposed collaboration technology will lead to more information being available and improved own-force reaction to incidents, but will require additional Intelligence analysis tools in the system to utilise the extra information.

The CWA, with focus group inputs (Figure 33), has been used to develop different system models (Figure 34, Figure 35 and Figure 36) for C2 in border safeguarding with a new collaboration technology. These models are the basis for identifying important variables and the causal loops between them in the system. The relationships between the lower levels of the ADH are used to identify possible causal links, while the higher levels of the ADH are used to understand the relationships. The elements in the values and priority measures layer of the ADH provide guidance in identifying the variables in the CLD. The purpose related functions show how the variables inter-relate, while the functional models indicate how the loops connect.

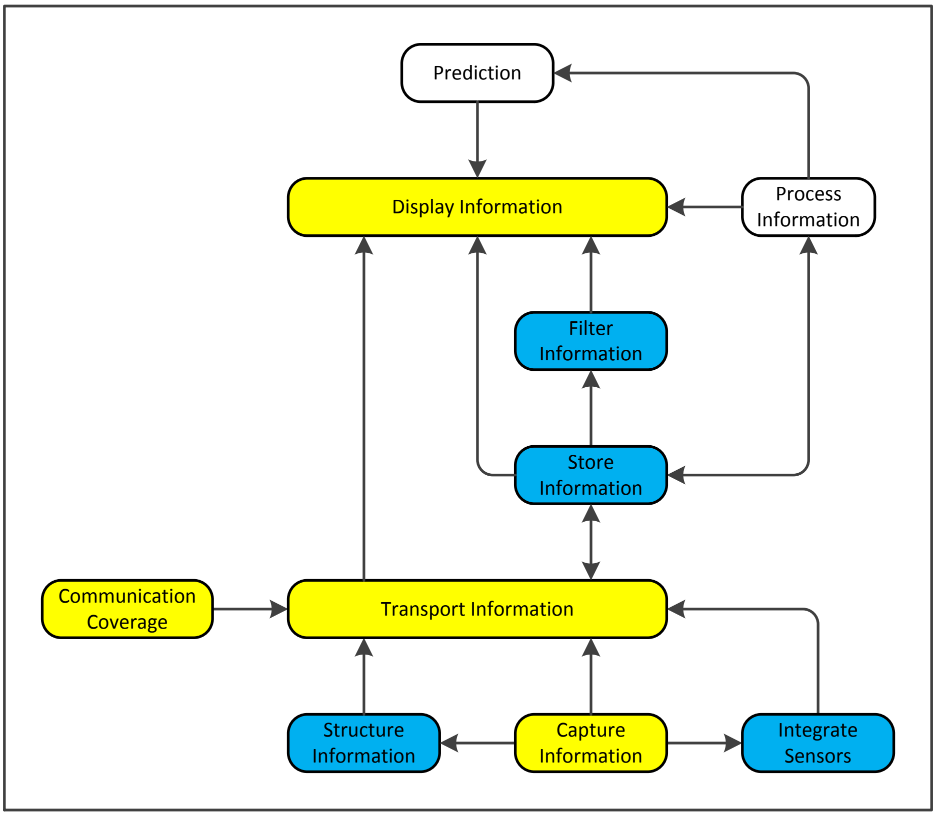

Figure 36: Object-related Functions of Command and Control Model for Border Safeguarding with New Technology

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5.3.4.2.2 Reference Causal Loop Diagram

A reference CLD for the C2 system in border safeguarding, as seen in Figure 37, was constructed from the understanding gained from the ADH and the resulting models (specifically Figure 33). As the WDA focuses on the effect of the Cmore on the system, the reference CLD is not so obvious. The value and priority measure elements (situation awareness and action) have to be augmented by the purpose-related functions (information, decisions, plans/orders). The main input to the C2 system is incidents and the output is action. The reference model also reflects the basic OODA loop variables, with the causal relationships between them, without the impact of the new technology.

The effect of interacting with criminals committing cross-border crime is also captured through the "incidents" variable. Military action should reduce the level of incidents, while incidents are a source of information. New incidents occurring will change the current situation to reduce the level of situation awareness developed. The three primary loops identified in the CLD are the following:

a) Own Force Feedback Loop. The outer loop uses available information (positional and status) to improve situation awareness and support decisions that direct own-force action through planning and orders. This reflects the basic OODA loop, and is a reinforcing loop (R1).

b) Criminal Action Loop. Observed criminal action (through sensors) adds to the available information to support situation awareness and decisions. The resulting own-force action addresses the criminal action and reduces it, which results in a balancing loop (B2).

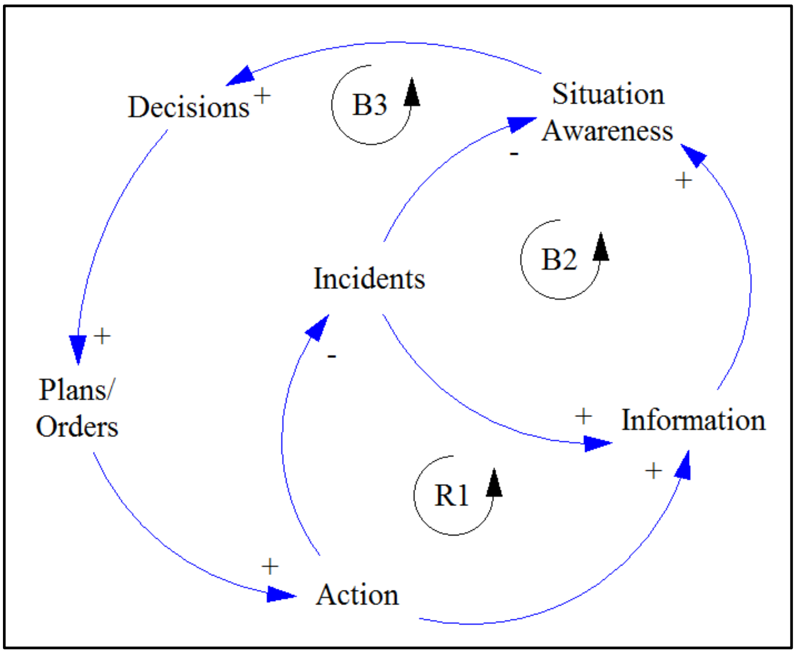

Figure 37: Causal Loop Diagram Reference Model for Border Safeguarding

c) Complexity Loop. Criminal incidents change the situation and reduce the developed situation awareness. This reduces the ability for effective action against the criminals and provides another balancing loop (B3).

5.3.4.2.3 Causal Loop Diagram for New Technology

This demonstration of the modelling methodology aims to assess the impact of new technology on the C2 process. The Cmore system enables more (human) sensors to gather information through smartphones. The Cmore displays in the command centre manage improved situation awareness displays and order distribution, for the better coordination of actions. The contribution of the capabilities in Cmore from the ADH (Figure 33) is added to the reference CLD in Figure 38.

Firstly, the elements in the values and priority measures related to Cmore (blue blocks) are added to the reference CLD. They are “Comprehension”, “Synchronisation”, “Collaboration” and “Community participation”. The links between the new elements and the existing elements in the reference CLD are determined by inspecting the ADH. The purpose-related functions linked to the new elements are scrutinised to determine their relationship with the existing reference CLD elements. For example, “Synchronisation” is linked to “Make decision” and “Plan actions”, which in turn are linked to “Control of information and resources” (or “Action” as implemented in the reference CLD). Therefore, “Synchronisation” is linked to “Plan actions” and “Action” in the CLD of Figure 38. This process is repeated for all the new variables. Logic and common sense are also applied to ensure that the CLD is useful to the stakeholders.

For further improvement, the purpose-related functions in the ADH of Figure 33 are analysed to determine the possible contribution of the CLD. The elements (blue blocks) identified to contribute to the CLD are “Analysis”, “Intelligence”, and “Information dissemination”. The links in the ADH are again analysed to determine their relationships in the CLD. For example, “Information dissemination” is linked to “Control of information and resources” (or “Action” as implemented in the reference CLD) and to other blocks that share relationships with “Information”. Therefore, “Information dissemination” is linked to “Action” and “Information” in the CLD of Figure 38.

The next step is also to look at the lower levels of the ADH of Figure 33 to identify further elements that can contribute to the CLD. The same process as discussed above is used to derive their relationships with the existing elements. This is repeated until the CLD adequately represents the system and problem situation for the stakeholders to discuss. Through this process, the ability of the WDA to support SD modelling is demonstrated. Care must be exercised not to make the model overly complex, as this will diminish its utility in supporting the understanding of the stakeholders. A rule of thumb to be applied on the number of elements in the CLD is seven plus or minus two (Miller 1956). As long as SME understand the diagram, the correct level of complexity is achieved.

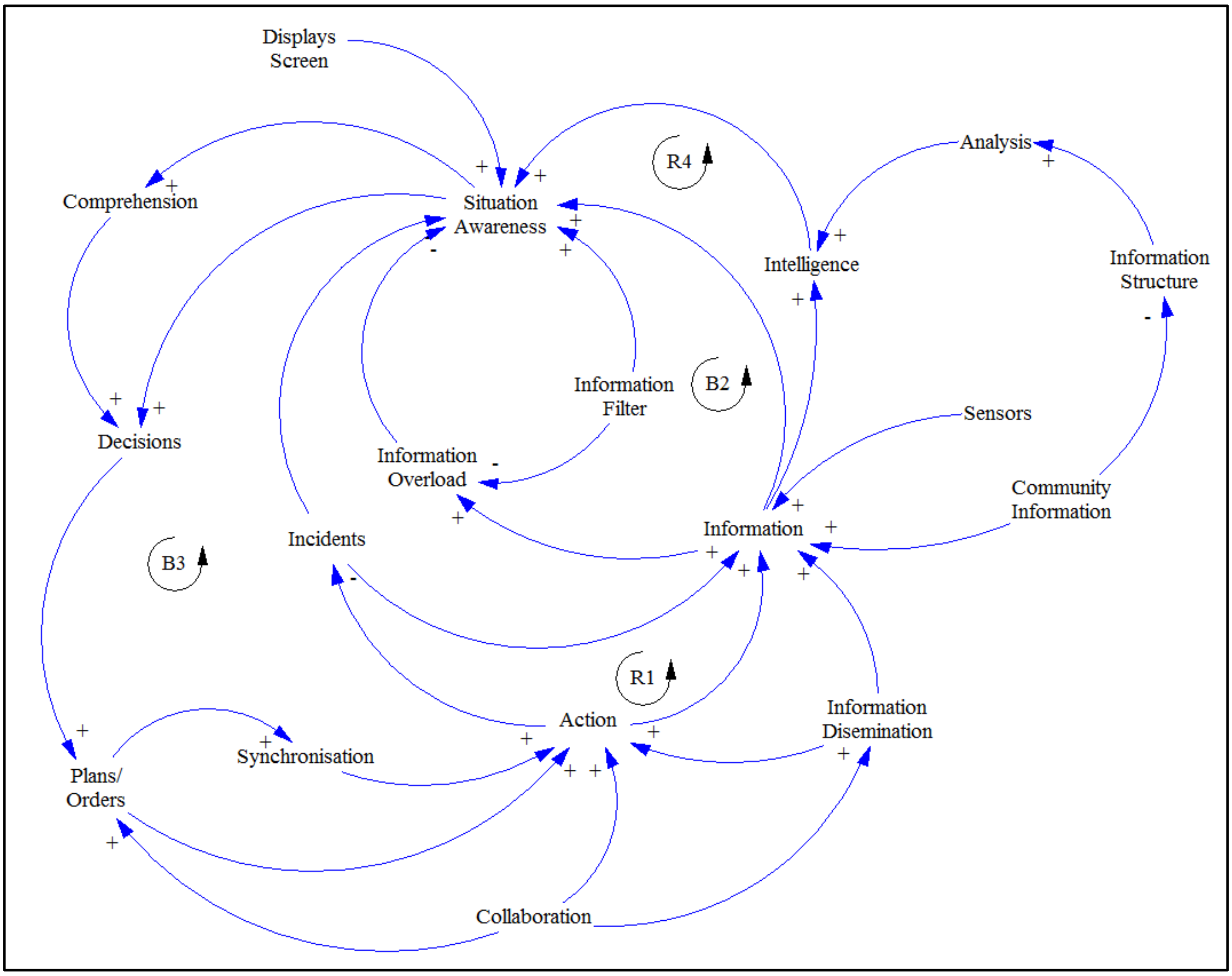

Figure 38: Causal Loop Diagram for Effect of New Technology on Border Safeguarding

The key loop to implement the new technology identified from the CLD in Figure 38, in addition to the initial three from the reference model, is the intelligence loop (R4), where the available information is analysed to improve situation awareness. The intelligence derived from available information will enhance the level of situation awareness gained through Cmore. This supports decisions on plans, with the assistance of situation awareness display screens and other planning tools.

Cmore also provides the ability to distribute orders and disseminate information to coordinate actions of own resources. However, this analysis focuses on using analysis tools to generate intelligence in support of situation awareness. Other issues identified from the focus group discussion are also added to the CLD. These include STS variables such as the structure of the organisation, and the effect thereof on collaboration and trust.

Collaboration and decision making requires trust, which is defined as the degree of a belief about the behaviour of other entities to cope with uncertainty. Trust is not taking risk per se, but rather it is a willingness to take risk. Trust is based on expectations of how another person will behave, based on that person's current and previous implicit and explicit claims. Trust is a perception and shapes behaviour. The difference between the entities perceptions and reality must be reduced (Mayer et al. 1995, Chan et al. 2013, Cho et al. 2011, Alberts 2011). In addition, information gained from sources outside of the military, with no training and experience in operations, requires structuring.

5.3.4.3 Stock and Flow Diagram

A reference SFD is constructed, as seen in Figure 39, as well as models of the C2 system's behaviour without the effect of the new collaboration technology. The structure of the SFD is derived from the information flows in the C2 model from Figure 35 and relationships identified in the reference CLD in Figure 37. As the dynamic hypothesis for this SD modelling is that the proposed collaboration technology will lead to more information being available and an improvement in own force reaction to incidents, this SFD focuses on the accumulation and application of information. Therefore, the stock that flows through the model is “information”. Information is gathered, distributed, processed and displayed to support planning and decision-making. These are related to the basic steps of the OODA loop.

Variables are added to represent the external environment as well as to match the variables' dimensions and units. The purpose of the SFD is to support simulations that assess the impact of the technology's different capabilities on the dynamic behaviour of the *whole* system. The details of the variables in the model are the following:

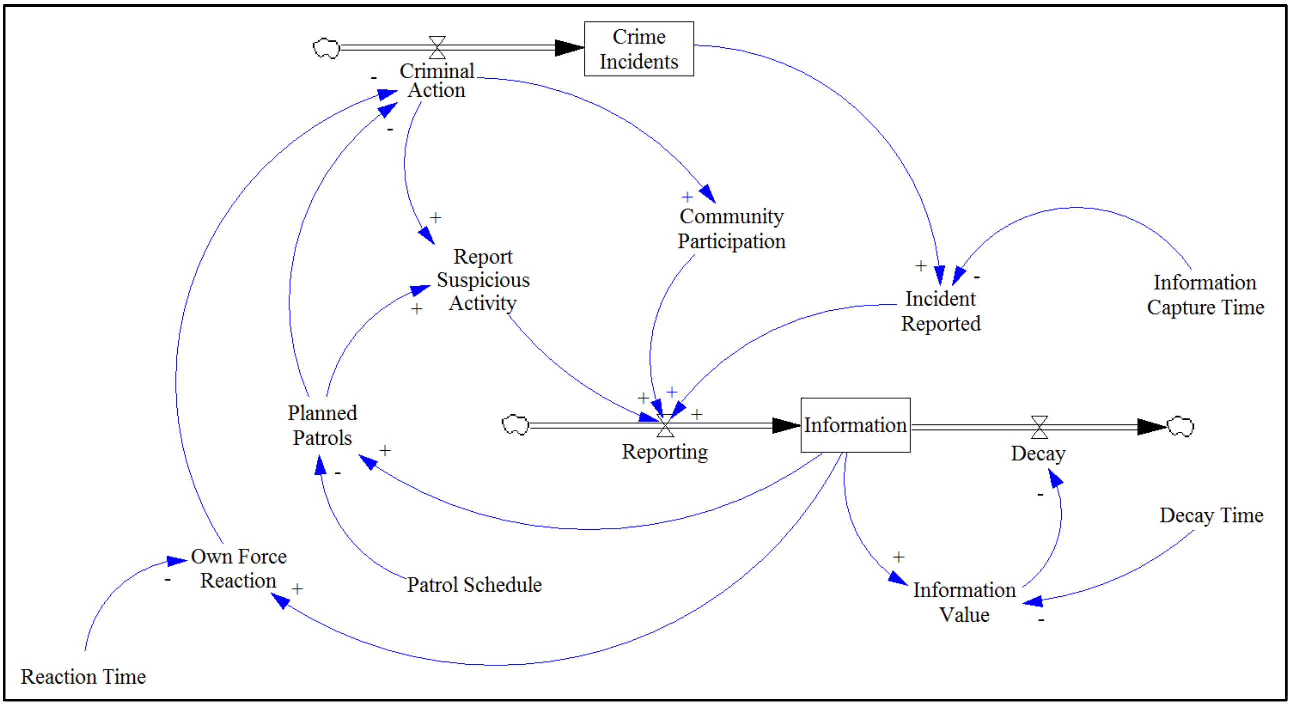

Figure 39: Reference Stock and Flow Diagram for Border Safeguarding

a) Crime Incidents. The stock and flow for border crime Incidents relates to the external environment for the C2 system in which to operate. Criminal action leads to the build-up of incidents, which need to be attended to by own forces. In this model the crime incidents build up, and are not depleted. Crime incidents that have occurred cannot be “undone”, and only serve as a source of information as they are reported to the various authorities.

b) Information. Information on border incidents is gathered through suspicious activity reported by planned patrols, the local community and from crimes reported. This leads to an accumulation of information in a database, which has a limited period of value. Therefore, the stock of information decays over time. The information leads to situation awareness in support of planning and decisions on patrols along the border or reaction to incidents in progress.

c) Own Force Reaction. If the available information indicates that a crime is in progress, own forces can take action. However, this takes time to set up and to move to the location of the crime being committed.

d) Planned Patrols. The intelligence and situation awareness is derived from the accumulated information support planning of patrols in the operational environment. Patrols may affect criminal action through the visibility of own forces as well as through the reporting of suspicious activities.

The CLD in Figure 38 identified collaboration as one of the variables affecting the action of own forces as well as the gathering of information. This is added to the SFD shown in Figure 40. The aim of the new technology is to enable human operators in the operational environment to be sources of information, perform intelligence analysis and assist in situation awareness. This includes reporting of own actions and statuses as well as the observation of incidents. The new technology also assists commanders in analysing the available information.

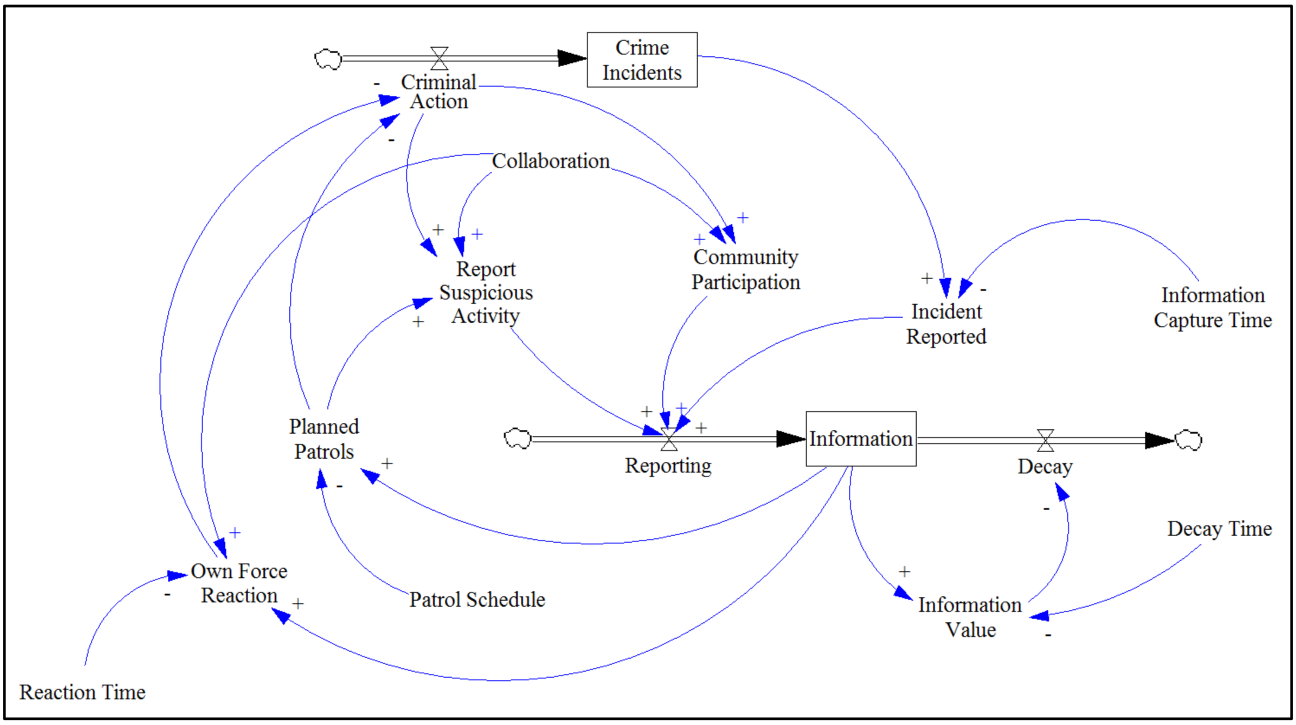

Figure 40: Stock and Flow Diagram for Effect of New Technology on Border Safeguarding

5.3.5 Demonstrate Artefact Ability in Context to Solve Problem

5.3.5.1 Inputs

SD simulation with the SFD from Figure 40 demonstrates the ability of the model to assess the impact of collaboration technology on the complex STS. The unit of the stocks is “Information” and the time unit is “Day”. The behaviour of the system is analysed to understand the requirements of the technology artefacts to be implemented as well as the impact thereof on the complex nature of the STS. The equations, explanations and assumptions used in the SFD for SD simulations are provided in Table 9.

The model input values and relationships between the variables were derived from focus group inputs. Even though they do not represent perfect values, they are sufficient at this stage of the modelling methodology to stimulate stakeholder discussions. All the flow control variables are forced positive with the “MAX” function in Vensim®, as information cannot be negative. At this stage no actual data is available, and the simulation outputs are used during stakeholder discussions.

Table 9: Variable Formulae for Border Safeguarding System Dynamics Simulations

Variable	Equation	Explanation
Criminal action	5 – (Reaction Force Awareness – Planned Patrol Awareness/2)	Five incidents occur per day. This is affected by the reaction force and patrols. Patrols are 50% effective.
Report suspicious activity	(Criminal Action + Planned Patrol Awareness)*Collaboration/3	This is the feedback from patrols of observed criminal actions, which is assumed to be a third. This is improved by collaboration.
Community participation	Fixed Delay ((Criminal Action*Collaboration)/3, Collaboration/2, 0)	The local population may also report criminal activities, which are assumed to be a third. Due to the processes to be followed, this is delayed by 2 days before being captured in the C2 system. A collaboration system that is available to the community may improve this.
Incident reported	Fixed Delay ((Crime Incident Information/Information Capture Time), Information Capture Time , 0)	The criminal incidents reported to the police also arrive in the system after an average delay. The value of the information is reduced due the capturing time delay.
Reporting	Report Suspicious Activity + Incident Reported + Community Participation	All sources of information are captured in the C2 Information system.
Information decay tempo	C2 System Information/Decay Time	Older information is of less value. The average decay time is assumed to be 0.5 days
Decay	Fixed Delay ((Information Decay Tempo, 0), 1 , 0)	The accumulated information starts diminishing in value after one day.
Planned patrol awareness	C2 System Information/Patrol Schedule	The scheduling and planning of patrols reduce the information available on current events.
Reaction force awareness	Fixed Delay ((C2 System Information/Reaction Time)*Collaboration , Reaction Time, 0)	When a criminal action is identified and requires reaction, time is still required to initiate, resulting in a loss of awareness due to the delays. This can be improved through collaboration.

5.3.5.2 Crime Incidents

The level of border crime incidents, as affected by the C2 system over the simulation period, is provided in Figure 41. Simulations were conducted with the contribution of the new collaboration technology, set to dimensionless values of 1 (no collaboration technology), 2 (limited collaboration technology) and 3 (enhanced collaboration technology). The simulation output indicates that in increasing the contribution of cognitive support technology, the incidents occurring are resolved in a shorter period to achieve a lower incidence (intensity) of incidents.

5.3.5.3 Information

The level of information in the system initially increases, as seen in Figure 42, because the new collaboration technology enables human operators to act as additional sensors. They report their positions and statuses as well as their observations on criminal activities. The oscillations in the level of information due to higher collaboration are because of the delays in the system becoming more prominent. However, the total accumulated information decreases, which is counterintuitive. The main reason for this is the increased effectiveness of the C2 system, to enable effective reaction to criminal behaviour, which curbs the criminal activity and reduces the number of incidents. As incidents are the main source of information, fewer incidents reduce the information available for situation awareness and decision-making.

5.3.5.4 Own-force Reaction

The level of own-force reaction, because of the situation awareness available to make decisions on actions, is shown in Figure 43. Again, the contribution of the new technology is clear from the amount of information available, and from the intelligence analysis support. A similar oscillation pattern to the information graph (Figure 42) is visible here. This is mainly due to the delays in the whole system. Another interesting feature is that the graph displays a level of equilibrium achieved in the system.

This is when the information in the system enables criminal activity to be addressed as soon as it occurs. This shows the requirement of effective intelligence to be ahead of the adversary in the OODA loop.

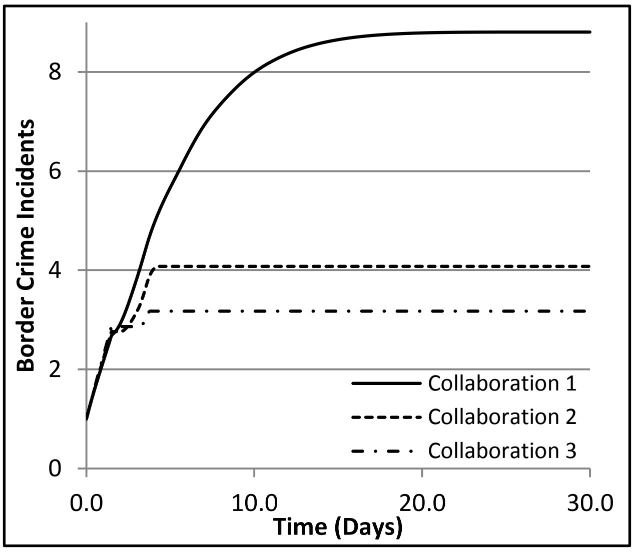

Figure 41: Level of Problem Situation

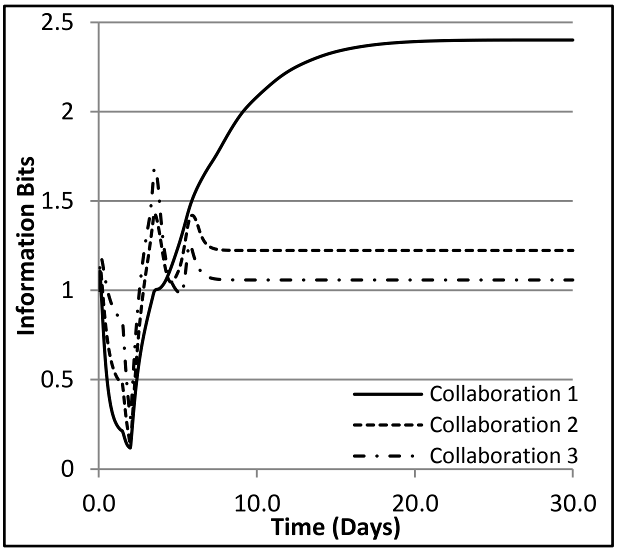

Figure 42: Level of Information

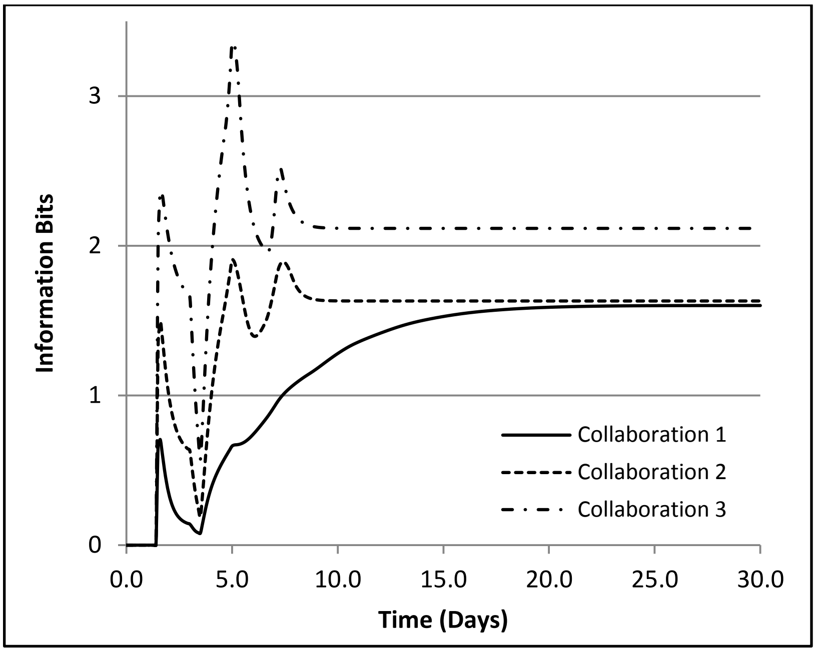

Figure 43: Level of Situation Awareness for Own Force Reaction

5.3.5.5 Conclusion

Despite using parametric SD simulations, the output indicates where and how the new collaboration technology will influence the system. Knowledge gained from this exercise can assist in planning experiments with the new technology in the C2 system. This should also be used to identify parameters for measurement with predicted expected values. The mode observed in the last two graphs indicates an overshoot in S-shaped growth, which is the result of delays in the feedback loops, causing an oscillation around the carrying capacity.

5.3.6 Evaluation to Determine Ability of the Artefact to Solve the Problem

5.3.6.1 Confirmatory Focus Group

The output of the SD modelling and simulations for this case study were discussed during a confirmatory focus group, consisting mainly of the same participants who participated in the exploratory focus group. The aim was to assess whether the models and SD simulations make sense and to understand the requirements for implementing the new technology in a C2 system. As per the modelling methodology developed in this thesis (Figure 32), this step should entail performing field experiments. However, this case study culminates with a confirmatory focus group only due to the time constraints of the project. A subsequent case study will employ the field experiments to gather empirical data.

Despite attempts to maintain the same focus group members as for the exploratory focus group, not all could make it and a few additional members attended. Thirty minutes of the planned duration were used for presenting the process, models and the simulation results to the focus group participants. These served as topics for the discussions, and the focus group attendees were asked to comment on the various model diagrams and simulation output graphs. The details captured during the focus group discussions are provided in Appendix B.2 for improvements to the models. A brief summary of the key aspects are as follows:

a) Cognitive Work Analysis. Only the link between "Decision support" to "Filter information" was identified as missing in the ADH in Figure 33.

b) System Models. The following issues were identified with the functional flow diagrams, and are provided in Figure 35 and Figure 36:

    i) Link "Sensing and Own-position reporting" to "Build SA" in Figure 35.

    ii) Take "Identify lead agency" out of the "Incident management process" to a higher level. In this diagram the "Lead agency" seems to be isolated inside the military system in Figure 35.

    iii) The military member of the focus group noted that the models seemed more complex than how C2 is performed through standardised processes.

c) System Dynamics Models. The following issues were identified with the elements in the CLD in Figure 38 and the SFD in Figure 40:

    i) The concept of information flow through the model was difficult to grasp. This should rather be related to awareness and not level-of-action in the model.

    ii) Change following names in Figure 40:

        - "Own-force reaction" to "Reaction-force awareness".
        - Add "Awareness" also to "Planned patrols".
        - Change "Information value" to "Decay tempo".

    iii) The impact of different types and quality of information on the system was not captured by the model, and was identified as being lacking.

    iv) Initially the group had difficulty understanding the SD models.

d) Simulation Graphs. The following issues were identified with the simulation results of selected stocks and variables (Figure 40), as presented in Figure 41, Figure 42 and Figure 43:

    i) Discussions lead to questions on the reasons for the oscillation behaviour of the information for decision-making and awareness for own reaction with the contribution of Cmore.

    ii) The effect of time and delays on the execution of tasks was identified as a parameter for further investigation.

    iii) Questions were asked on how information is utilised in the model and the effect of different qualities.

iv) The members suggested that the graphs should be simplified to assist understanding.

v) The graphs were compared with the scenario of a missing child and the resulting emergency reaction.

vi) The sources of information in the system were discussed to consider the relative importance and quality.

e) Corrective Actions. The following corrective actions were performed to update the models and simulations in preparation for possible experimentation:

i) Link “Decision support” to “Filter information” in Figure 33.

ii) Link “Sensing & own position reporting” to “Build SA” in Figure 35.

iii) Take “Identify lead agency” out of the “Incident management process” to a higher level. In this diagram the “Lead agency” seems to be isolated inside the military system in Figure 35.

iv) Change the following names in Figure 40 as it will improve interpretation and understanding of the models and the simulation results:

- “Own-force reaction” to “Reaction-force awareness”.
- Add “Awareness” also to “Planned patrols”.
- Change “Information value” to “Decay tempo”.
- Change the stock “Crime incidents” to “Crime incident information”.
- Change the stock “Information” to “C2 system information”.

v) Investigate the reasons for the damping, frequency, flattening and dips in the level of information in Figure 42 and Figure 43 with additional simulations.

vi) Describe and indicate the underlying assumptions better.

vii) Reduce the simulation lines to two per graph to indicate only the system performance with and without the influence of the collaboration technology.

viii) Investigate the implication of different qualities of information.

ix) Simulate the impact of no incident, and only patrol on the level of information.

Despite SD being an unfamiliar and specialised modelling approach, the output simulations enabled the focus group members to gain some understanding of the system's behaviour. This lead to asking questions about certain characteristics of the output graphs. In turn, this helped to focus the analysis and modelling of the system in preparation of field experiments. Even with some flaws present in the model, it can still be used to learn about the influence of the variables on system behaviour. One clear output is showing the effect of delays on the stability of the system, as is predicted by the theory on C2. The models may also be used to investigate the role and contribution of the different sources of information. More data from experiments will improve models and simulations.

5.3.6.2 Updates to Models

The updates to the Purpose-related Functions model from Figure 35 are presented here, in Figure 44. However, this update should not affect the resulting CLD and SFD. The variable of Collaboration represents the ability of the technology to facilitate collaboration in the complex STS. The web-based system enables community members to participate in reporting suspicious behaviour in support of the situation awareness of the reaction force. The aim of the model and resulting simulation is to assess the effect the collaboration technology will have on the overall performance of the system.

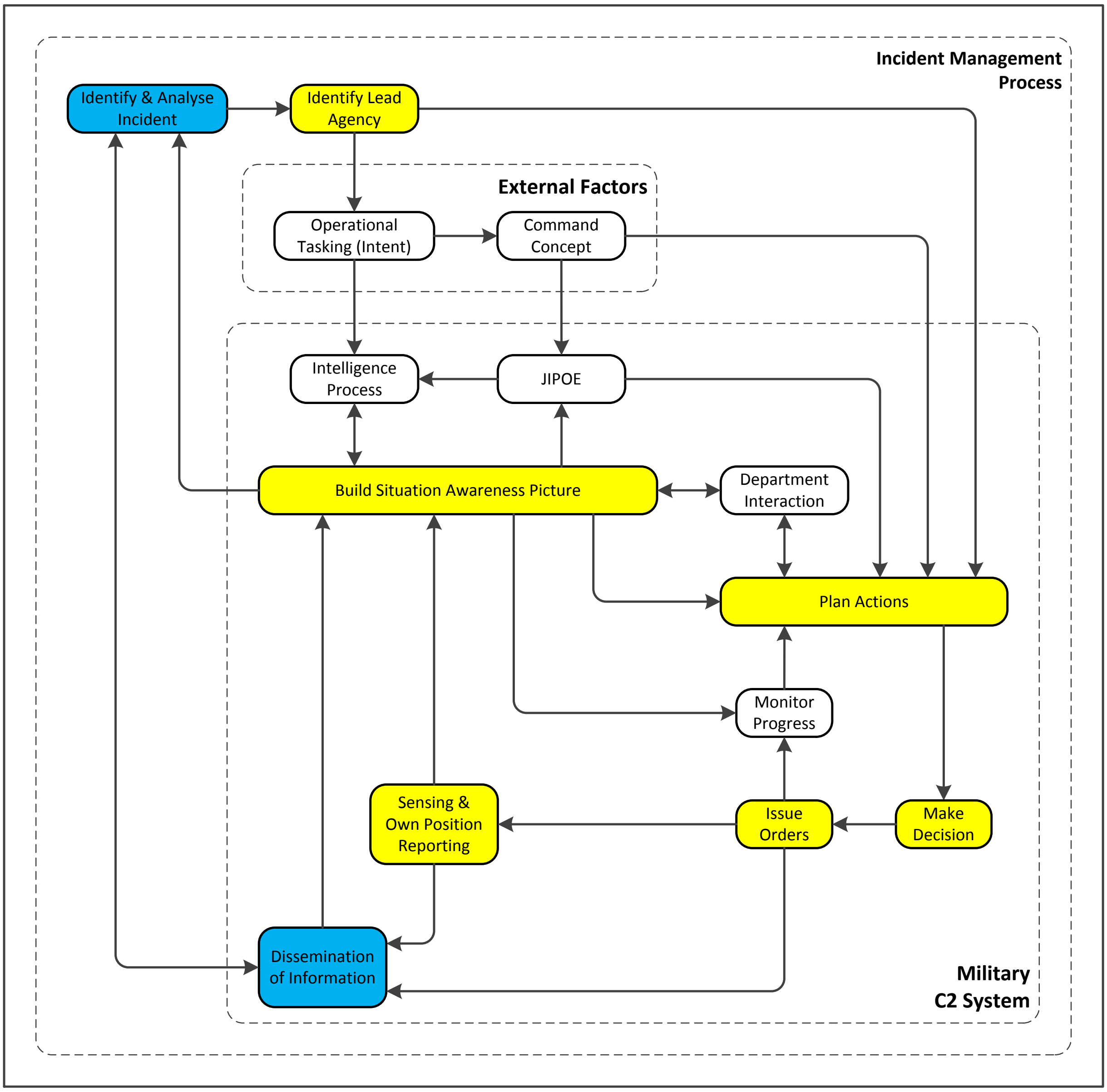

Figure 44: Updated Command and Control Purpose-related Functions for Border Safeguarding with New Technology

This addresses mainly the process and level of authority of the different role players, and affects only the detailed planning of the experiment. Again, the colour scheme of yellow for the current capability and blue for the new technology is used. The updates to the name changes in Figure 40 are shown here, in Figure 45. This should assist in interpreting the model and understanding the simulation outputs. The new names reflect better the objectives and intention of the SFD.

5.3.6.3 Updates to Simulations

As stated before, the stock flowing through the model is “Information” and the time unit is per day. With naming changes, suggested by the implemented confirmatory focus group, the simulation outputs were reanalysed to interpret the meaning of the graph shapes. Firstly, the reaction-force awareness values with and without the influence of Cmore were redrawn, as seen in Figure 46. This improves the interpretation and understanding of the contribution of Cmore.

In order to investigate the reasons for the damping, frequency, flattening and dips in the level of information, the main contribution variables were redrawn on a graph for collaboration (2) of Cmore only. This is shown in Figure 47, and is related to the new, more-descriptive names in Figure 45. Also, the graph focusses on the first 10 days, where all the interesting behaviour in the graph is situated. In this graph the shape of the different variable information levels helps improve learning about the system behaviour and the effect of delays. Initially the Criminal action is in a slow decline due to the patrols limiting free movement. This leads to a decline of the C2 system information, due to less information being available to be reported by the patrols and community participation.

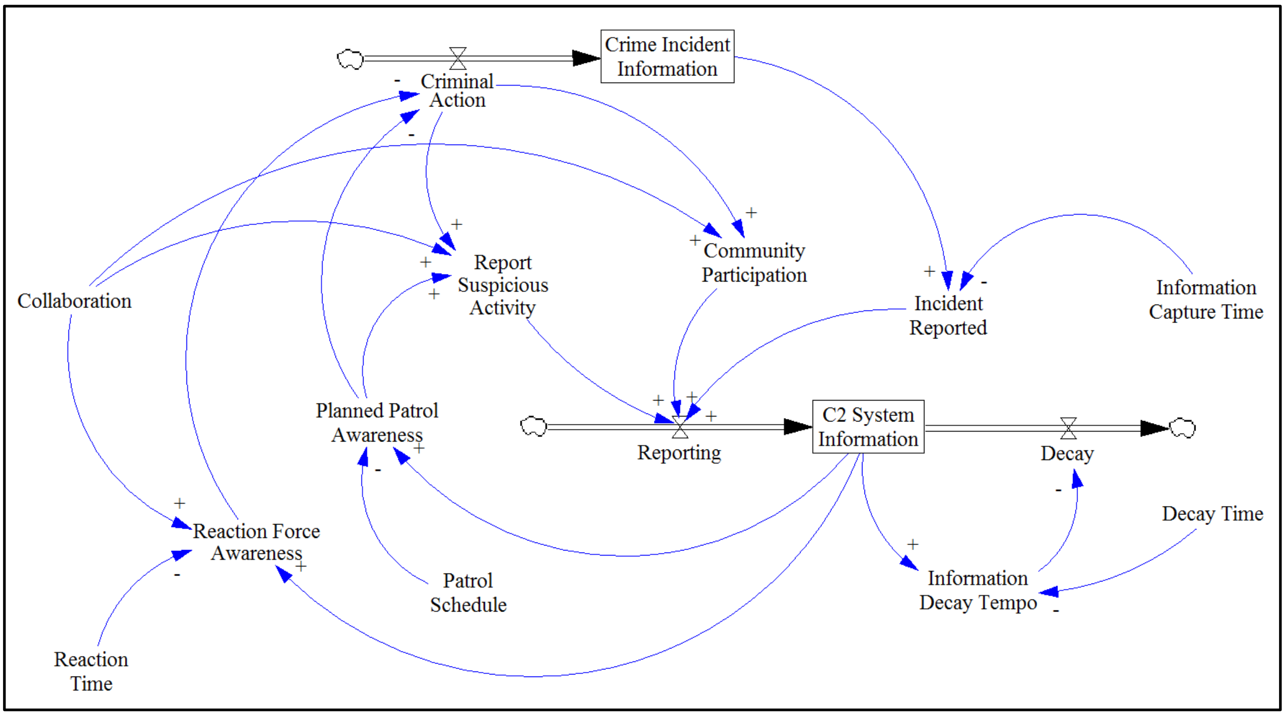

Figure 45: Updated Stock and Flow Diagram for Effect of New Technology on Border Safeguarding

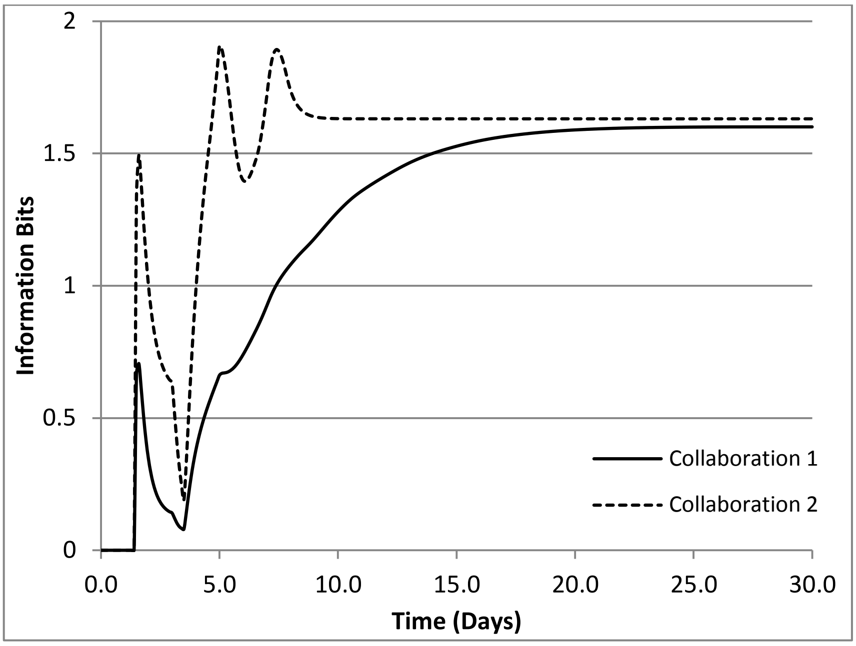

Figure 46: Level of Situation Awareness for Own Force Reaction

After 1.5 days, reaction by own forces is initiated (due to the delay), which stops the criminal action. This, in turn, reduces the information available for collection by the planned patrols and community participation. With no information to react upon, the planned patrols and reaction force awareness are unable to prevent criminal action.

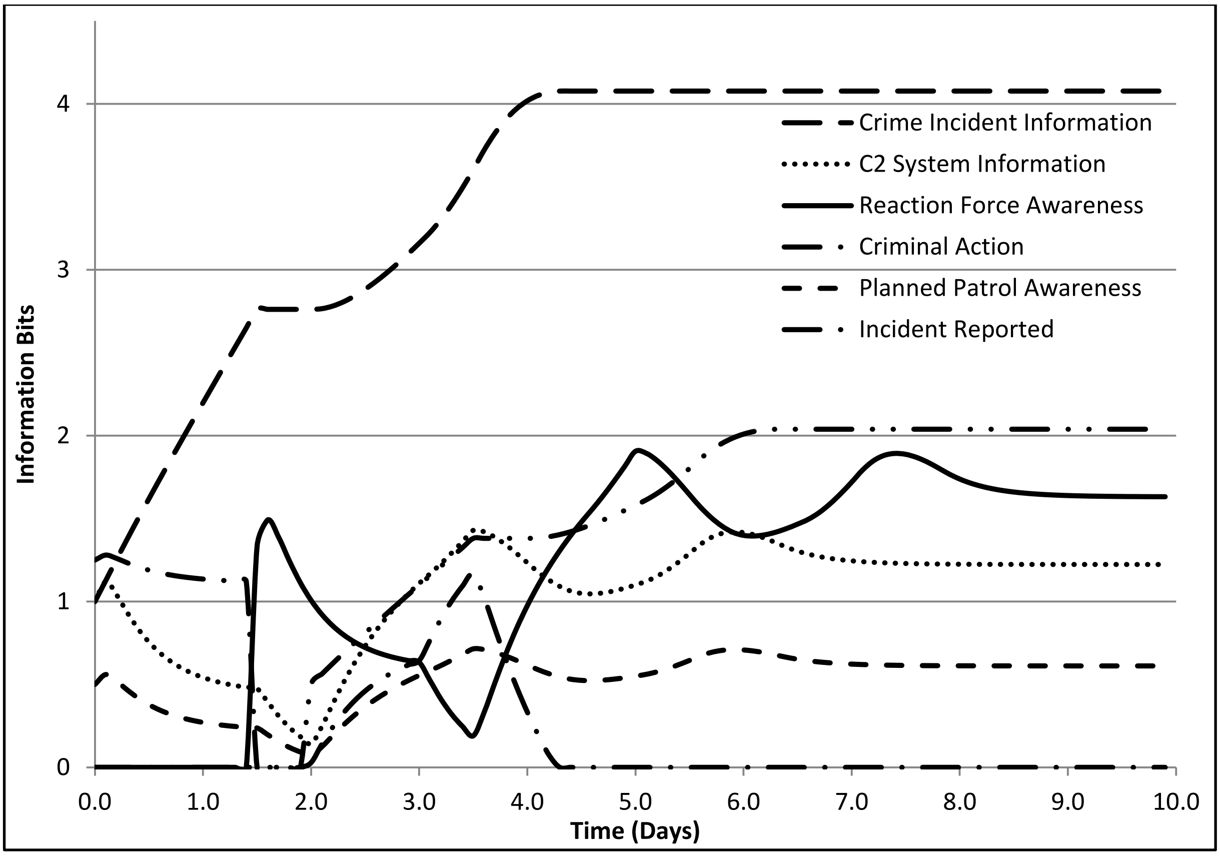

Figure 47: Influence of Collaboration Variables

After two days, criminal action is allowed to pick up again, resulting in the growth of the level of crime incident information. In the meantime the patrols and community may also be starting to report observed criminal behaviour. However, due to the bureaucratic delay of two days for formal reports on incidents to reach the C2 system, the level of information is radically increased.

Since a delay of 1.5 days is required to initiate own force reactions, the criminal action continues to increase. At 3.5 days the reaction force awareness is at a minimum, and criminal incidents are at a maximum because of this. From this point onward, reaction force awareness is supported by formal reports on incidents.

With the sharp increase of reaction force awareness, the criminal incidents are prevented again as they decrease to zero. The information still in the system and delays enables reaction force awareness to increase. The lack of incidents causes the level of C2 system Information to decrease again. Despite no “criminal incidents”, information from past incidents still flows in from past incidents. This affects the effectiveness of patrols and planned patrols. Eventually, when all the information from past incidents is reported and used in the C2 system, all the graphs stabilise at a steady level. The oscillations are mainly due to the different time delays in the system between receiving information and taking action on it.

If no incident occurred, no information will be in the system. This negates the comment from the focus group that information generated by own forces moving around will skew the output graphs. Patrols cannot be planned, as there is no information on criminal activity. The effect of different quality of information was not investigated, due to time constraints and the available information at this stage of the research. This would require an intensive upgrade to the SD models and the information required to support this assumption is not yet available. This could be an opportunity for future research.

5.4 Conclusion

Careful modelling and analysis are required to assist in developing complex STSs. This is applicable where human commanders use a C2 system consisting of decision support and communication to make sense of a situation in support of decision-making, planning, and the distribution of orders. Effective modelling can support experimentation to gain an understanding of the system requirements under diverse conditions.

This Chapter discussed the theory on C2, to motivate it as a complex STS. The theory also demonstrates the modelling methodology and impact of a new technology on a C2 system. The C2 theory also forms the basis for the modelling and analysis in the next two demonstrations.

The role of a new web-based collaboration technology Cmore in a C2 system for border safeguarding is modelled to support SD simulations. The models are used to simulate aspects of the system, which highlights some counterintuitive behaviour that designers and developers of the

C2 system should consider. Also, the effects of delays in the system have been demonstrated. These can be used to guide the allocation of development priorities, and to plan better measurements during field experiments.

The modelling methodology proved useful in modelling a complex STS, in support of simulation and learning. The ADH helped to develop system models and a CLD of the system and problem situation. These in turn supported developing the SFD for simulation of dynamic behaviour. The modelling outcomes and simulation results were verified using a confirmatory focus group. This demonstrated that the models and constructs, developed though the proposed methodology, can assist in eliciting information of the problem situation and the environment from the stakeholders. This proved to be useful to improve knowledge about the problem and solution space, even if the models and simulations were not absolutely accurate.

The hypothesis developed for this research is that a modelling methodology, which addresses human work and dynamic interaction, supports understanding the effect of new technology on complex STSs. The insight gained into the complex behaviour of the system in this demonstration supports the hypothesis of this research, as illustrated by the responses from the focus groups. Very few examples exist in the literature where the dynamic interaction between humans and a new technology for military C2 have been modelled, simulated and verified. This also represents a novel contribution of this research.

To demonstrate further the modelling methodology, the impact of the same web-based collaboration technology, Cmore, is modelled in similar C2 systems. The two other systems are in support of anti-poaching operations and neighbourhood watch patrols. Despite using similar C2 principles, the main differences between the thesis case studies are the operational environments and constraints. This may necessitate focussing on different aspects of the generic C2 models.

6 DEMONSTRATION OF THE MODELLING METHODOLOGY FOR NEW TECHNOLOGY IN ANTI-POACHING OPERATIONS

> "It's better to be boldly decisive and risk being wrong than to agonise at length and be right too late."
>
> Marilyn Moats Kennedy

6.1 Introduction

The aim of this chapter is to demonstrate the ability of the modelling methodology through a second case study, as per the second stage of the research design, seen in Figure 48. Rigour in this research is achieved through demonstrating the ability of the modelling methodology (research artefact) to model the effect of a new technology in a complex sociotechnical system (STS). The demonstration is in the form of a case study, where the impact of the new technology is modelled and evaluated through simulation.

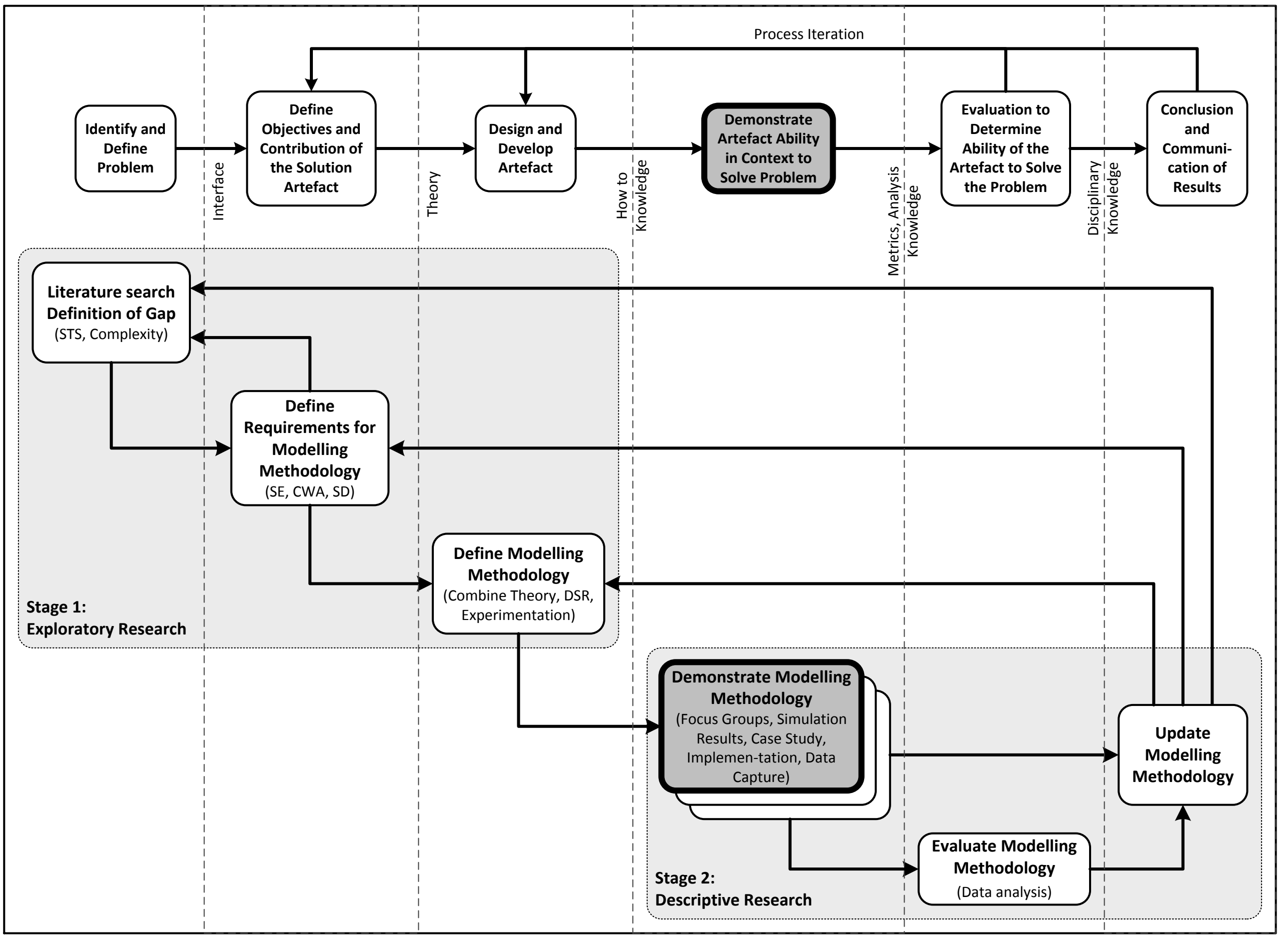

Figure 48: Research Design

This case study addresses the modelling of a technology for collaboration, coordination, information gathering and intelligence analysis in an anti-poaching operations (APO) command and control (C2) system. In principle, this system is similar to a military-type C2; however, the civilian organisation and conservation operational environment have different constraints than purely military operations. This theoretical information is used to initiate modelling of the STS.

This chapter firstly discusses the available literature on the operational environment of APO and the supporting C2 system. The aim is to capture the high-level requirements and constraints of the complex STS where a new technology will be introduced to address shortcomings. Using the methodology from Chapter 4, the C2 system for APO with the new technology is modelled, assessed and demonstrated through computer simulation. The resulting models and understanding of the system are evaluated during a field experiment and demonstration of the technology. Empirical qualitative data is gathered on the use and results of the new technology to be compared with the models and simulation outputs, in order to determine the utility of the modelling methodology.

The collaboration technology, Cmore, is similar to what was developed for a military C2, as modelled in Chapter 5. Since a C2 for APO is a complex STS, the modelling methodology should be able to determine the effect of new technology on the whole system. This implementation of the methodology depends on interacting with the people in a conservation system to assist in determining the functions, constraints and problems to be modelled.

The aim of this case study is not to solve the rhino poaching problems experienced in the Kruger National Park (KNP). Rather, this study develops models of the C2 system in support of APO to assess the enhancement of the system by introducing a new technology.

6.2 Case Study Context

6.2.1 Kruger National Park

The KNP covers almost 2 million hectares (about the size of Israel) of a vast and challenging topography that consists mainly of a heavily forested landscape of mixed woodland and Mopani bushveld. On the 356 kilometre eastern border with Mozambique, the Lebombo Mountains make for rugged terrain that is difficult to patrol and that enables rhino poaching teams to slip in and out of the park often undetected. In an effort to cover more terrain in support of the rangers, South African National Parks is employing sophisticated surveillance technology from public and private military firms (Anderson & Jooste 2014, Lunstrum 2014).

6.2.2 Poaching

The Kruger National Park (KNP) is South Africa’s most iconic and visited protected area because of its abundance of fauna and mega fauna, specifically the "big five". South Africa also holds 73%

of the world’s remaining rhino population, with most of these in the Kruger (Emslie et al. 2012). This makes the KNP the world’s single most important rhino conservation site. Despite many decades of good growth rates, 2008 marked a sharp increase in rhino poaching incidents, which grew to the unprecedented number of 606 lost in 2013, as seen in Figure 49 (Emslie et al. 2012, Lunstrum 2014). If the intensity of trend of poaching continues, the white rhino population of Kruger National Park will start to decline by 2016, leading to possible extinction. This may also dent South Africa’s reputation, public image and eco-tourism industry, as well as represent moral obligation issues (Ferreira & Okita-Ouma 2012).

This trend is complemented by a skyrocketing demand for rhino horn from Vietnam and China, despite the illegality of its sale. Rhino horn is mostly popular for its perceived medicinal properties, despite consisting predominantly of keratin. Modern socioeconomic and societal changes in some Asian countries have also led to an increase in rhino horn demand, disassociated with traditional Chinese medicinal uses. The price of the rhino horn varies from $65,000 to $100,000 per kilogram making it roughly twice as valuable as 24K gold. As a result, the rhino poaching and horn trade have transformed into a transnational commodity chain run by major criminal syndicates. Various insurgency militias and resistance groups in Africa are also turning to poaching to finance their operations (Anderson & Jooste 2014, Emslie et al. 2012, Ferreira & Okita-Ouma 2012, Lunstrum 2014).

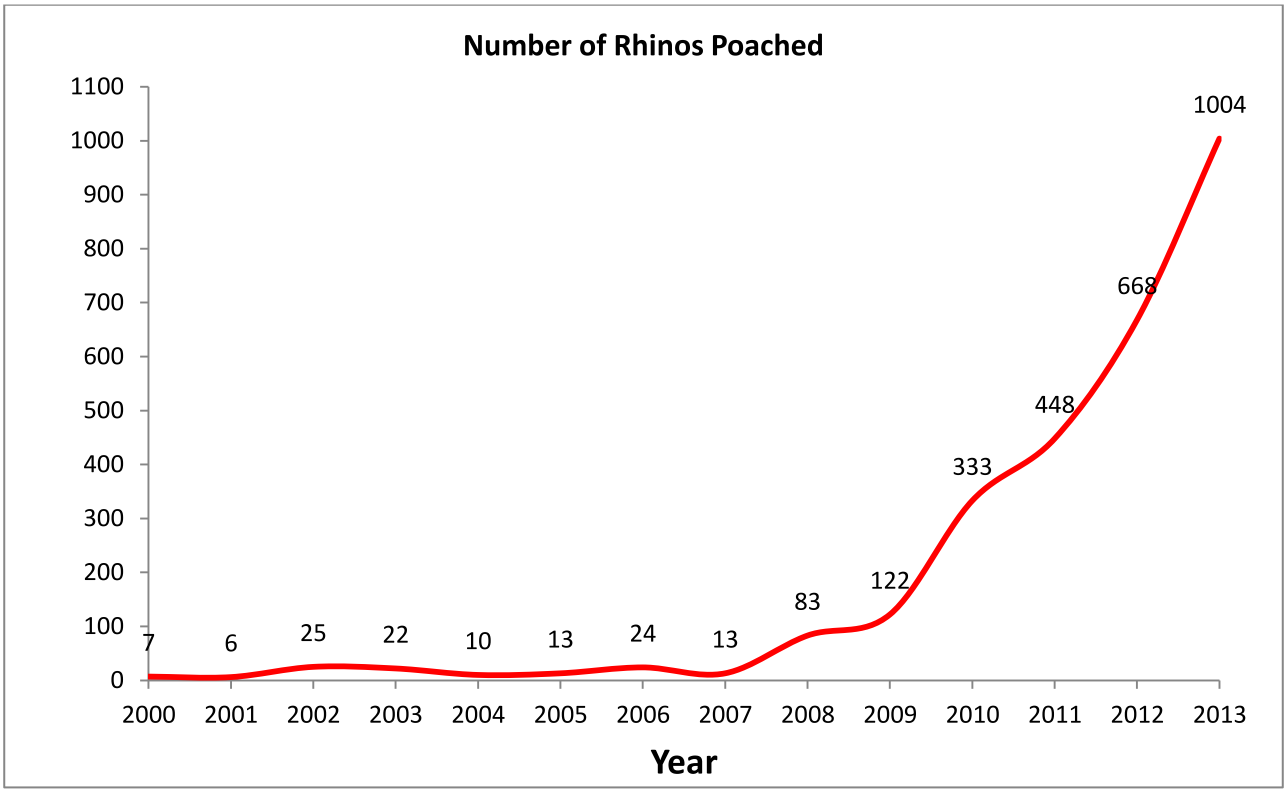

Figure 49: Rhino Poaching Statistics (Emslie et al. 2012)

Poaching teams also tend to be militarised and well trained, armed with a variety of weapons. Due to newly forged links between Asian and Eastern European organised crime networks and those in Africa, poachers are being supplied with high-powered weaponry and advanced tactical gear. This has increased the risk to wildlife rangers who now have to combat these dangerous groups. Poaching profits also encourage the corruption of authorities, which degrades cooperation between various participants in anti-poaching operations. Both the poachers and the anti-poaching teams are willing to engage in deadly force, resulting in a conservation-related arms race. Many poachers use Mozambique to trade and export the rhino horns, as wildlife legislation there is lax and poorly enforced. Another concerning factor is the recent discovery of the first elephant killed for its ivory in a decade (Anderson & Jooste 2014, Lunstrum 2014).

As members of the poaching teams may end up earning between US$1,000 and US$9,000 per kilogram, depending on their position and role, there is no lack of willing participants. Rhino horn is generally light (about 4 kg) and quick to remove by an expert, which means catching an escaping poaching team can be difficult. The resulting rise in rhino poaching has raised concerns for the future of the species, including possible extinction. This may also dent South Africa’s reputation, public image and eco-tourism industry (Department of Environmental Affairs 2010).

6.2.3 Anti-poaching Operations

South African National Parks embarked on an anti-poaching initiative, starting with the appointment of a veteran ex-SANDF general to take charge of operations. His tasks include militarised responses with joint forces and intelligence gathering. In 2013 South Africa’s Department of Environmental Affairs also increased the number of deployed rangers in the Kruger from 500 to 650. Other efforts included improved C2 structures, specialised intelligence analysis units, expanded air capability, canine trackers and night operation enhancements. South Africa has also deployed several hundred South African National Defence Force (SANDF) troops for border safeguarding, which also supports APO. During 2013 the rangers arrested 86 poachers, while 47 died during clashes with South African authorities in KNP (Anderson & Jooste 2014, Lunstrum 2014).

Reversing the poaching trends remains extremely difficult. Patrolling and monitoring the KNP for the growing numbers of armed poachers remains costly and difficult. The poachers also remain highly motivated due to favourable economic conditions for illegal smuggling of rhino horns across international borders. Despite many of the poachers having little training, they often operate at night and employ effective tactics for evading detection and hunting their prey. Most are armed with automatic rifles (e.g. AK-47) which are supplemented with large-calibre hunting rifles. Despite the successes, the number of poachers increases exponentially as well as the sophistication of their resources (Anderson & Jooste 2014). Steps required to improve APO include the following (Anderson & Jooste 2014, Montesh 2013):

a) Community programs to educate and foster local cooperation.

b) Improved training of rangers.

c) Support and resupply of deployed rangers.

d) Counter-intelligence to reduce the information filtering to crime syndicates through the monitoring of suspected staff members.

e) Enhanced mobility of rangers through small planes and helicopters.

f) Technology for sensing abnormal animal behaviour and fence tampering.

g) Revised C2 structures for the rapid relay of information to a central command post to expeditiously reposition and redirect units.

h) Enhanced domain awareness of rangers through unmanned aerial vehicle (UAV) with day and night observation technologies.

i) Information technology to enable the distribution, recording and display of captured information.

j) Intelligence analysis tools for poaching patterns, tip-offs from informants, and biometric and forensic data on wildlife remains, with extensive recordkeeping to optimise ranger deployments.

k) Planning tools to support APO, utilising the available information and derived intelligence.

6.2.4 Command and Control

The C2 process for APO is based on traditional military concepts with voice (radio) communication. An operation centre records all incidents, which typically include gunshots detected, tracks (spoor) discovered and the recovery of carcasses (rhino and elephant). The required action or reaction is activated and monitored from the control centre. A limited texting function currently exists to forward information to pilots and special rangers. The last five points ((g) to (k)) in the list from the section above relate to improvements planned for the C2 system. It is here where a technology such as Cmore can contribute. This case study is also a technology push to improve a current complex STS. The main issues for C2 are the following:

a) Limited Personnel. Currently the total number of staff at the operations centre is less than five, with radio operators working shifts. Many of the personnel perform double roles.

b) Multiple System Interfaces. Many sources of information are available, requiring integration into a common situation awareness picture (SAP). This also includes different communication solutions to distribute information to other participants in the system.

c) Distributed Resources. The rangers that execute the anti-poaching operations are assigned to the different section rangers in the KNP. The section rangers request assistance and share information with the rangers on the ground. Distribution of the common SAP to all the section rangers enhances their own anti-poaching operations.

d) Limited Resources. Only a few aircraft (with pilots) and special rangers are available for reacting to information. The right decision should be made when committing these to an incident.

e) Collaboration and Coordination with Neighbour Reserves. Many neighbour reserves on the border of the KNP form a buffer. These also have anti-poaching operations and are a valuable source of information. Effective collaboration and sharing of information enhances the system.

f) Limited Information. The main source of information is reports of incidents, which include shots heard, spoor found or carcasses found. These are captured into a database for intelligence and trend analysis. The information must be utilised to support decisions on applying resources and planning pre-emptive operations.

The rate of incidents reported is not very high, typically less than five per day. However, quick reaction improves the possibility of success. There are few, but critical decisions to be made daily. These centre on the commitment of resources to a reported incident.

6.2.5 Anti-poaching Operations as a Complex Sociotechnical System

APO can be viewed as a complex STS because it consists of humans interacting with each other in small teams, using processes, structure and technology, as seen in Table 10. The information in this table is a summary of the theoretical and literature discussion above. It takes the same format as that used in Chapter 5 (Table 8).

However, currently the technology utilised is limited. It consists mainly of procedures, radios and manual paper-driven reporting. This analysis focuses on the C2 system supporting APO. The C2 system consists of sensors, a communication infrastructure, situation awareness and decision-support subsystems.

6.2.6 Technological Support Required for Anti-poaching Operations

As with any complex STS, technology can be applied to support or enhance human work. The same collaboration technology, Cmore, as discussed in Chapter 5 (5.2.7), is introduced into the APO C2 system, is modelled as a new technology to be implemented in this C2 system. The focus is on supporting the control room through information analysis and situation awareness. The contributions of Cmore to the APO C2 system comprise the following:

a) Human Sensor. The Cmore mobile and base station can be used to record incidents for distribution to the command centre, other rangers and the SANDF. Modern technology may convert any ranger, tourist or official into a sensor or source of information through web-based technology on smartphones. Information captured on incidents may include text, photo, time, date and GPS location.

b) Information Distribution. Distributing and communicating captured information leads to raised awareness. This, in turn may lead to the increased reporting of incidents.

Table 10: Comparing Anti-poaching Operations with a Sociotechnical System

Complex System	Anti-poaching Operations
Technology (Tools, devices, techniques)	Coordination and control systems utilise automation and mediated interaction in the form of communication, computerised presentation and decision-support systems as an interface for commanders to analyse accumulated information. The ability of rangers to attend to incidents and gather information for Intelligence analysis is affected by the ability of the interfaces to provide the required stimuli.
Human Influence (Social humans with knowledge, skills, attitudes, values, needs)	Individuals and/or teams, consisting of rangers, the SANDF, the police and coordinators interact with one another in a C2 system, with their own ideas, motives and objectives. The operators may be of different social and cultural backgrounds, making interaction and perception complex. Rangers may endure hardships in the field while being deployed, making specific interaction harder to predict.
Work (Task interdependence, unstructured and uncertain Work)	Currently, processes and procedures for sense-making, decision-making are limited due to a lack of technological support, the vastness of the area of interest and the complexity of the situation. This is also affected by risk and uncertainty where the level of activity varies from boredom to crises response. Different tasks require different time scales, from long periods with limited activity to urgent and immediate action.
Organisation (Authority structures)	The organisational and authority structure is different between the rangers and supporting SANDF units. Internal politics and authority over resources also affects reaction to poaching incidents.
Environmental Interactions (situated cognition)	The operational environment is harsh and difficult to predict, with dangerous wild animal, armed poachers, and tourists. Due to the ruggedness and vastness of the area, quick reaction is hampered. Poachers continually and actively attempt to avoid the rangers.
Information (Information and knowledge system)	Data must be converted into to information, and then into knowledge to support situation awareness, understanding and decision-making. Valuable information is available if captured and managed correctly during patrols, intelligence operations or by other sensors.
System Behaviour (Unpredictable, dynamic complex, non-deterministic, emergent)	An APO is dynamic due the unpredictable environment, as incidents, which can be anything, can occur at any time and place. Unpredictable poacher behaviour and ranger responses provide for non-deterministic system behaviour. The data available for situation assessment may be incomplete, with uncertainty in complex environments making awareness of the true state of the work environment difficult. Participants react differently within the operational environment when scared and inexperienced.
Agility (Humans provide agility)	Rangers have to deal with unanticipated events by improvising and adapting, in order to implement contingencies to ensure resident safety.

c) <u>Workflow</u>. All members should be aware of what the legal and suitable actions of the rangers should be at a specific incident. The workflow must be streamlined to reduce time-wasting through unnecessary actions. Good reporting will ensure that the right information quickly gets to the decision makers. The technology can be applied to support operators of the system. This includes tags and automated incident recording to increase the ease and speed of the system in operation.

d) <u>Blue Force Tracking</u>. The tracking of rangers and other assets will enable the control centre operator to keep track of all to ensure their safety.

e) <u>Intelligence Analysis</u>. The recorded information can be analysed to detect patterns of poaching, incidents and crime to highlight problem areas. Web-based technology with supporting tools (software packages) to analyse recorded information on incidents supports anti-poaching intelligence. The analysis tools available are heat maps of incident counts, filtering, map annotations and search capability.

f) <u>Incident Recording</u>. The system enables command centre operators to record all incidents in a standardised database. Every incident must be recorded or created only once. Later it can be updated or information can be added. The workflow must not be labour-, or effort-intensive.

g) <u>Situation Awareness</u>. The control room should contain a situation display of the latest incidents, along with the location of APO participants and crime intelligence on maps of the KNP. Information on the SAP must support making crucial decisions in the operation centre.

h) <u>User Management</u>. The access of users is controlled through accounts with user names and passwords. Different roles can also be assigned different responsibilities and access to data in the system.

i) <u>Response Management</u>. Directions to the allocated incident, if it is suitable for the ranger patrol member to attend, are given. Messages, chat or orders (graphical) are used to direct patrollers to incidents.

This section introduces the concept of APO within the context of complex STS. The possible contributions of technology are also discussed. The next section provides the context of the case study for demonstrating the modelling methodology. New technology must go further than just catching poachers in the act, but must also prevent them from killing animals. A limiting factor of Cmore is its reliance on a high-bandwidth network. Due to the remoteness and ruggedness of KNP, adequate cellular network reception is limited. This has to be considered in analysing the impact of the technology on C2 for APO.

6.3 Case Study Execution

6.3.1 Modelling Methodology

The same modelling methodology (Figure 50), as developed in Chapter 4, is used to model and evaluate the effect and contribution of new web-based collaboration technology (Cmore) in an APO C2 system. The technological capabilities of Cmore described in the previous section may enhance APO to stem the poaching tide. The degree of success and contribution of new technology in the complex STS still needs to be understood in support of establishing new operational procedures and policies. The modelling outputs can also support developing a change management process (Rodrigues et al. 2006, Reddi & Moon 2011).

A new technology cannot simply be dumped into a complex STS, with there being an expectation of its smooth adoption, and positive results or improvements. It may result in a waste of time and money if not accepted by the people working in the complex STS. Modelling of the complex STS and the capabilities of the new technology assist in understanding its impact on human behaviour and the dynamics in the system. This understanding is required in planning to introduce the technology, for maximum benefit to all stakeholders.

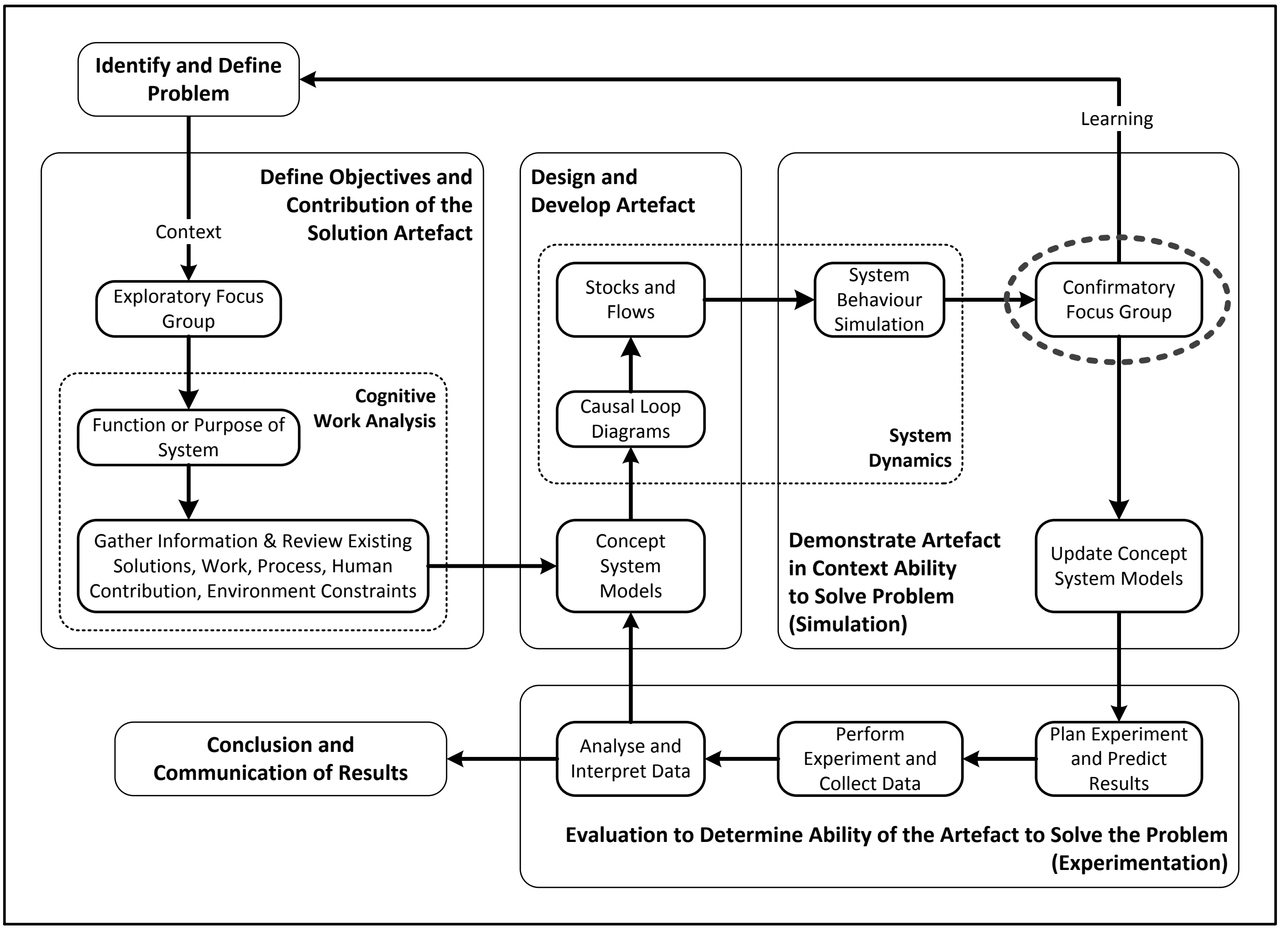

Figure 50: Modelling Methodology for Anti-poaching Operations

It is important to remember that the artefact developed through this methodology is a model of the contribution of the technology to the complex STS. Modelling is done to understand the system's behaviour in a complex context. It may lead to identifying leverage points in the system, to assist in defining requirements, as well as to decisions on a possible implementation project. The detailed execution of the modelling methodology is described in the next sections.

6.3.2 Identify the Problem

Due to the severity and complexity of the poaching problem, an effective C2 system is required to optimise the application of limited available resources. The specific APO-related problems to be solved by the new technology are information gathering, situation awareness in the operations centre and intelligence analysis in support of decisions on the commitment of the limited available resources. This effort is in support of developing a new operations centre for the APO.

The current voice and paper-based reporting system is not very effective because important information can be lost in the post-report recording. Codifying diverse bits of information into a common database difficult and making such information readily accessible through a common and user-friendly interface is lacking. Despite the radio-based voice communication being effective for operational control, it is not suited to capturing all available information on an incident. The often-neglected additional contextual information should improve analysis and interpretation of the incident reports.

The artefact to be developed is a model of the problem situation, of how the new technology will improve or influence the current APO C2 system. The expectation is that the new technology, Cmore, will improve APO as a complex STS, but it is not clear whether it will be readily adopted and what the resulting behaviour of the system will be. Therefore, the aim of this modelling and assessment effort is to determine how this web-based collaboration technology will assist APO efforts. The preceding problem identification is part of the research problem, as experienced in this context. An additional focus is to understand the factors that support a positive adoption of the technology.

The model needs to help identify the changes in the organisation and policies required to effectively implement the new technology. Even if the basic model seems similar to the one in the case study in the previous chapter, the differences in the environmental and operational factors lead to differences in the models and simulations performed.

6.3.3 Define Objectives and Contribution of the Solution Artefact

6.3.3.1 Focus Group

The solution artefact developed through the methodology is a model of the contribution of a new web-based collaboration technology in an APO C2 system. An exploratory focus group with C2 subject matter experts (SMEs), consisting of designers, developers and users of C2 systems, was conducted to gather information on the requirements of a C2 system for this case study context. The discussions and knowledge gained during this focus group are built on the foundation established in Chapter 5. The work domain analysis (WDA) from Chapter 5 (Figure 33) was used as a starting point for this focus group. The questions addressed in the focus group to identify the priorities and inputs to the modelling process are the following:

a) What is the purpose of C2 in APO? (Also look at the different levels of strategy, operations and tactics.)

b) Which C2 functions executed during APO can be supported with Cmore? (Situation assessment, sense-making, decision-making, planning, tasking, control, etc. Is the list complete?)

c) What are the constraints on the success of the C2 system? (Information, resources, situation awareness, accuracy, time delays, etc.)

d) What are the shortcomings in C2 that can be addressed by technology?

e) Where can a new technology such as Cmore contribute to the effectiveness of the C2 system? (Typical capabilities in Cmore are sensing, information distribution, information management, information display, information analysis, planning tools and order distribution in reference to the variables and functions discussed.)

f) How will the technology influence the way people do the work in the system? (Which social, cultural factors may affect technology adoption)

g) What will be the effect of the technology on the timeline of events?

This information was the input to the WDA along with existing literature on APO and C2, as provided in previous sections. A summary of the focus group planning, composition, output and analysis is provided in Appendix C.2.

6.3.3.2 Cognitive Work Analysis

The WDA is performed by constructing an abstraction decomposition hierarchy (ADH) for the work performed in the APO C2 system. The available information from the literature, documents and the interviews was used to populate the ADH, as seen in Figure 51, to determine the relationship between the new technology, old technology and the purpose of the system.

An initial ADH was constructed from literature to support the focus group discussion. This framework was used to sort the transcripts into themes (ADH layers) and to identify important concepts and their relationships, as seen by the highlighted phrases in Appendix C.2.

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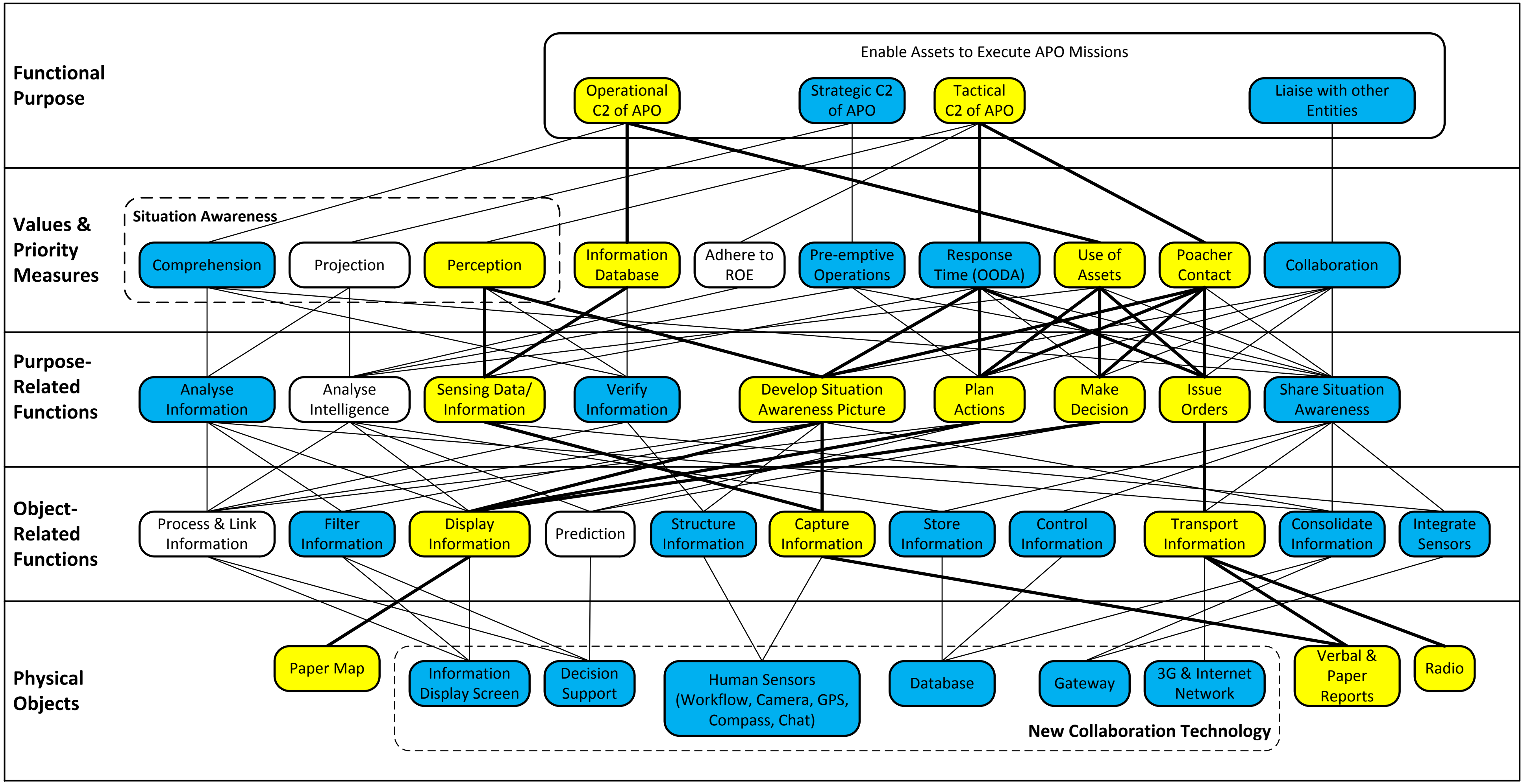

Figure 51: Work Domain Analysis for Anti-poaching Operations Command and Control with New Technology

In Figure 51 the yellow blocks indicate the physical and functional elements that the current technology supports. The blue coloured blocks show how the new technology can increase or enhance the functionality. The blocks with no colour indicate uncertainty about being supported by either technology. This may guide the development of future tools and capabilities. The knowledge gained through the WDA can now be incorporated into the functional-flow models of the system.

The purpose of the C2 system is to curb poaching incidents through controlling and coordinating APO assets. Efforts can be enhanced through liaising with neighbour reserves and other anti-poaching participants, such as the police and the SANDF. C2 can take place at three – strategic, operational and tactical – levels. Each level has its own timeline and objectives, with different requirements of the work processes and supporting technologies.

The success of the C2 is determined by the optimised use of the available resources through situation awareness and the optimised allocation of assets. At this stage the situation awareness tools in the operations centre only support perceiving the current situation. Other priorities of the system include the accuracy of the information database, adherence to rules of engagement (RoE), the effectiveness of pre-emptive operations, response time (reducing the OODA loop), the effective use of the limited available assets, the ability to engage with poachers, as well as improved collaboration with all OPA participants. The immediate contributions of Cmore should be improvements in comprehension of the SAP, planning operations, reducing reaction time and supporting collaboration between participants.

The current voice, paper and spreadsheet-based system can support the basic C2 functions in the control centre, which include (gathering) sensing information, establishing the SAP, making decisions, planning actions and sending orders. However, in addition to these functions, the web-based collaboration technology will improve distributing digital (not only voice) information, as well as analysing and verifying the available information in support of understanding the situation.

The physical elements, in the lowest level of the ADH, list the elements or capabilities of the two comparative technologies. The physical objects currently available in the system to enable operating the APO C2 system are paper-based maps with limited use of Google Earth to plot incidents and reports received through radio reports. The verbal radio reports are captured on paper slips before being imported into to a spreadsheet-based database. These objects provide the object-related functions of information transport, communication coverage, information capture and information display.

The physical objects in Cmore represent the digitised version of the current manual technologies. These consist mainly of smartphones for blue force tracking and capturing information, as well as a centralised database. The Cmore portal or base station can be situated at any point where the information is required for situation awareness and decision-making regarding APO. A “gateway” capability ensures that other sources of information can be integrated.

The additional object-related functions, as provided by the physical objects, include the ability to filter, structure, store, control and consolidate the information, as well as to integrate various sensors. The blocks with no colour are identified as being required in the ideal system but do not have all the required technical support in the two technologies. This has to be performed cognitively by the operators in the command centre.

The purpose-related functions are standard C2 functions and are applicable for strategic, operational and tactical roles, although the detailed processed and tools may differ. These differences are visible in the functional system models. The ADH structured the information from the literature, doctrine documents, a site visit and the outputs of the exploratory focus group. It is subsequently used to support the development of models for the C2 system in APO.

6.3.4 Design and Develop the Artefact

6.3.4.1 System Models

The information from the SMEs, ADH and C2 theory is used to construct a functional flow diagram for operating the APO C2 system, as seen in Figure 52. Again, the yellow blocks indicate the contributions of the old technology, and the blue blocks indicate the additional capability added by the new technology. The functional flow diagram consists mainly of the purpose-related functions level of the ADH, and for completeness is enhanced with a few functions from the object-related functions. The main source of information on poaching incidents is the rangers in the KNP, who can be on patrol or busy with other activities. Their first task is to report the information to their section rangers over the radio network. The radio operators in the command centre can intercept these messages to provide a heads-up warning to the operations centre. The section rangers consolidate and verify this report into an official report with additional information.

In the operations centre, the radio operators record and update all incidents on paper slips (templates). The incident information is used to plan and execute an immediate response to the incident at an operational or tactical level. This is captured in a spreadsheet database for input to a Google Earth display and other information analysis tools. The accumulated information in the database is used to identify hot spots for strategic-level planning or operational planning focussed on covert or pre-emptive operations. This information can be communicated to the section rangers through daily, weekly or monthly reports, to support their planning of local operations with their staff (rangers).

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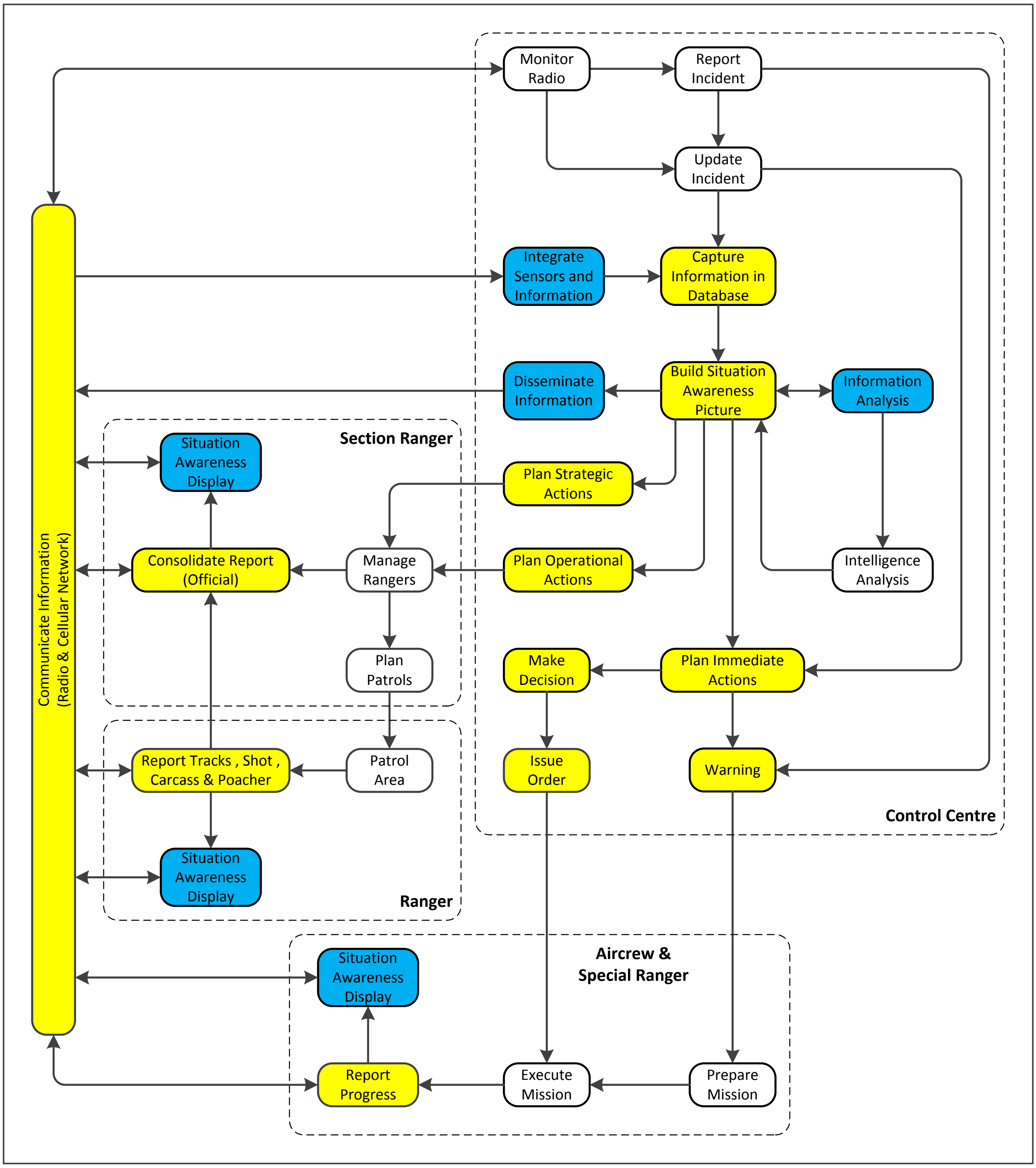

Figure 52: Detailed Anti-poaching Operation Purpose-related Functions with New Technology

Cmore supports integrating more sensors and other information into the information database. The ability to structure and filter the available information also enables information analysis for an improved situation awareness picture. Information can be disseminated to more participants in digital format, to support collaboration during planning of operations. Due to the web-based architecture, each person with network (cellular) connectivity can have the situation awareness picture and capture additional information.

The quality of decisions made in the operation centre improve the success of pre-emptive or reaction operations. The situation awareness display requires additional tools to assist in the decisions made. The primary decisions made in the operations centre are based on the commitment of resources to a specific incident. This is influenced mainly by the availability of resources, priority of the incident and the probability of success where time and distance factors play a major role.

Another view of the APO C2 system is to link the object-related functions into a functional flow diagram, as seen in Figure 53. This sheds light on the integration and loops in operating the system. Again, the colour coding of the current system and the contribution of Cmore were applied. The model with the physical element functions looks very similar to the models in Chapter 5. This is because the same collaboration technology is modelled, albeit for a different scenario. The capability of the physical system does not change a lot. The only influence is integrating the various elements. The functional system models help in constructing the SD models.

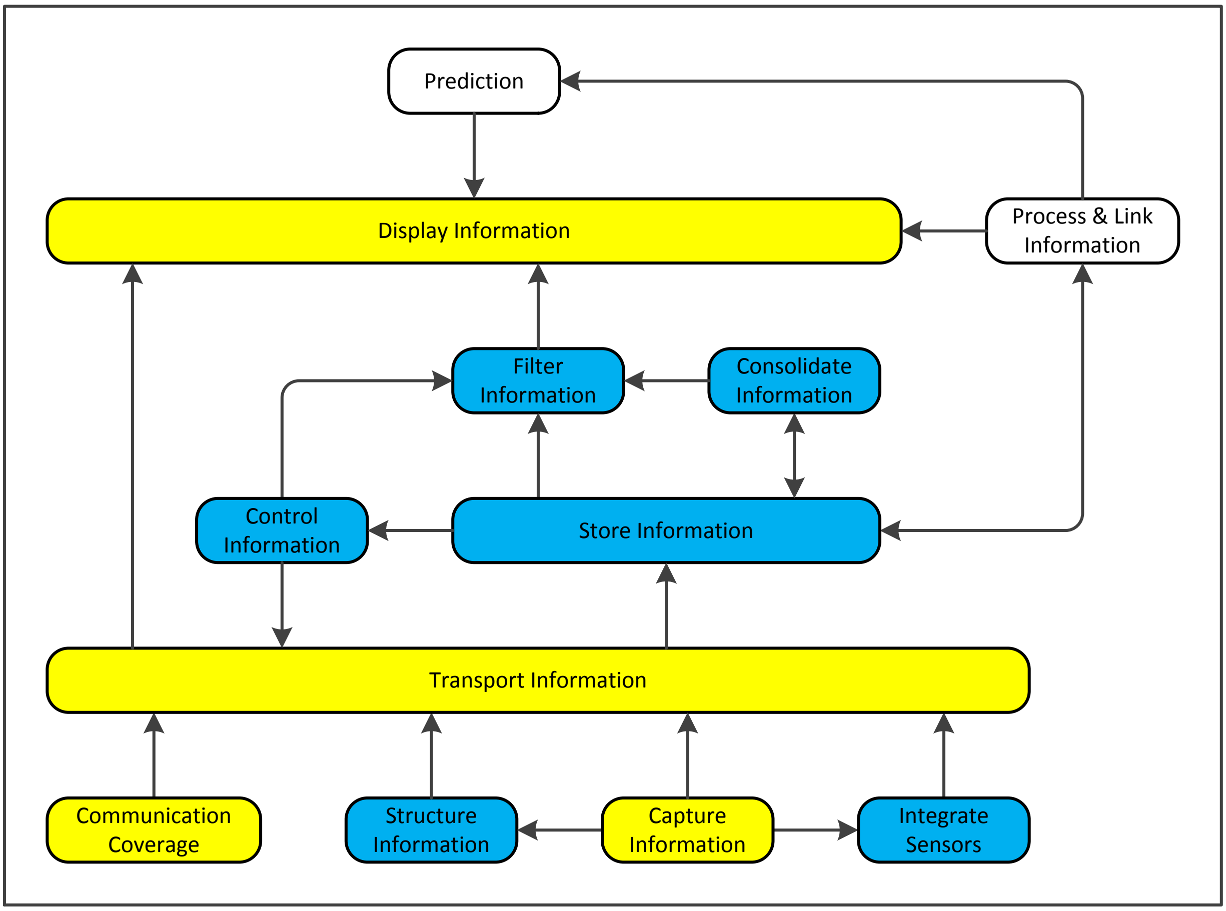

Figure 53: Object-related Functions Model of Anti-poaching with New Technology

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6.3.4.2 Causal Loop Diagram

6.3.4.2.1 Process

The dynamic hypothesis for SD modelling in this demonstration is that the proposed collaboration technology will lead to more information being available and improved ranger reaction to poaching incidents, but will have a requirement for additional Intelligence analysis tools in the system to utilise the extra information.

The CWA, with focus group inputs, in Figure 51, has been used to develop different system models (Figure 52 and Figure 53) for C2 in APO with a new collaboration technology. These models are the basis for identifying important variables and the causal loops between them in the system. The relationships between the lower levels of the ADH are used to identify possible causal links, while the higher levels of the ADH are used to understand the relationships. The elements in the values and priority measures layer of the ADH provide guidance to identify the variables in the CLD. The purpose-related functions show how the variables interrelate, while the functional models indicate how the loops connect.

6.3.4.2.2 Reference Causal Loop Diagram

A reference CLD for the APO C2 system, as seen in Figure 54, was constructed from the understanding gained in the previous section, with the ADH and the resulting models. The elements in the reference CLD consist mainly of the values and priority measure elements of the WDA (Figure 51), which include “Situation awareness”, “Information”, “Asset use”, “Response time” and “Poacher contact”. The main input to the C2 system is “Poacher action”, and the output is “Ranger action”. The reference model also reflects the basic OODA loop variables with the causal relationships between them without the impact of the new technology.

This model reflects the causal loops in the current system without the presence of Cmore. The main loops identified in the CLD to guide the SD simulations and address the dynamic hypothesis are the following:

a) Response Time Loop. This loop uses the available information (positional and status) to improve situation awareness, to reduce the response time. This reflects the basic OODA loop and is a reinforcing loop (R1).

b) Asset Use Loop. The next loop considers optimally using the limited and available assets. The situation awareness should improve the decisions on when and where to commit the resources. This also reflects the basic OODA loop and is a reinforcing loop (R2).

c) Complexity Loop. Poaching incidents change the situation and reduce the developed situation awareness. This reduces the ability for effective action against criminals, resulting in a reinforcing loop (R3).

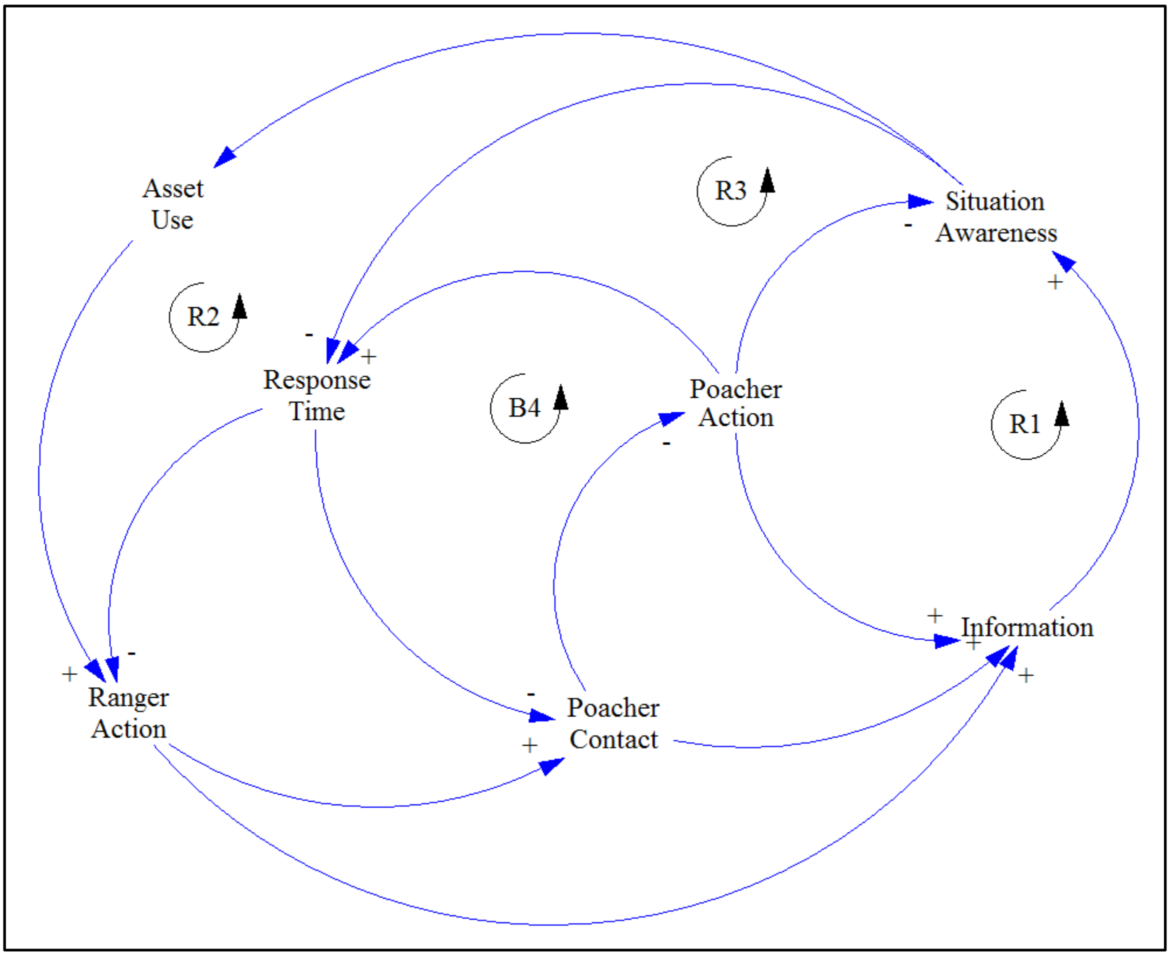

Figure 54: Causal Loop Diagram Reference Model for Anti-poaching Operations

d) Poaching Reduction Loop. Effective reaction and poacher contact decrease the number of successful poaching incidents. This results in a balancing loop (B4), as the reduced number of incidents reduces the available information in the system for situation awareness in support of decisions.

The modelling of the contribution of the new technology in C2 does not account for the contribution of tourists. This is not yet defined and is excluded to maintain simplicity in the models, to assess the use of the technology by rangers.

6.3.4.2.3 Causal Loop Diagram for New Technology

The aim of this demonstration is to assess the impact of new technology on the APO C2 system. Cmore provides the ability to integrate more sensors and disseminate information to more participants in support of shared situation awareness. It also provides a means to structure and filter information in support of situation awareness development and information analysis. The aim is to improve reaction time and decisions on when and where to commit the limited resources. The contribution of the capabilities in Cmore is added to the reference CLD in Figure 54. The additional

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variables are derived from the blue blocks in the Values and priority measures layer of the ADH in Figure 51.

Firstly, the elements in the Values and priority measures related to Cmore (blue blocks) are added to the reference CLD. They are “Pre-emptive operations” and “Collaboration”. The links between the new elements and the existing elements in the reference CLD are determined by inspecting the ADH. The purpose-related functions linked to the new elements are scrutinised to determine their relationships with the existing reference CLD elements. For example, “Collaboration” is linked to “Share situation awareness” and “Make decisions”, which in turn are linked to “Situation awareness”, “Response time” and “Asset use”. These links are therefore implemented in the CLD of Figure 55. This process is repeated for all the new variables. Logic and common sense are also applied to ensure that the CLD is useful to the stakeholders.

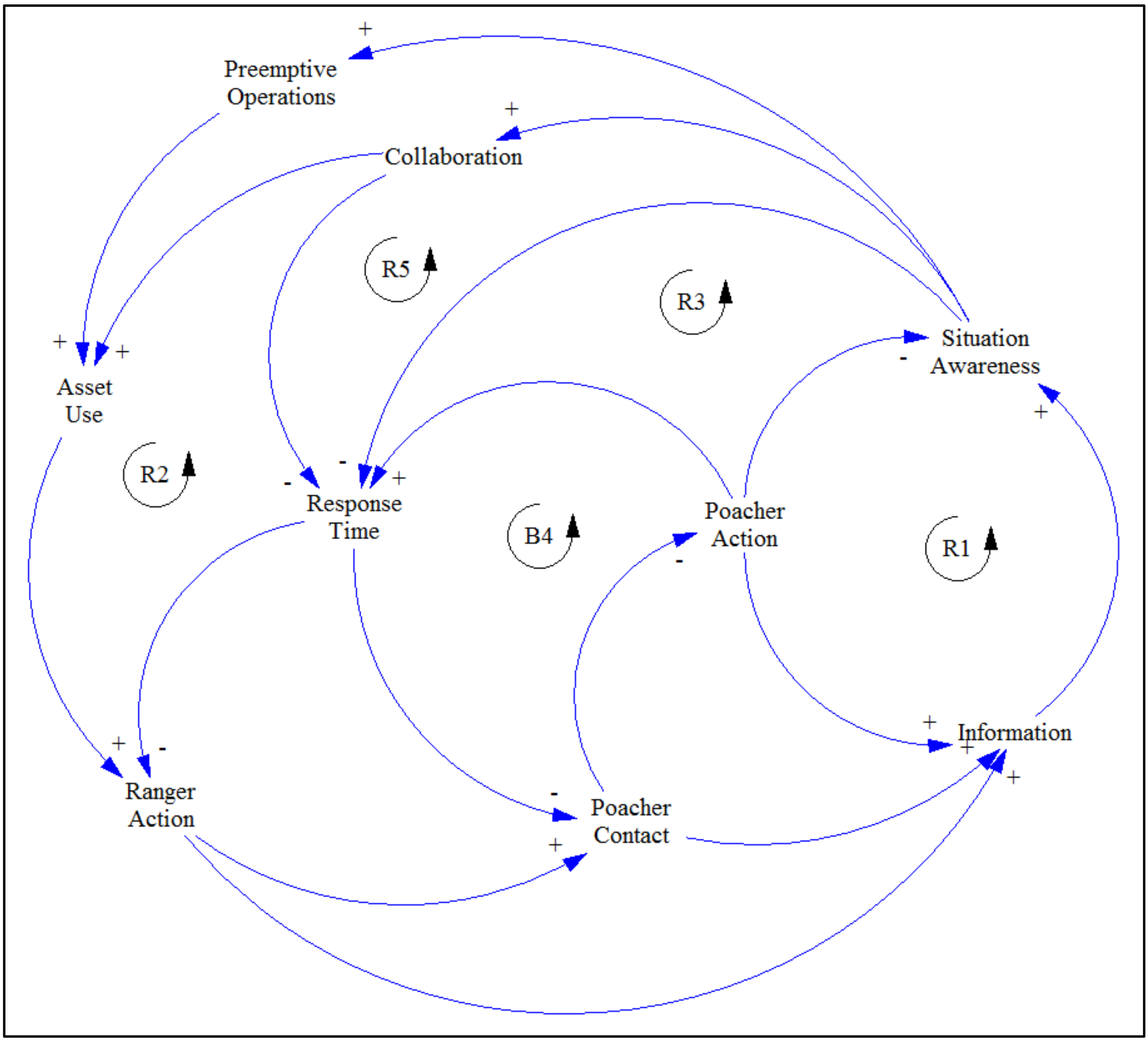

Figure 55: Causal Loop Diagram for Anti-poaching Operations with New Technology

The lessons learnt from Chapter 5 were used to improve the construction of the ADH (Figure 51) to ensure that the elements required for the CLD are present in the values and priority measures layer. Through this process the ability of the WDA to support SD modelling is demonstrated. Care must be exercised not the make the model overly complex, as this will diminish its utility of supporting the understanding of the stakeholders.

As seen with the reference CLD in Figure 54, identifying the important loops is required to initiate stock and flow diagram (SFD) modelling and simulation. The key loop in implementing the new technology identified from the CLD in Figure 55, in addition to the initial loops from the reference model, is the collaboration loop, where the situation awareness is distributed to other participants to improve applying assets in response to an incident (R5). Cmore provides the ability to disseminate information to coordinate the actions of own resources. The section rangers then have access to all the information available in the operations centre, to develop a shared situation awareness of the poaching situation. This helps them to plan focussed pre-emptive operations, as well as to assist in knowing what further information is required.

6.3.4.3 Stock and Flow Diagram

The CLD (Figure 55), WDA (Figure 51) and Physical System Function diagram (Figure 53) are used to compile the structure of the SFD, as seen in Figure 56, for the APO case study. As the dynamic hypothesis for this SD modelling is that the proposed collaboration technology will lead to more information being available and improved ranger reaction to poaching incidents, this SFD focuses on accumulating and applying information. Therefore, the stock that flows through the model is “Information”. Information is gathered, distributed, processed and displayed to support planning and decision-making. These are related to the basic steps of the OODA loop. Variables are added to represent the external environment, as well as to match the variables dimensions and units. The purpose of the SFD is to support simulations that assess the impact of the different technology capabilities on the dynamic behaviour of the whole system.

The variable of situation awareness is not included in this diagram, as it closely relates to the information available and the use thereof. As different types of information have different contributions to situation awareness, it is very difficult to effectively model the generation of situation awareness. Therefore, in this model it is assumed that the amount of information gathered equates to situation awareness for the exploratory purposes of the research. Although quality and timeliness of information is important and affects situation awareness, it is not considered in this SD model.

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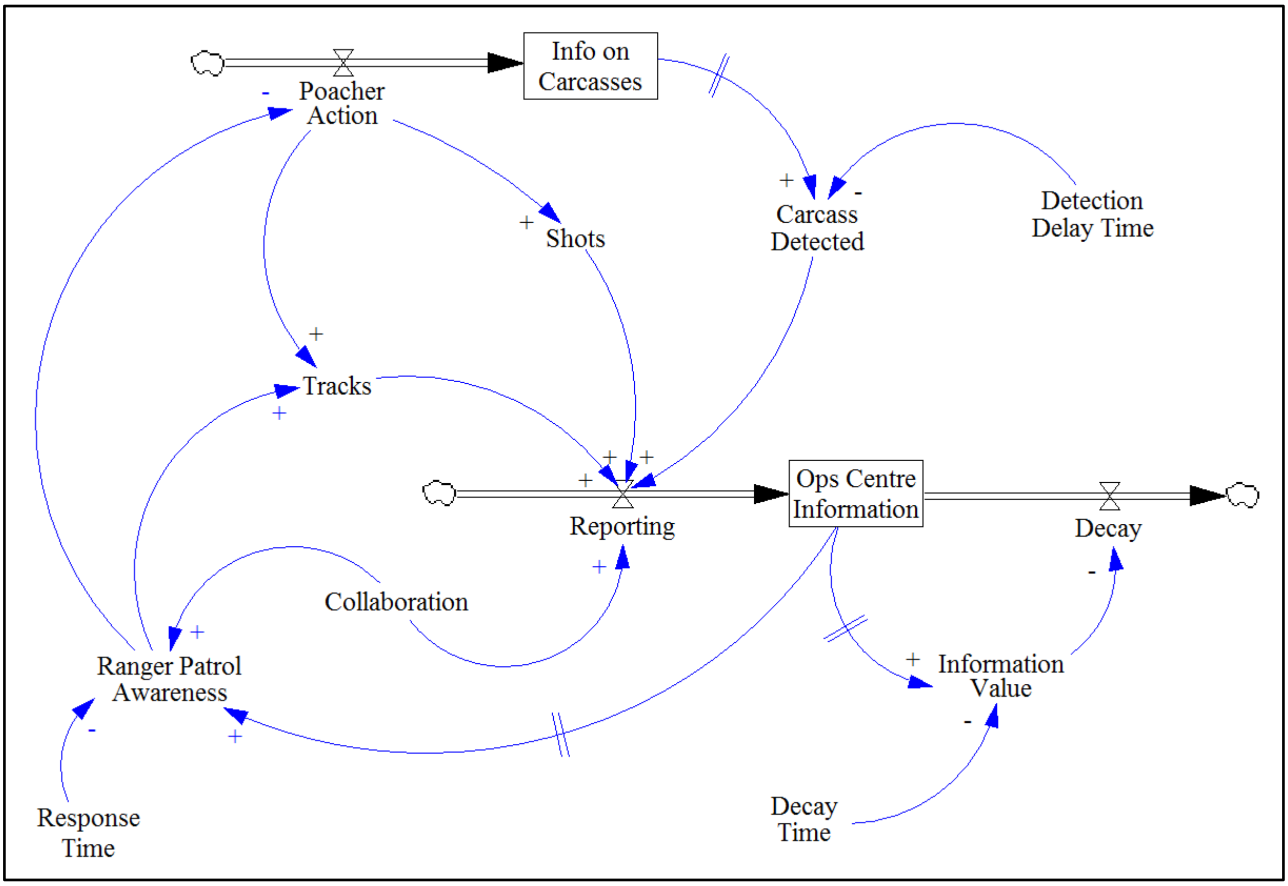

Figure 56: Stock and Flow Diagram for Anti-poaching Operations with New Technology

Poacher actions lead to accumulating carcasses, which are a source of information. However, they may only be discovered days or weeks after the incident. The other sources of information are tracks detected and shots heard. All of the information is reported to the operations centre. Another important factor is that the value of information for effective action decays over time. The information available (situation awareness) in the operations centre supports planning ranger patrols and allocating assets. With the rangers in the right areas, more poacher tracks can be found, leading to an increase in information, and to the faster and more effective engagement of poachers.

This model achieves a reasonable approximation of the current situation experienced in anti-poaching operations, as reported by Anderson & Jooste (2014) and Emslie et al. (2012). However, the aim of the modelling in this case study is to analyse the impact of the new collaboration technology on the STS. The main aspect included in the model is the effect of the collaboration achieved with Cmore. Collaboration enhances the availability and use of information to plan ranger patrols and reporting the gathered information.

This is the leverage point, and it affects the ability of the APO resources to engage poachers before an animal is killed. This model is used to perform simulations to assess the contribution of the new technology in the APO C2 system. The simulations focus on operational-level information and the decision on when and where to commit a resource.

6.3.5 Demonstrate Ability to Solve Problem Artefact in Context

6.3.5.1 Inputs

SD simulations with the SFD in Figure 56 are used to analyse the effect of the new technology on the dynamics of the system. Various forms of inputs can be utilised, although actual information from the environment is preferred. The simulations are used to ensure the model makes sense and the factors (leverage points) in the system are understood. The equations applied in the SFD for the simulations are provided in Table 11.

Table 11: Variable Equations for Anti-poaching Operations System Dynamics Simulations

Variable	Equations	Explanation
Poacher Action	(5-Ranger Patrol Awareness/5)	Five attempted incidents occur per day. This is affected by the ranger patrols, which are assumed to be 20% effective.
Shots	Poacher Action/10	Only one of ten possible shots are heard and reported.
Tracks	Poacher Action/5+Ranger Patrol Awareness	Only one in five tracks of poachers are found. This is enhanced through ranger patrols being in the right location.
Carcass Detected	Fixed Delay (Info on Carcasses/Detection Delay Time), Detection Delay Time , 0)	The carcasses found are reported to the operation centre after an average delay. The value of the information is reduced due the capturing time delay.
Reporting	(Shots + Tracks + Carcass Detected)*Collaboration/2	All sources of information are captured in the operation centre information system. It is assumed that normally only half the available information is correctly recorded. Effective collaboration improves the ability to report information.
Information Value	Fixed Delay (Ops Centre Information/Decay Time, Decay Time , 0)	Older information is of less value. The average decay time is assumed to be 0.25 days
Ranger Patrol Awareness	Fixed Delay ((Collaboration*(Ops Centre Information/(Response Time*3))), Response Time/Collaboration, 0	The operational control of APO uses the information gathered to plan ranger patrols. It is assumed that a third of the available information can be used to enhance the awareness of patrols. The response time reduces the value of the available information. The collaboration capability enhances the effectiveness of patrols.

The main input from the external environment is poaching activity taking place. In this simulation it is assumed to be a fixed number of attempts of five per day for the purpose of exploring the system's behaviour. The number of poachers available and the demand for their products are not modelled, as in this model they are assumed to be inexhaustible. Therefore, contact with poachers will only reduce their ability to kill animals but not reduce the number of attempts. The unit of measurement is the amount of information flowing through the system, and the unit of time is in days. The simulations were performed for a period of 300 days.

Despite the many aspects available for investigation, the simulations centred on the contribution of the collaboration capability of the new technology to the success of the overall system in the operational environment. Collaboration is viewed as a dimensionless constant and is used with the different values of one and two to simulate the effect with and without Cmore. This indicates the degree to which the technology can affect the outcomes of the system. The collaboration capability enables more information to be gathered into the situation awareness picture from the rangers, section rangers and neighbouring reserves, as described in previous sections. It also enables distributing information integrated with, and supporting analysis to these entities, to enable better control during operations as well as proactive behaviour.

6.3.5.2 Information on Carcasses

The simulated number of carcasses detected resulting from poacher action is shown in the graph in Figure 57. The number of carcasses with no collaboration resembles the current state experienced in the KNP over a typical 300-day period (Anderson & Jooste 2014, Emslie et al. 2012). The average delay in detecting carcasses is three days. The effect of ranger activities ensures that there is some degree of levelling-off in the graph. Figure 57 also shows that effective collaboration decreases the effect of poaching activities.

6.3.5.3 Operations Centre Information

Information in support of anti-poaching operations consists mainly of tracks found by rangers on patrol, shots heard by anyone and carcasses found by foot and air patrols. Shots and tracks are reported immediately, while carcases may be found days or weeks after the incident. For the simulations, detecting carcasses is delayed by three days. Due to the vastness of the KNP, very few incidents may be reported as a result of tracks or shots. Collaboration increases the ability of various participants to contribute to gathering and instantly reporting information.

The impact of the contribution of Cmore is shown in Figure 58. The outcomes are interesting and somewhat counterintuitive. The collaboration capability ensures that more information is available up to the point where more information is available without the new technology. One reason is that with the new technology the amount of poaching incidents is reduced, resulting in less information being available to report, despite the capability of the new technology.

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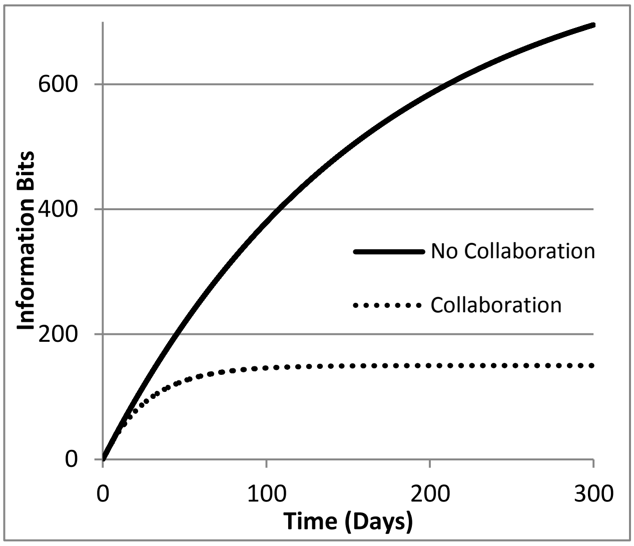

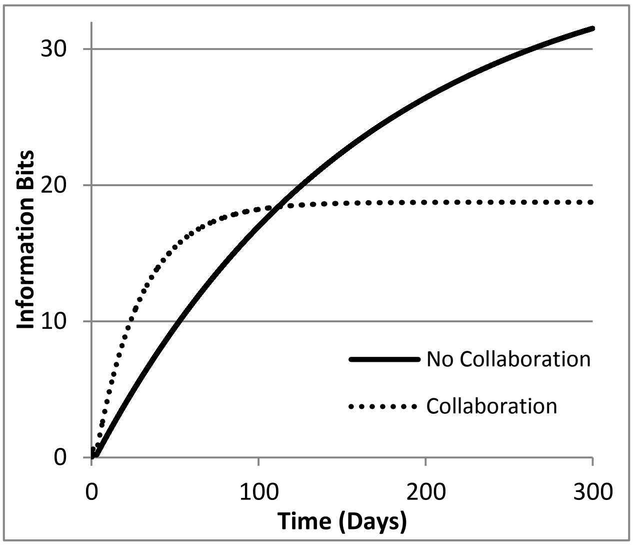

Figure 57: Information on Carcasses

Figure 58: Operations Centre Information

This indicates that the system will find a level of equilibrium at a low level of animals killed. This graph highlights the need to be able to work more effectively with lower levels of information in the system. Therefore, the required tools for information analysis should be included.

6.3.5.4 Ranger Patrol Awareness

The ability of ranger patrols to intercept poachers or detect their tracks, before or after an incident, is mainly supported by the amount information available for situation awareness, planning and decision-making. Even if rangers know exactly where to go, there is still a reaction time required to plan and execute an operation. However, collaboration assists the ranger patrols in going to the right areas and finding the poachers through a shared situation awareness, as seen in Figure 59. Clearly, more incidents can be effectively addressed until the system reaches a limit due to the available information to react on. This means that collaboration enhances the ability to utilise fully the available information for poaching incidents.

6.3.5.5 Information on Poacher Action

The ability of poachers to perform their deeds is inhibited by the effectiveness of poacher patrols, as seen in Figure 60. The effect of collaboration improves the effectiveness of the ranger patrols to combat poaching. Even though this graph may be proven to be unrealistic, as in reality it may be impossible to prevent all possible cases of poaching, it still indicates the possible impact of effective collaboration.

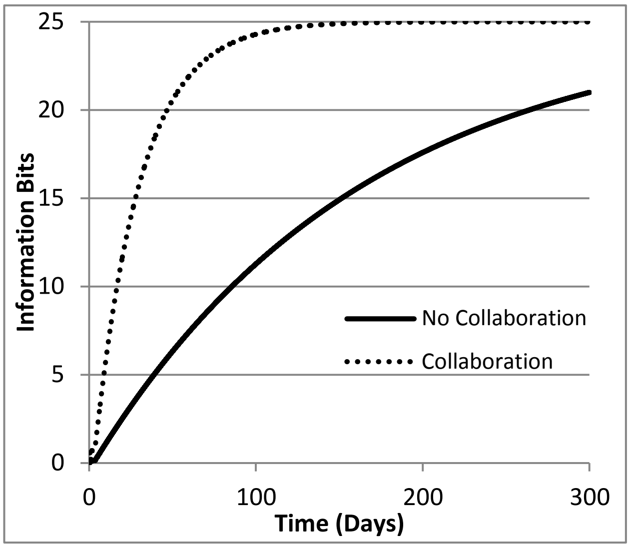

Figure 59: Ranger Patrol Awareness

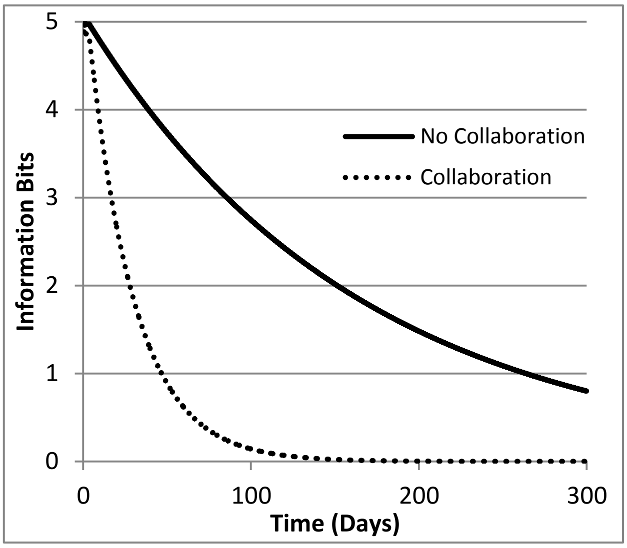

Figure 60: Information on Poacher Action

6.3.5.6 Conclusion

Effective collaboration between the rangers, section rangers and the operation centre increases the amount of information captured and pre-empts actions in response to incidents. The increase in the amount of information improves the situation awareness and decisions, while awareness by the section rangers of what is unfolding improves their ability to make contact with the poachers.

This enables decentralising the tactical control of anti-poaching operations, to become more responsive and agile. It also serves as a guideline on what aspects to measure during experiments with the new technology.

As anti-poaching operations become more effective, and more poachers are apprehended, there will be less information available from tracks, shots or carcases to plan further operations. This effect in the system is somewhat counterintuitive and highlights the need to consider using less information that is available more effectively. As quality and availability of information were not considered in the current SD modelling and simulation, these findings provide a case for investigating them.

6.3.6 Evaluation to Determine Ability of the Artefact to Solve the Problem

6.3.6.1 Confirmatory Focus Group

The output of the modelling and SD simulations was discussed during a confirmatory focus group, as part of the modelling methodology (Figure 50). The focus group consisted mainly of the same participants who participated in the exploratory focus group. The aim was to assess whether the models and SD simulations make sense and add to understanding the requirements for implementing the new technology in an APO C2 system. The case study in Chapter 7 employs field experiments to gather empirical data.

Thirty minutes of the planned duration was used to present the process, models and the simulation results to the focus group participants. These served as topics for the discussions, and the focus group attendees were asked to comment on the various model diagrams and simulation output graphs. The details captured during the focus group discussions are provided in Appendix C.6, for improvements to the models. A brief summary of the highlights and key aspects of the confirmatory focus group are as follows:

a) Cognitive Work Analysis. The confirmatory focus group participants felt that the ADH was adequate.

b) System Models. The following issues were identified with the functional flow diagram, as provided in Figure 52:

    i) Add the capability to display and share the situation awareness from the control centre. Arrows should indicate the flow of information to and from the different situation awareness displays.

    ii) A common intent is required; this will assist in a shared situation awareness if all look at the same information displayed.

    iii) The ability to share information and situation awareness enables the tactical intent. This is achieved through mission planning.

c) System Dynamics Models. The following issues were identified with the elements in the CLD in Figure 55 and SFD in Figure 56:

    i) Change the variable name “Assets” to "Resources", "Effectors" or "Sensors". This tends to become confusing with the general managerial use of the word *asset*, which includes information, buildings, vehicles, etc.

    ii) List the assumptions made to construct the CLD.

    iii) Add a direct link from situation awareness to the ranger action. If the rangers know about a regular crossing point, they can plan ahead and leapfrog to engage the poachers there.

    iv) Moving the poacher action variable out of the inflow will improve understanding.

    v) The variable “Information on carcasses” may be better interpreted if it is referred to as the “Number of carcasses”, instead.

d) Simulation Graphs. The following issues were identified with the simulation results of selected stocks and variables, as presented in Figure 57, Figure 58, Figure 59 and Figure 60:

i) There is a need to have a look at possible nonlinear things or effects in the system. This will make it useful to identify the tipping point behaviour.

ii) Collaboration can vary over a range of zero to one, even over a parabolic, or S-curve, distribution.

iii) The poacher action needs to be increased to a more realistic representation. The increase is also not stable; it increases towards the end of the year.

iv) The carcass information is difficult to define and easy to attack. Rather consider Carcass reports or Carcasses detected. However, the units must still be considered in the model.

v) Perform simulations for a longer period, to analyse the long-term effects.

e) Corrective Actions. The following corrective actions were performed to update the models and simulations in preparation for possible experimentation:

i) Add the function of “Share situation awareness” in a blue block on the right-hand side, with arrows to “Situation awareness display” in the functional diagram in Figure 52.

ii) Change the variable name “Assets” to “Resources”, “Effectors” or “Sensors” in the CLD of Figure 55.

iii) Add a direct link from “Situation awareness” to the “Ranger action” variable in Figure 55.

iv) The variable “Information on carcasses” needs to be changed to prevent confusion in Figure 56. Consider “Animal carcasses” to provide the amount of animals killed.

v) Distinguish between “Poacher action” and the effective killing of animals. This can be achieved by adding the variable “Information on carcasses” to the inflow of the stack in Figure 56.

vi) Change the vertical axis label in Figure 57 to reflect better the information on the graph.

vii) Perform simulations for a longer period, to analyse the long-term effects.

Despite SD being an unfamiliar and specialised modelling approach, the output simulations enabled the focus group members to gain some understanding of the system's behaviour. This lead to asking questions about certain characteristics of the output graphs. In turn, this helped to focus the analysis and modelling of the system on preparing for field experiments. One clear output is showing the effect of delays on the stability of the system, as predicted by the theory on C2. The models may also be used to investigate the role and contribution of the different sources of information. More data from experiments will improve models and simulations.

6.3.6.2 Updates to Models

The updated version of the Purpose Related Functions model from Figure 52 is presented in Figure 61. Since the communicating information is not a purpose-related function from the ADH, it is replaced with “Share Situation Awareness” per the ADH. All participants will share the information on their smart devices to enable shared situation awareness. The changes to the different models should assist in interpreting the model and understanding the simulation outputs.

The updated CLD is shown in Figure 62. The variable “Asset use” was changed to “Resource employment” and the link between “Situation awareness” and “Ranger action” was added. These changes place the CLD more in line with the mental models of the system stakeholders, as derived from the confirmatory focus group.

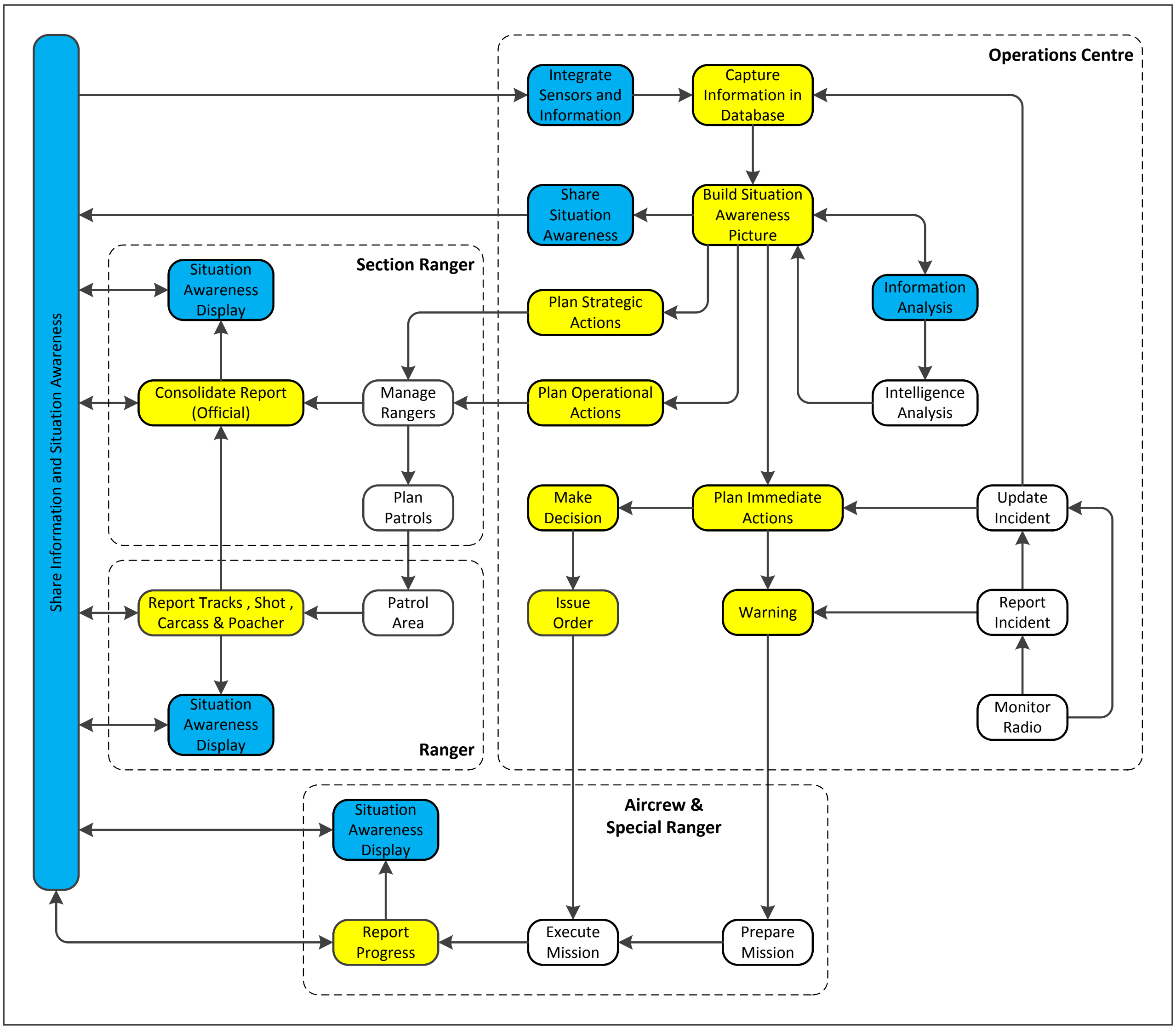

Figure 61: Updated Purpose-related Functions for Anti-poaching Operations with New Technology

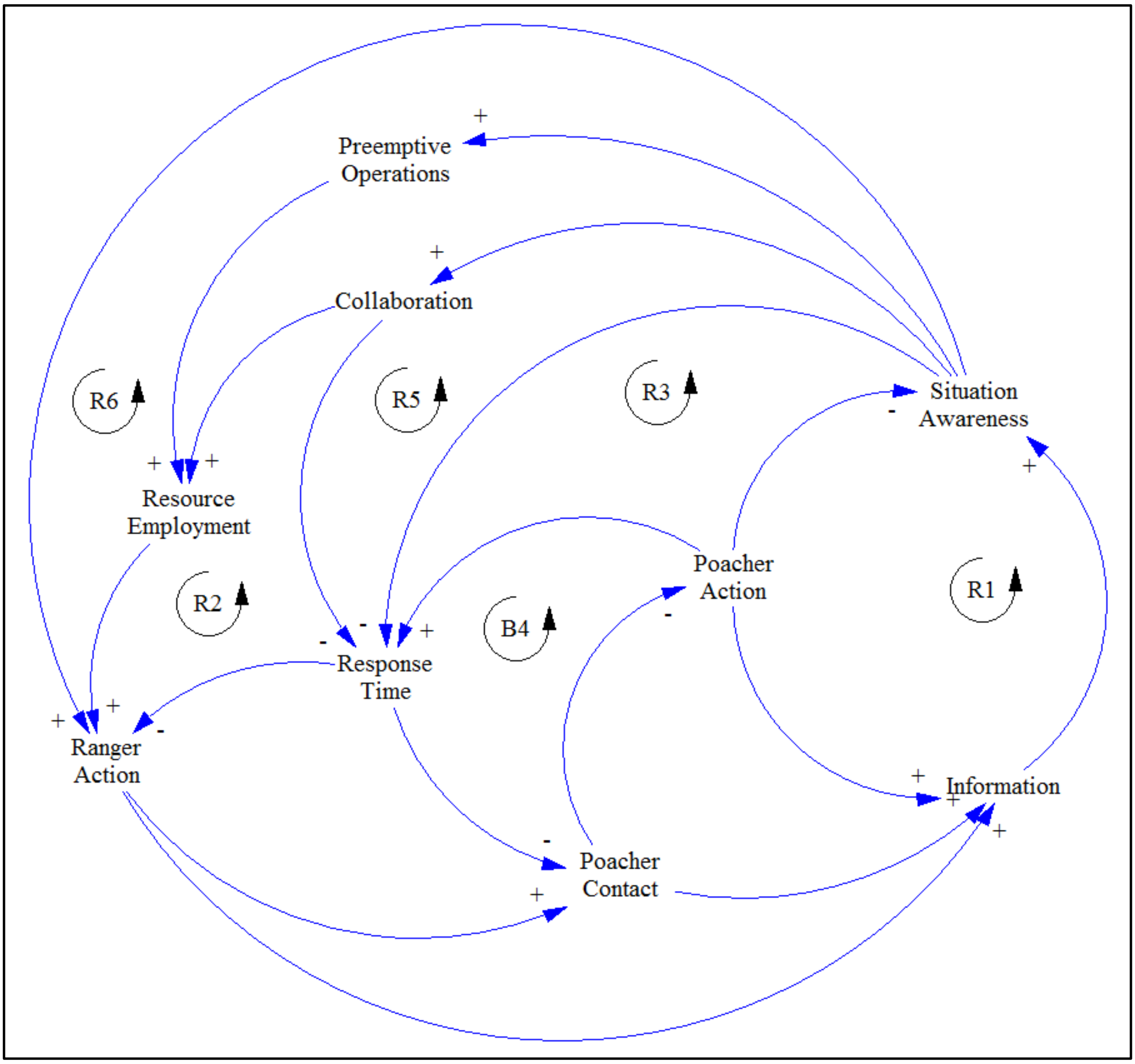

Figure 62: Updated Causal Loop Diagram for Anti-poaching Operations with New Technology

The updated SFD is shown in Figure 63. The changes in the diagram make it easier to distinguish poacher action from the poaching taking place. This change results in the tracks of poachers being detected even without the act of poaching, or killing of, an animal taking place. Also, tracks may only be detected long after a poacher has passed. The new names reflect better the objectives and intention of the SFD. The effect of poaching activities, as shown in the CLD (Figure 62), is also included in the model. Lastly, patrols are not 100% effective in curbing poaching, hearing shots and finding tracks, due to the size of the KNP and the rugged terrain. This is implemented through the “Patrol effectiveness” variable. These changes are used to perform an updated set of simulations.

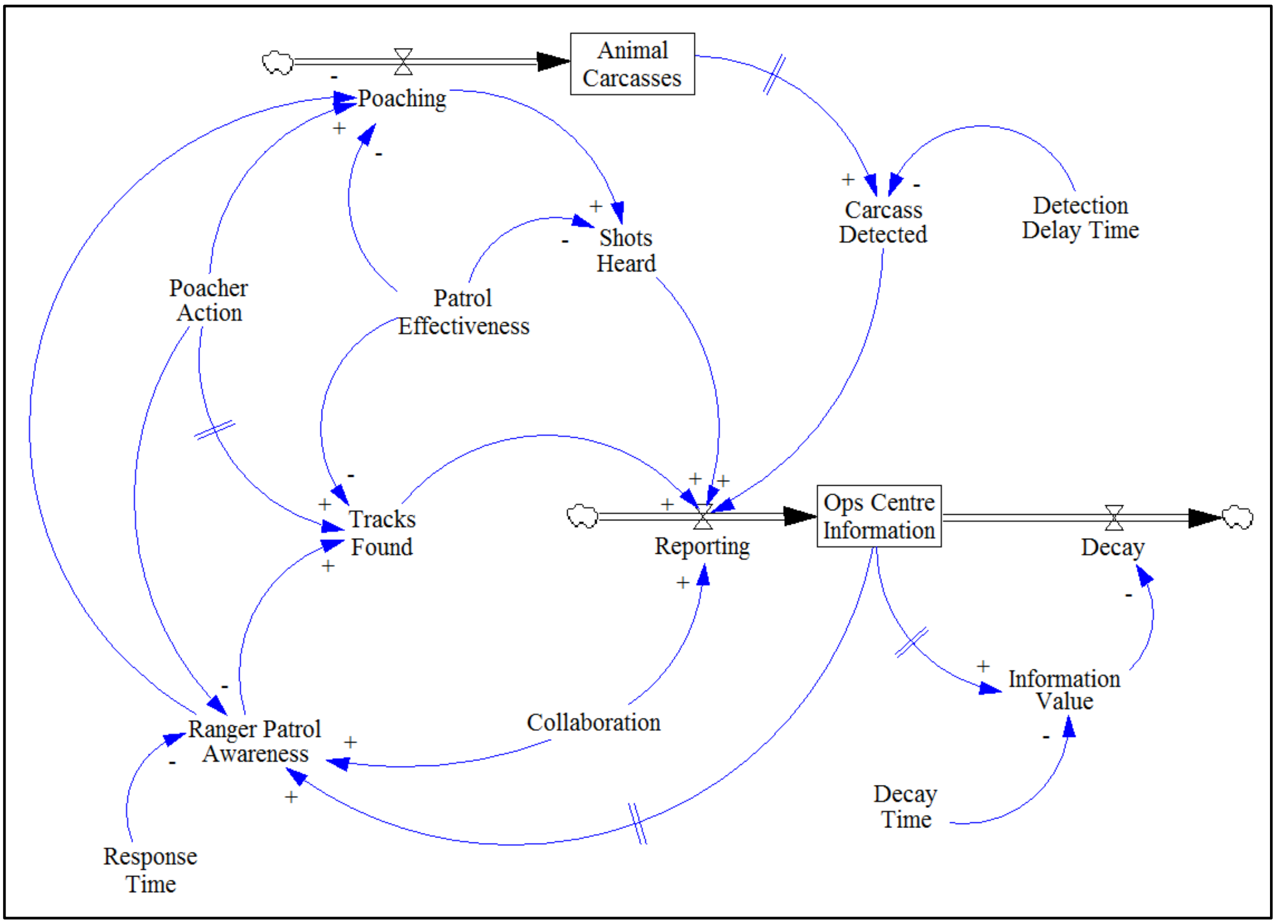

Figure 63: Updated Stock and Flow Diagram for Anti-poaching Operations with New Technology

6.3.6.3 Updates to Simulations

This SD SFD (Figure 63) is again used to perform simulations to assess the contribution of the new technology in the anti-poaching operations C2 system. The simulations focus on operational-level information and the decision on when and where to commit a resource. The time for simulation is changed to hours (instead of days) to accommodate ranger response delays. Therefore the period of the simulations is increased to 5 000 hours, which relates to 200 days. The equations used for the new simulations are discussed in Table 12.

As stated before, the stock flowing through the model is “Information” and the time unit is "Per day". With naming changes, suggested by the confirmatory focus group implemented, the simulation outputs were reanalysed to interpret the meaning of the graph shapes. The changes to the SFD, as seen in Figure 63, and the simulation period led to additional insights into the system. The simulation outputs now more closely reflect the information captured during the confirmatory focus group discussion.

Table 12: Updated Variable Equations for System Dynamics Simulations of Anti-poaching Operations

Variable	Equations	Explanation
Poacher Action	(RAMP(0.001, 5, 10000))/24	Poacher action increases over time, starting at five incidents per day.
Poaching	Poacher Action-Ranger Patrol Awareness/Patrol Effectiveness	Ranger patrols limit “successful” poaching, achieved through their situation awareness of being at the right place at the right time, as allowed by their effectiveness.
Carcasses Detected	Fixed Delay (Info on Carcasses/Detection Delay Time), Detection Delay Time, 0)	The carcasses found are reported to the operations centre after an average delay. The value of the information is reduced due the capturing time delay.
Shots Heard	Poaching/(Patrol Effectiveness)	The shots heard are limited by the effectiveness of the ranger patrols.
Tracks Found	Fixed Delay (Poacher Action/5 + Ranger Patrol Awareness/Patrol Effectiveness, 4, 0)	Only one in five tracks of poachers are found. This is enhanced through ranger patrols being in the right location.
Reporting	(Shots Heard + Tracks Found + Carcass Detected)*Collaboration	All sources of information are captured in the operation centre information system. Effective collaboration improves the ability to report information.
Information Value	Fixed Delay (Ops Centre Information/Decay Time, Decay Time, 0)	Older information is of less value. The average decay time is assumed to be 0.25 days
Ranger Patrol Awareness	Fixed Delay ((Collaboration*(Ops Centre Information/(Response Time))-Poacher Action*4), Response Time/Collaboration, 0)	The operational control of APO uses the information gathered to plan ranger patrols. Response time reduces the value of the available information. Collaboration capability enhances the effectiveness of patrols. Poacher action reduces the situation awareness developed from information.

As seen in Figure 64 collaboration limits the ability of poachers to kill animals. However, due to the ever-increasing number of poaching attempts, collaboration alone will not win the fight.

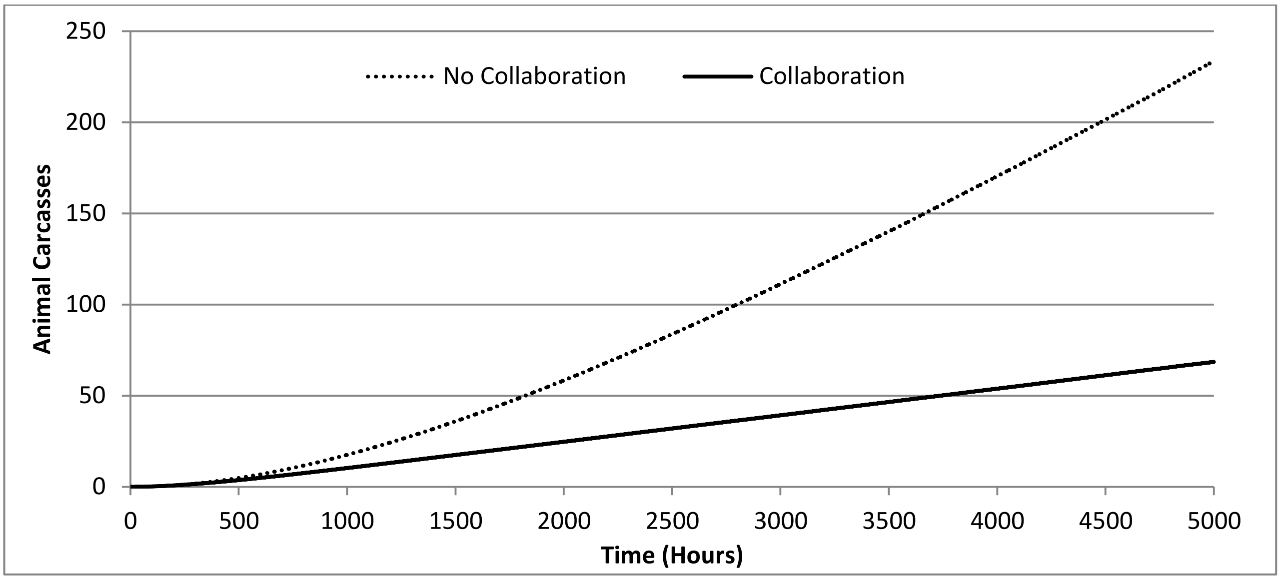

Figure 64: Updated Simulation of Animal Carcasses Found

The collaboration capability among the rangers, section rangers and the operation centre ensures that more information is available up to a point (75 days), as seen in Figure 65. One reason is that with the new technology the amount of poaching incidents is reduced, resulting in less information being available to report despite the capability of the new technology. Therefore, the tools for information analysis should be carefully considered in the requirements for the solution system. The simulation also shows that only introducing a new technology will not make a big difference in patroller situation awareness.

The ability of ranger patrols to intercept poachers or detect their tracks is mainly supported by the amount of information available for situation awareness, planning and decision-making. Despite perfect information being available, a reaction time is still required to plan and execute an operation. As seen in Figure 66, collaboration improves ranger patrol awareness in planning and executing operations.

Finally, as seen in Figure 67, the number of poaching incidents is reduced, mainly through the situation awareness of the ranger patrols. This indicates only a small decrease, as a growing number (slope) is assumed as the input to the model. The main lesson to be taken from these graphs is that although Cmore will improve APO, an isolated effort will not effectively curtail poaching activities.

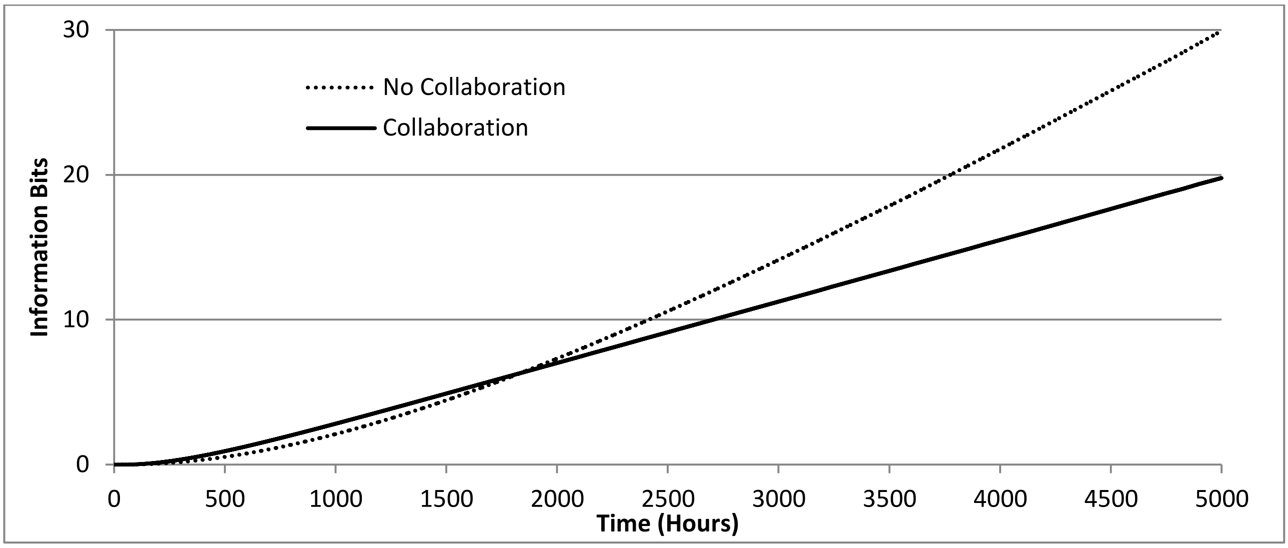

Figure 65: Updated Simulation for Information in the Operations Centre

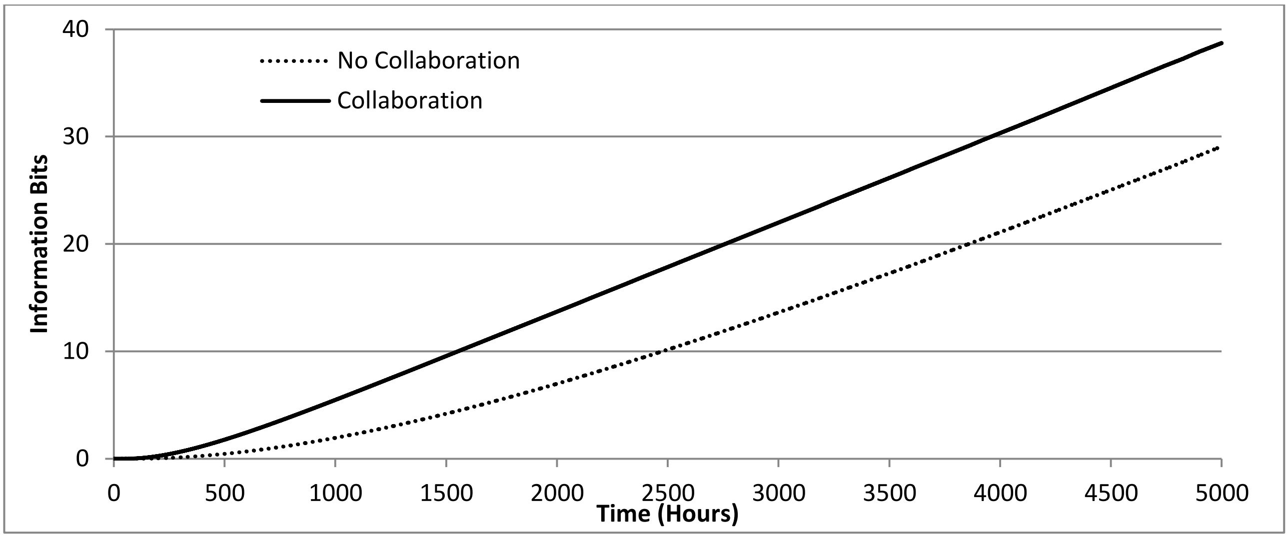

Figure 66: Range Patrol Awareness

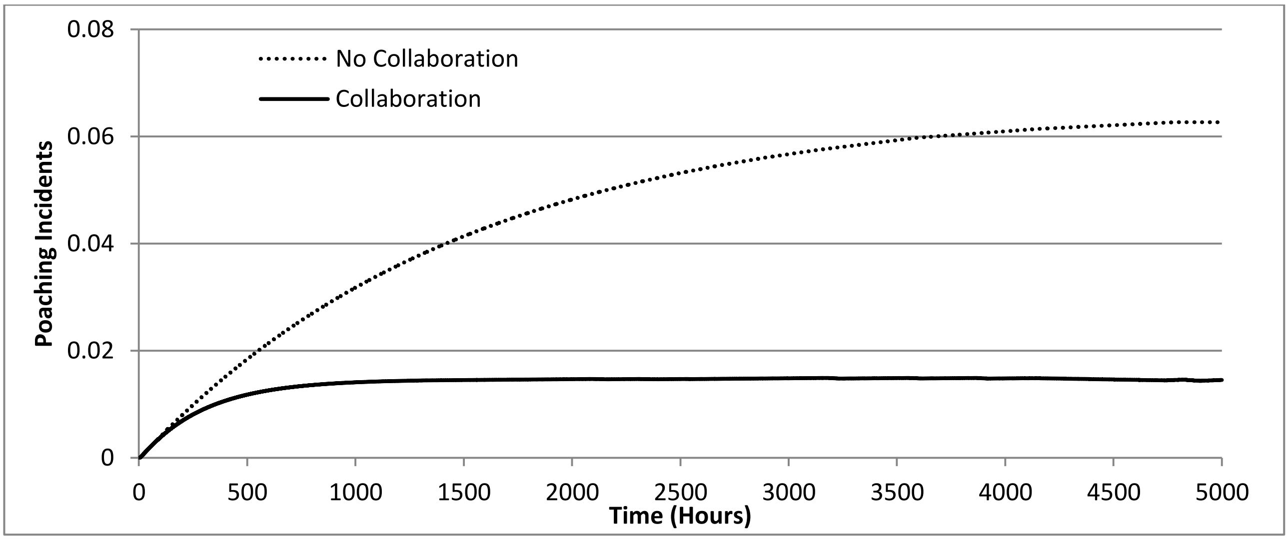

Figure 67: Updated Simulation for Poaching Taking Place

6.4 Conclusion

The case study has shown that the modelling methodology can be applied to investigate the contribution of a new technology in a complex STS. At the outset of this case study, no existing models could be found to support the SE process of C2 in APO. The CWA was used to analyse the work performed with the new technology in the APO C2 system. The SD modelling and simulation built on this to identify the leverage points in the system.

The simulations highlighted some counterintuitive behaviour that designers and developers of the C2 system should consider. This can be used to guide allocating development priorities, as well as planning better measurements during field experiments. Despite applying the same technology as in Chapter 5 (Cmore), but here in a different environment, other issues could be identified and investigated. The same methodology leads to considerably different constructs and models. It also highlights other possibilities, uses and applications of the new technology in the environment. The lack of oscillatory behaviour is also due to a smaller system with a less formal structure and delays operating over large geographical areas.

The modelling outcomes and simulation results were verified using a confirmatory focus group. This demonstrated that the models and constructs developed though the proposed methodology can assist in eliciting information on the problem situation and the environment from the stakeholders. This proved to be useful to improve knowledge about the problem and solution space, even if the models and simulation were not absolutely accurate. The SD models and information gained from them can subsequently be used to support decisions on the choice of technology or policy to improve the situation in the system. The updated models and simulations from the second iteration show that a learning loop can be employed.

The hypothesis developed for this research is that a modelling methodology that addresses human work and dynamic interaction will support understanding the effect of new technology on complex STSs. The insight gained into the complex behaviour of the system in this demonstration supports the hypothesis of this research, as illustrated by the responses from the focus groups. No examples exist in the literature where the dynamic interaction between humans and a new technology for APO has been modelled, simulated and verified. The simulations on indicated that after 75 days, the information with the collaboration technology will be less than without it. Therefore, care has to be taken to ensure that the adoption of the new technology will not be limited through its success. This also represents a novel contribution of this research. Experience gained in applying the methodology in Chapter 5 contributes to the improved modelling and simulating of results in this chapter.

The next chapter provides the third, and last, demonstration of the modelling methodology considered in the research. However, the demonstration follows the entire process, from problem identification through to an experiment to update the models with the captured information.

7 DEMONSTRATING THE MODELLING METHODOLOGY FOR NEW TECHNOLOGY IN COMMUNITY POLICING FORUMS

"Know the enemy, know yourself – your victory will never be endangered.

Know the ground, know the weather – your victory will then be total."

Sun Tzu, The Art of War, C. 500 B.C.

7.1 Introduction

The aim of this chapter is to demonstrate the ability of the modelling methodology through a third case study, as seen in Figure 68 the second stage of the research design. Rigour in this research is achieved through demonstrating the ability of the modelling methodology (research artefact) to model the effect of a new technology in a complex sociotechnical system (STS). The demonstration is in the form of a case study where the modelled impact of the new technology is evaluated during a field experiment. The experiment with the new technology in a complex STS will provide empirically qualitative data on the system's behaviour.

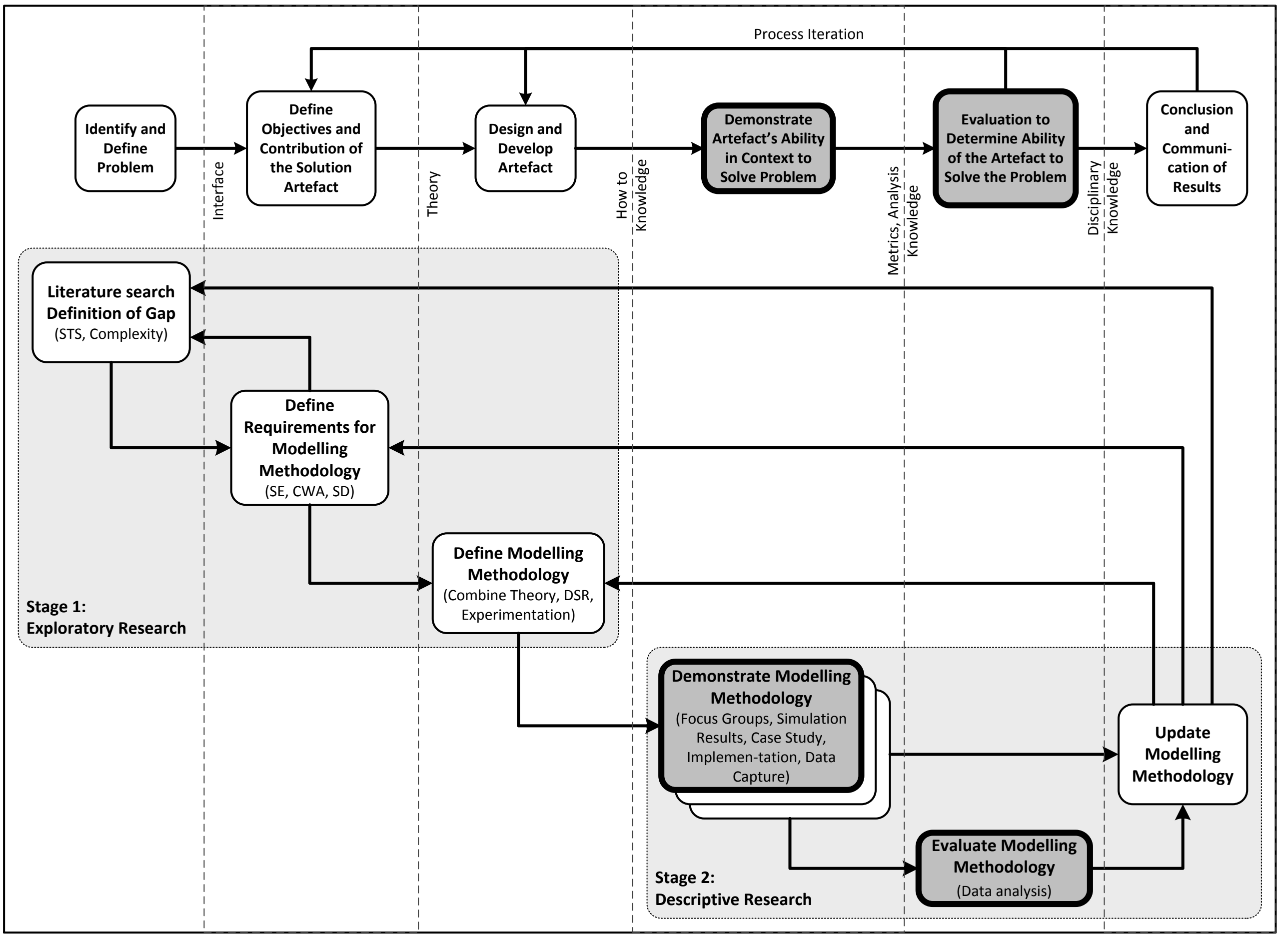

Figure 68: Research Design

This case study addresses the modelling of a technology for collaboration, coordination, information gathering and intelligence analysis in a community policing forum (CPF) system. This is the same Cmore system as modelled for military command and control (C2) and anti-poaching operations in the previous chapters. However, the civilian volunteer operational environment of CPF results in different constraints and behaviours to be investigated. This chapter adds more value, as the modelling and simulation culminate in an empirical experiment with the new technology in a complex STS, the CPF.

This chapter firstly discusses the background of the operational environment of the CPF and the supporting neighbourhood watch (NW) from the perspective of the literature. The aim is to capture high-level requirements, constraints and problems of the complex STS. The CPF and NW system with the new technology is modelled, assessed and demonstrated with the modelling methodology, as developed in Chapter 4.

A CPF system provides a difficult and complex implementation of the new technology, as the participants are volunteer residents operating in a complex, and sometimes dangerous, environment. These limitations on the different role players result in modelling the role of the technology problematic. This provides a representative case study for demonstrating the modelling methodology. Since CPF and NW are complex STSs, the modelling methodology should be able to determine the effect of new technology on the whole system. In this case the methodology implementation depends on interacting with the people in the CPF and NW system, consisting of patrollers and coordinators, to assist in determining the functions, constraints and problems to be modelled.

SD simulations are used to simulate the behaviour of the system in preparation of the field experiment. The resulting models and understanding of the system are then evaluated during a field experiment with the technology in a real CPF and NW. Empirical-qualitative data was gathered on using and improving the situation awareness of the new technology. The outcomes are compared with the models and simulation outputs, to determine the utility of the modelling methodology.

7.2 Community Policing and Neighbourhood Watch

7.2.1 Community Policing Forum

CPFs were established by section 19(1) of the South African Police Service (SAPS) Act 68 of 1995. The aim of a CPF is to ensure police accountability, transparency and effectiveness in the community. A CPF consists of a group of people, from different communities, and police representatives who meet to discuss safety problems in the community (Pelser 1999, Minnaar 2010). The SAPS is required by law to consult with local communities as an official strategy for implementing change, to ensure a safer environment. The powers and functions of a CPF, according to the Police Act, include the following:

a) Promoting accountability of the local police to the community, and the co-operation of the community with the local police.
b) Monitoring the effectiveness and efficiency of the police serving the community.
c) Distributing resources.
d) Handling complaints and charges.
e) Patrolling residential and business areas.
f) Keeping records, writing reports and making recommendations to the station commissioners and their superiors.
g) Asking questions about local policing matters, and requesting enquiries when necessary.

Nowadays, the focus of the CPF is crime-prevention and community policing. Community policing is a policy and strategy for proactively utilising community resources to achieve more effective crime control, to change crime-causing conditions. The police and the community form a partnership to cooperate in organising events to ensure a reduction in crime and safer neighbourhoods. As a result, communication between the police and the community remains essential (Meyer & Van Graan 2011, Munneke 2012).

Public participation and private initiatives, in the form of resident associations, are increasingly taking responsibility for security in communities. The focus is shifting from 'bandit catching' to 'problem-solving', in which all stakeholders at the local level have to interact, cooperate and exchange information. This requires empowered communities to gain control over their environment, through NWs. In turn, this often leads to complex security networks at the local level that can benefit from technological support (Bénit-Gbaffou 2006).

The effectiveness of policing in reducing crime in residential neighbourhoods requires a faster response time, which depends on quick communication. For this, the police require information on crime from the community. This is based on the concept of intelligence-led policing, in terms of which proactive strategies are employed to gather information (Bezuidenhout 2008). Crime intelligence consists of tactical and strategic intelligence, both of which are essential to successful policing. Tactical intelligence provides information on when and where a crime will take place, while strategic intelligence relates to wider indicators such as areas of increased crime. Intelligence-led policing depends on voluntary community involvement and community policing for problem-solving and crime prevention (Zinn 2010, Meyer & Van Graan 2011).

7.2.2 Neighbourhood Watch

The objective of a community policing is to assist in eliminating crime from a neighbourhood, to enhance resident safety. The main NW instrument is patrolling of the neighbourhood by members in vehicles, which leads to greatly reduced crime in some areas. Patrols consist of ordinary volunteer citizens from the community acting as the “eyes and ears” of the police. They report incidents, suspicious persons or potential crime scenes without getting involved in dangerous situations (Bezuidenhout 2008, Zinn 2010, Meyer & Van Graan 2011).

The local security system consists of residents, patrollers, shift coordinators, private security firms and police. An effective NW requires communication between these participants regarding the whereabouts of perpetrators, suspects, suspicious vehicles, etc. As patrollers are unarmed, they allow the police or security companies to deal directly with crime incidents. The ways NW systems operate differ from area to area, due different situational circumstances. Coordination can be performed from a control room or the residences of the coordinators. Most NW and CPF systems have a paper-based system for recording incidents (Zinn 2010, Meyer & Van Graan 2011).

Suitable technology is required to capture information from the community and to distribute it to the police. The current approach, in the case-study context, is through anonymous telephonic or SMS “crimeline” reporting systems. However, effectively integrating reports on incidents and suspicious behaviour by the NW is lacking. Furthermore, the handover of information and intelligence between patrolling shifts is mostly verbal, if any at all. Most CPFs also employ various social media applications, but these are disparate and focus on raising safety awareness in the neighbourhood. A generic set of requirements for a successful and functioning NW system, which can be supported by technology, such as discussed in this thesis, includes the following characteristics (Meyer & Van Graan 2011, Zinn 2012, Minnaar 2012):

a) A communications network consisting of radios or cellular technology that covers the whole neighbourhood.

b) A control room to coordinate patrols and to initiate reaction by the police or private security company to an incident.

c) Sensors, such as closed circuit television (CCTV) surveillance cameras, to capture information on vehicles and persons entering or leaving the neighbourhood.

d) A data base of all incidents and reports of suspicious persons and vehicles, behaviour or objects in the neighbourhood. This can be enhanced with crime statistics and intelligence received from the police.

e) Effective links with the local police and other neighbourhood watches to exchange crime intelligence to prevent crime proactively. This includes real-time communication to expedite reaction to an emergency or criminal incident.

The case study in this chapter focuses on enhancing the ability of patrollers and coordinators through situation awareness for coordination and control.

7.2.3 Neighbourhood Watch as a Complex Sociotechnical System

An NW in a CPF can be viewed as a complex STS because it consists of humans interacting with one another in small teams, using processes, structure and technology, as seen in Table 13.

Table 13: Comparing Neighbourhood Watch to a Sociotechnical System

Complex System	Neighbourhood Watch
Technology (Tools, devices, techniques)	Coordination and control of the system is achieved through voice (radio) and some form of social media. These are not integrated. Cmore provides an integrated system for gathering information, analysing it and controlling the patrollers. The ability of patrollers to attend to incidents and gather intelligence information for analysis is affected by the ability of the interfaces to provide the required stimuli.
Human Influence (Social humans with knowledge, skills, attitudes, values, needs)	The NW system consists of individual patrollers and coordinators in teams, who interact with private security companies and the police. Patrollers are volunteers with various motives, objectives, experience, social and cultural backgrounds, making interaction and perception complex.
Work (Task interdependence, unstructured and uncertain work)	Currently, process and procedures for sense-making and decision-making are limited, due to a lack of technological support. Patrols are procedural, focussing on visibility to discourage criminals and being the eyes and ears for security professionals. Patrolling is affected by risk and uncertainty, where the level of activity varies from boredom to crisis response. Different tasks require different timescales, from long periods with limited activity to urgent and immediate action.
Organisation (Authority structures)	The organisational and authority structure is not very strong, with many participants working on a volunteer basis and in different teams on a rotation basis. A limited number of participants operate in a hierarchical command structure.
Environmental Interactions (Situated cognition)	Despite the physical environment being constant, other constraints, such as socioeconomic and legal ones, also exist. The criminals seek to avoid, distract or confuse patrollers. Most patrollers operate at night when visibility is inhibited.
Information (Information and knowledge system)	The possible sources of information include the patrollers, video cameras at key points and random reports from residents. This information is reported mostly via radio and is mostly recorded in an incidents book. At best, the reports are incomplete, with limited contextual information. Cmore may automate this process to assist with analysing and distributing information.
System Behaviour (Unpredictable, dynamic complex, non-deterministic, emergent)	The NW system is dynamic due the unpredictable environment, as incidents, which can be anything, can occur at any time and place. Unpredictable criminal behaviour and NW patroller responses provide for non-deterministic system behaviour. Various forms and timing of criminal activity can occur, and patrollers may choose different courses of action when confronted with them. The data available for situation assessment may be incomplete, and uncertainty in complex environments makes awareness of the true state of the work environment difficult. Participants react differently when scared and inexperienced within the operational environment.
Agility (Humans provide agility)	Controllers have to deal with unanticipated events by improvising to implement contingencies, in order to ensure resident safety. The safety risk to volunteer patrollers must be enhanced while enabling private security and the police to address any situation.

The information in the table is a summary of the theoretical and literature discussion above. However, currently the technology utilised is limited and consists mainly of procedures, radios and manual paper-driven reporting. This is the same format used in Chapter 5 (Table 8) and Chapter 6 (Table 10).

7.2.4 Technological Support for Neighbourhood Watch

As with any complex STS, technology can be applied to support or enhance human work. The same collaboration technology, Cmore, as discussed in Chapter 5 and Chapter 6 is modelled and introduced in the NW and CPF system. The focus is on supporting patrol coordinators and patrollers through information analysis and situation awareness. Typical contributions of the smartphone- and web-based architectures are as follows:

a) Human Sensor. Modern technology can convert residents, including non-patrolling residents, into a sensor and information sources through web-based technology on smartphones. Many near or attempted criminal incidents often are not reported to the police due to the perceived futility of the effort. This information is effectively lost. The Cmore mobile and base station can be used to record incidents, linked to photos and position (GPS).

b) Information Distribution. The distribution and communication of captured information and crime awareness to the community leads to raised awareness. This, in turn may lead to the increased reporting of incidents.

c) Workflow. A workflow consists of the required information being recorded, as well as ensuring that a standardised process in managing reports is followed.

d) Blue Force Tracking. Tracking of patrollers and other participants enables the patrol coordinator to keep track of all participants and monitor their safety. Less-travelled roads can be identified, and the patroller requested change patterns.

e) Intelligence Analysis. Web-based technology with supporting tools (software packages) to analyse recorded information on incidents supports crime intelligence. This can be reported to the CPF management and the police, to increase awareness. In Cmore this is implemented through heat maps, filtering and map annotations.

f) Situation Awareness. Cmore provides the patrol coordinator with a web-based situation awareness that includes incidents, patroller location (Blue Force Tracking) and annotated areas of interest (hotspots).

g) User Management. The access of users is controlled through accounts with user names and passwords. Different roles can also be assigned different responsibilities with corresponding levels of access to data in the system.

This section introduces the concept of NW and CPF within the context of complex STS, along with the possible contributions of technology. The next section demonstrates the ability of the modelling methodology to model the impact of Cmore in a complex STS.

7.3 Case Study Execution

7.3.1 Modelling Methodology

The modelling methodology developed in Chapter 4, as seen in Figure 69, is used to model and evaluate the effect and contribution of new web-based collaboration technology (Cmore) in a CPF with NW patrols. The solution artefact referred to in the modelling methodology (Figure 69) is the set of models used to investigate the effect of Cmore in the complex STS.

The technological capabilities of Cmore may assist in enhancing community policing and neighbourhood safety. The degree of the contribution and application in the complex STS still needs to be understood. The artefact developed through this methodology is a model of the contribution of the technology in the CPF as a complex STS. This is used to understand the dynamic system behaviour of NW patrollers and coordinators with the new technology.

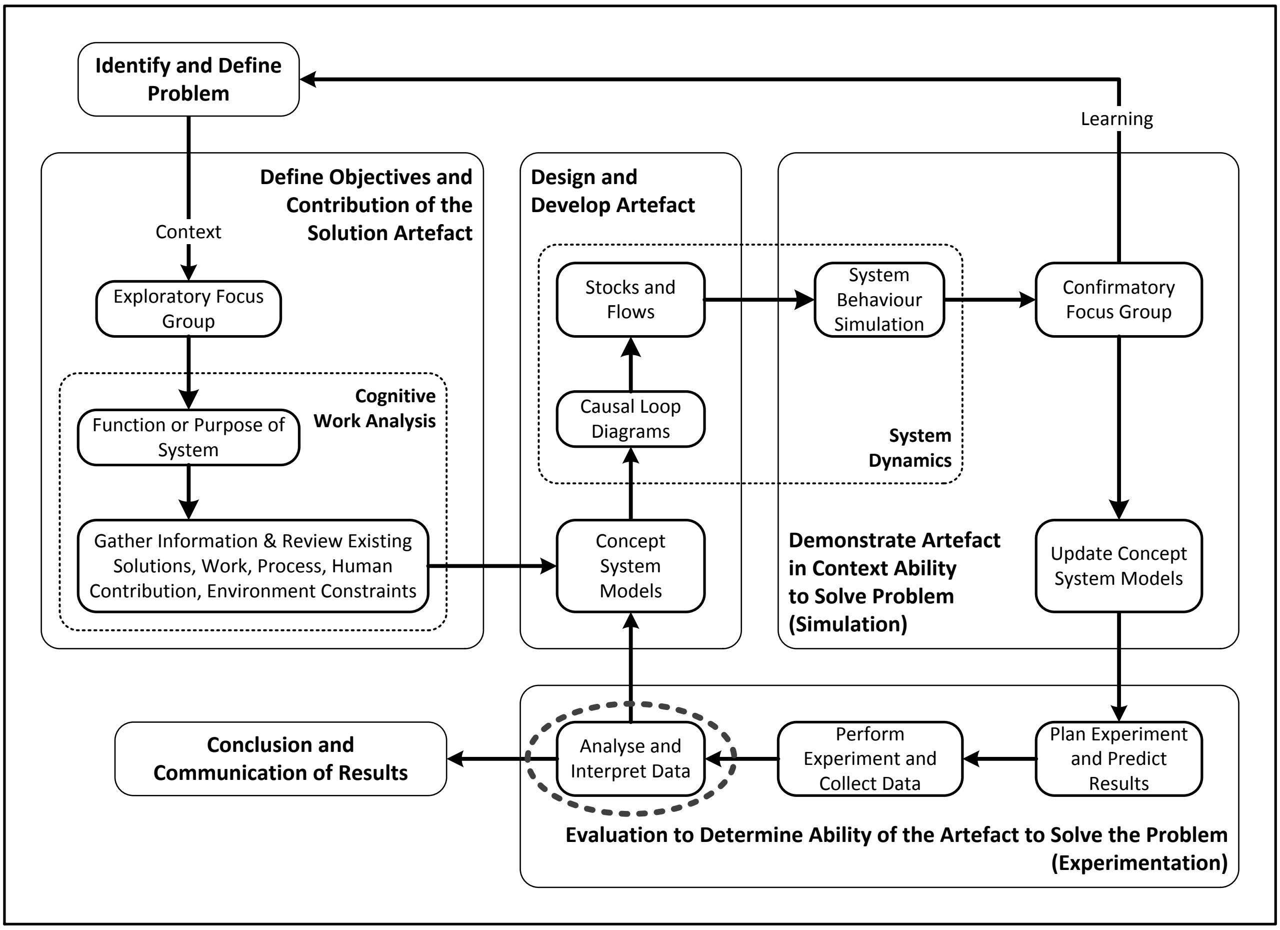

Figure 69: Modelling Methodology for Neighbourhood Watch

This understanding is required in planning to introduce the technology, for maximum benefit to all stakeholders. This may lead to identifying leverage points in the system, to assist in defining requirements and making decisions on a possible implementation project. The detailed execution of the modelling methodology is described in the next sections.

7.3.2 Identify the Problem

Similar to the previous two chapters, this demonstration is another example of “technology push”, as the CPF participants may not be aware of its shortcomings or the availability of suitable technologies. The expectation is that the new technology will improve the NW as a complex STS, but it is not clear what the resulting behaviour of the system will be. The specific problem to be solved by Cmore is the development of situation awareness for coordinators and patrollers. This includes the tasks of gathering, collating and filtering information for situation awareness, and developing crime intelligence.

The current voice and paper-based reporting system used in the CPF case study is not very effective, because only a few incidents are captured. Despite radio-based voice communication being effective for controlling patrols, they are not suited to gather adequate information on an incident. Even though some CPFs apply social media tools, such as Facebook and WhatsApp, they have disparate capabilities and are not integrated. Patrollers tend to go about their routine business without considering the longer-term requirements for information. There is also no formal method for structuring and collating the captured information. The often-neglected additional contextual information would improve the analysis and interpretation of the incident reports.

The aim of this modelling methodology demonstration is to determine how Cmore will improve a NW and CPF system. Effectively distributing situational information and supporting intelligence should enable a shared awareness between the various community policing participants, to control and coordinate crime prevention actions. This problem identification is part of the research problem, as experienced in this context.

7.3.3 Define Objectives and Contribution of the Solution Artefact

7.3.3.1 Focus Group

An exploratory focus group was conducted with the Cmore development team, C2 experts and CPF members to determine the current problems experienced and the possibility of the new technology to improve the system. The focus group was preceded with a presentation on the capabilities of Cmore. The questions addressed in the focus group to identify inputs to the modelling process were the following:

a) What is the purpose of C2 in CPF?

b) Which C2 functions executed during NW patrols in a CPF can be supported with Cmore?

c) What are the constraints on the success of the C2 system?

d) What are the shortcomings in C2 that can be addressed by technology?

e) How can a new technology such as Cmore contribute to the effectiveness of the C2 system?

f) How will the technology influence the way people do the work in the system?

g) What will be the effect of the technology on the timeline of events?

The outputs of the focus group were the functions and processes executed as well as the constraints of the system. The discussions and knowledge gained during this focus group also built on the foundation established in Chapter 5 and Chapter 6. The information captured in the focus group is summarised in Appendix C.3. This information was the input to the work domain analysis (WDA), along with the existing literature on community policing and C2, as provided in previous sections.

7.3.3.2 Cognitive Work Analysis

The WDA is undertaken by constructing an abstraction decomposition hierarchy (ADH) for the work performed in the NW and CPF. The available information from the literature, documents and the focus group inputs were used to populate the ADH, as seen in Figure 70, to determine the relationship between the new technology and the purpose of the system. An initial ADH was constructed from literature to support the focus group discussion. This framework was used to sort the transcripts into themes (ADH layers) and to identify important concepts and their relationships, as seen by the highlighted phrases in Appendix C.3.

The WDA makes the links between elements of the new technology and the higher-level functions. The values and purpose-related functions provide the link between the physical elements and the system's overall purpose. The yellow blocks indicate the elements and functions of the system with the current technology, while the blue blocks highlight the contribution of the new technology. Cmore also performs the functions in yellow. The white blocks are important elements identified but not yet supported through the current and proposed technology.

The functional purpose of NW in the CPF is to make the neighbourhood safe for citizens. However, this can be decomposed into the functional purposes of the C2 system in the NW, which are coordinating the patrollers (volunteer residents), initiating responses from the police to incidents, as well as supporting the CPF and police with crime-related intelligence. The success of these functions depends on the values and priority measures of the system, which enable the NW patrols to serve effectively as the eyes and ears of the police and the CPF. Since patrollers are citizen volunteers with limited training, their safety during patrols is essential.

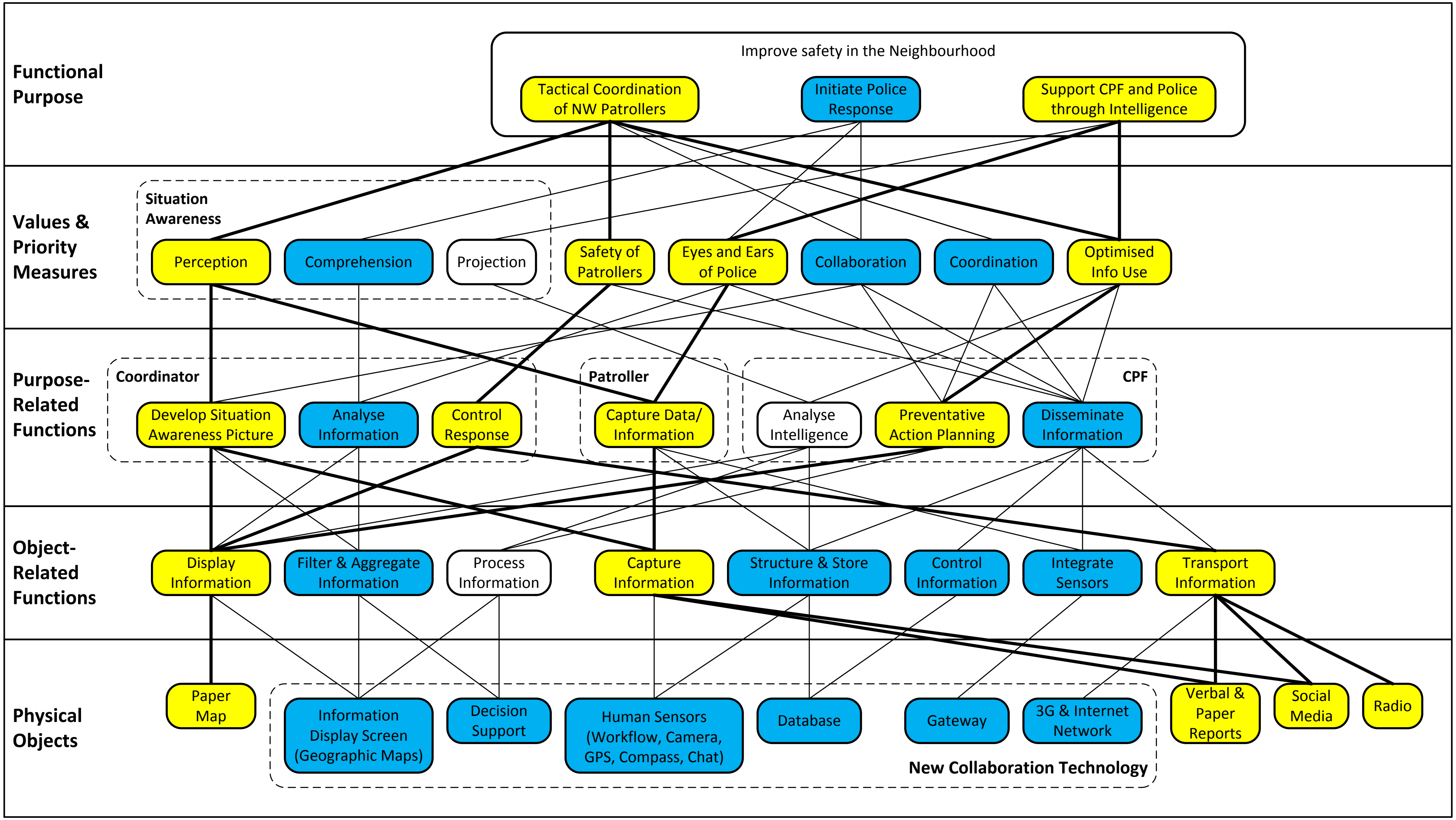

Figure 70: Work Domain Analysis for Neighbourhood Watch with New Technology

The situation awareness of the patrollers and coordinators, through the optimised use of the available information for collaboration and synchronisation improves the effectiveness of the CPF. The collaboration technology has to enable recording incidents (with text and photos), displaying the information and managing the distribution of the information.

The purpose-related functions of the whole system are reporting observations (capturing information) and analysing them to support sense-making, and situation awareness. These are done to identify incidents and to make decisions on immediate (tactical) action or later attention (operational or strategic). The exchange of information facilitates synchronising, coordinating and collaborating patrollers and coordinators. A function not yet supported with the current and new technology is intelligence analysis in support of the "Projection" level of situation awareness. The CPF management can use the intelligence to plan preventative actions and to interact with the police to ensure a safe environment.

The current physical objects for the NW patrols consist mainly of radios for verbal communication, which can be supported by paper reports. Even with the limited application of social media, this does not go beyond sharing the information with the residents. As seen in Figure 70, these do actually support most of the purpose-related functions even though they are often at a limited level. Through implementing Cmore many more object-related functions are available in support of purpose-related functions. These centre on integrating information sources as well as on structuring, storing, filtering, aggregating and controlling information. The ADH inputs are now used to support developing system models of the NW and CPF system.

7.3.4 Design and Develop the Artefact

7.3.4.1 System Models

The aim of this step is to develop models that represent the system's structure, operation and behaviour. No detailed visual model diagram was found in the literature as a reference for NW and CPF, or their interaction with the police. The existing C2 literature, documents, focus group and CWA (Figure 70) were used to compile a functional flow diagram, as seen in Figure 71. The purpose-related functions of the ADH provide the work functions performed by people. The ADH helps to understand the relationship between the functions, to develop the functional diagram. The yellow blocks indicate the contributions of the current technology, and the blue blocks indicate the additional capability added by Cmore. In some cases the new technology may add to the functions supported by the old technology; however, these stay yellow.

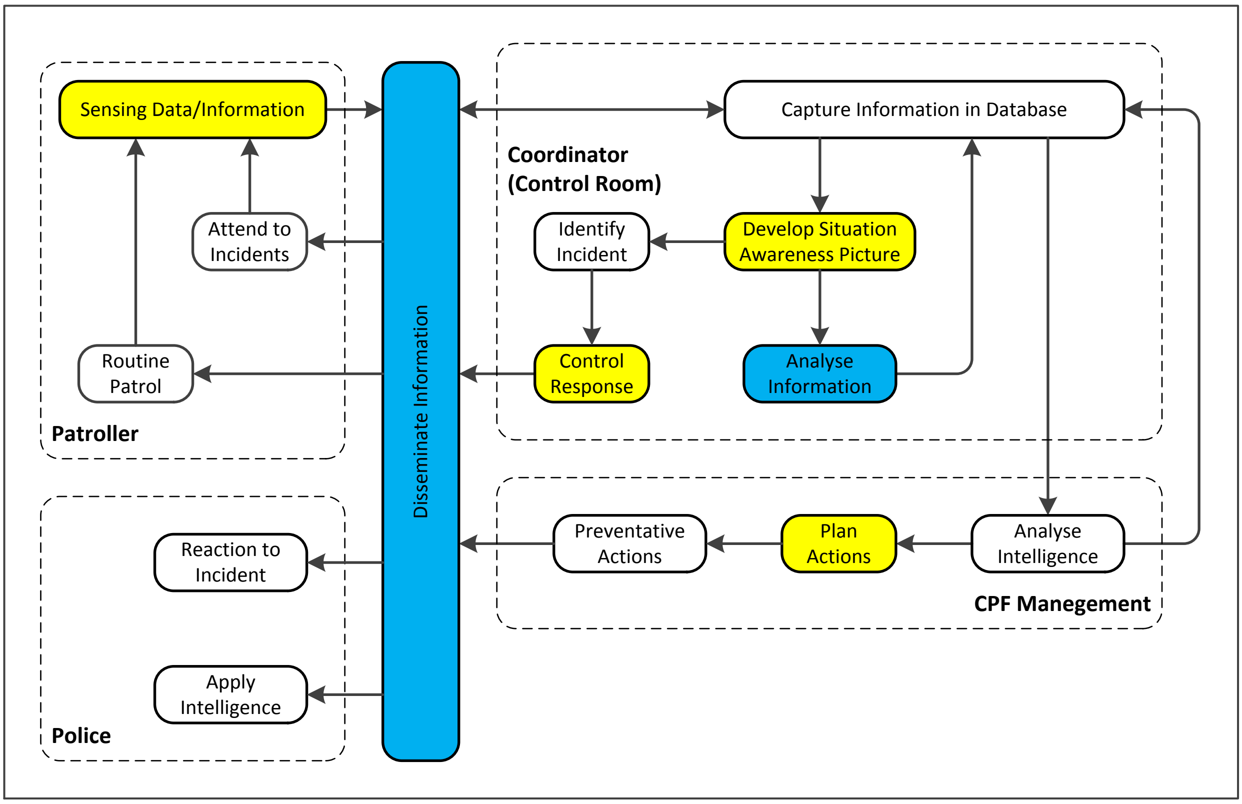

Figure 71: Detailed Community Police Forum Purpose-related Functions for Neighbourhood Watch with New Technology

Patrollers are the main source of information on crime and other incidents in the neighbourhood that they report over the radio or cellular network. The control room operator or shift coordinator can intercept these messages and record them in an incidents book. The incident information is used to execute an immediate response to the incident or to plan future actions. Cmore supports the automated capturing and integrating of more sensors into the information database. The ability to structure and filter the available information also enables information analysis for an improved situation awareness picture. Information can be disseminated to more participants in digital format to support collaboration and synchronisation during the planning of operations. Due to the web-based architecture, each person with network (cellular) connectivity has access to the situation awareness picture and captures additional information.

Another view of the NW patrol C2 system entails linking the object-related functions from the ADH into a physical functional-flow diagram, as seen in Figure 72. This helps to understand the integration and loops in operating the physical system. Again, the described colour coding of the current system and the contribution of Cmore are applied. Cmore assists in gathering information into a database as well as providing the tools for assessing the information, to generate intelligence and situation awareness. The structure, as supported by the CWA, indicates that the new technology makes a major contribution.

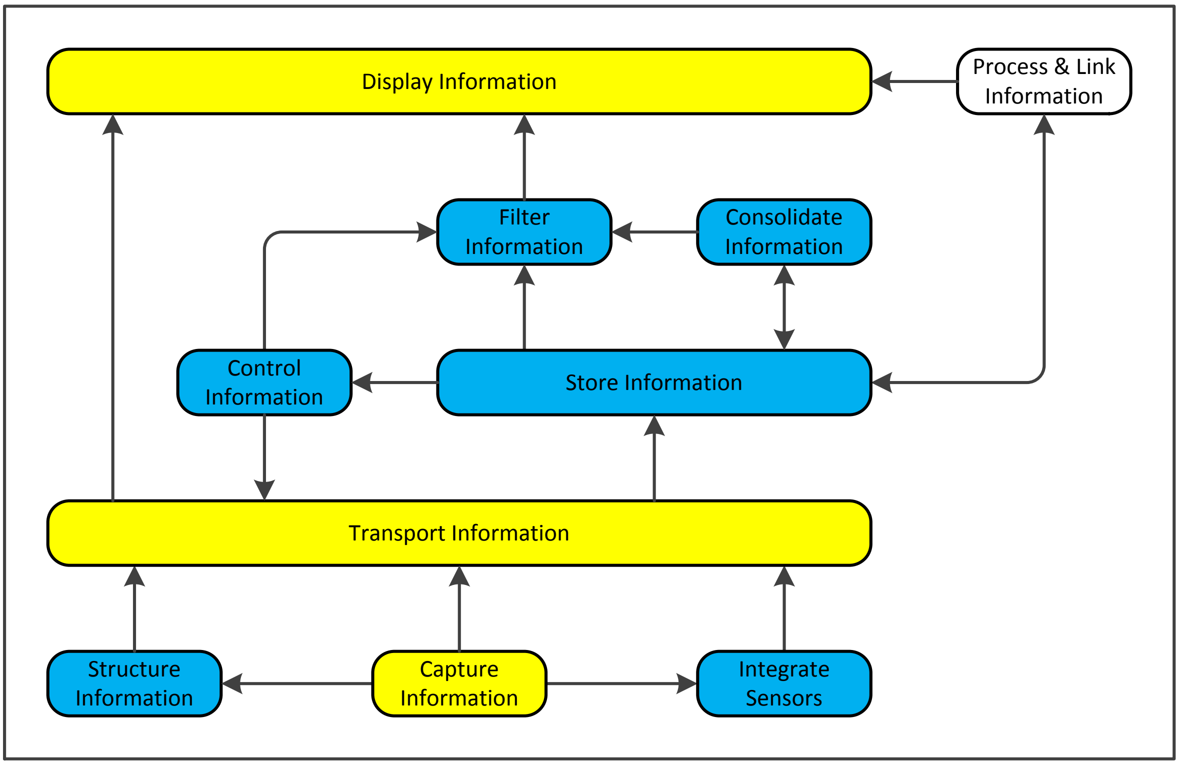

Figure 72: Physical System Model for Neighbourhood Watch with New Technology

7.3.4.2 Causal Loop Diagram

7.3.4.2.1 Process

The dynamic hypothesis for the SD modelling and analysis in this case study, as supported by the CWA, is that Cmore will improve coordination of patrols through disseminating information in support of a shared situation awareness. This implies that patrols are more effective in reporting more suspicious behaviour, faster, and in attending to more incidents. The models developed in the previous section are now used to identify the important variables in the system and the causal loops between them.

The CWA, with focus group inputs, in Figure 70 has been used to develop different system models (Figure 71 and Figure 72) for C2 in CPF with a new collaboration technology. These models are the basis for identifying important variables and the causal loops between them in the system. The relationships between the lower levels of the ADH are used to identify possible causal links, while the higher levels of the ADH are used to understand the relationships. The elements in the values and priority measures layer of the ADH provide guidance in identifying the variables in the causal loop diagram (CLD). The purpose-related functions show how the variables interrelate. The functional models also indicate how the (feedback) loops connect.

7.3.4.2.2 Reference Causal Loop Diagram

The reference CLD in Figure 73 was established using the information from the WDA (Figure 70) and systems thinking. This model reflects the causal loops in the current basic system without Cmore. The elements in the reference CLD consist mainly of the values and priority measure elements of the WDA (Figure 70), which include “Situation awareness”, information as “Eyes and ears of the police”, “Information use” and “Patroller safety”. The main input to the C2 system is “Criminal action” and the output is “Patroller awareness”. The reference model also reflects the basic OODA loop variables with the causal relationships between them without the impact of the new technology.

Information on incidents and the location of the patrollers increases situation awareness in the system. The situation awareness is used to initiate the police response to crime incidents. Situation awareness also leads to improved information utilisation for police reaction as well as for patroller safety and patroller awareness. This is achieved through proper information exchange interfaces. The main loops identified in the reference CLD are the following:

a) Safety Loop. Using the available Information (positional and status) improves the situation awareness, to improve the safety of patrollers. With the patrollers feeling safer, their commitment and speed of response are improved. This reflects the basic OODA loop, and is a reinforcing loop (R1).

b) Patroller Awareness Loop. The next loop considers optimally using the available information in response to criminal incidents. The situation awareness should improve awareness of what information is required and how to respond to it. This also reflects the basic OODA loop, and is a reinforcing loop (R2).

c) Complexity Loop. Criminal incidents change the situation and reduce the situation awareness gained from the existing information. This reduces the ability for effective action against the criminals, resulting in a reinforcing loop (R3).

d) Criminality Reduction Loop. Effective reduction in criminal action decreases the occurrence of crime. This results in a balancing loop, the reduced number of incidents, reduce the available information in the system for situation awareness in support of decisions (B4).

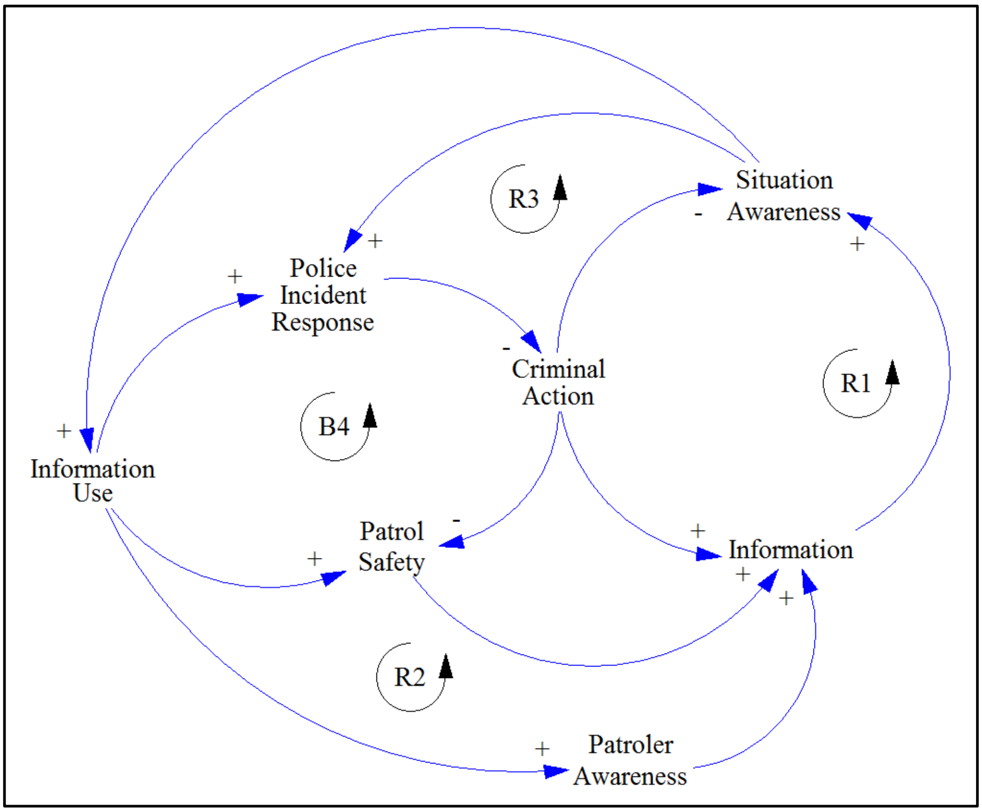

Figure 73: Reference Neighbourhood Watch Causal Loop Diagram

7.3.4.2.3 Causal Loop Diagram for New Technology

The aim of this demonstration is to assess the impact of new technology on patrols and coordinators. Cmore provides the ability to capture and disseminate more information to all participants in support of shared situation awareness. Structuring and filtering of information support situation awareness development and information analysis. Cmore aims to improve the use of available information for effective response to incidents. The contribution of Cmore is added to the reference CLD in Figure 73, as seen in Figure 74. The additional variables are derived from the elements in the values and priority measures layer of the ADH in Figure 70.

Firstly, the elements in the values and priority measures related to Cmore (blue blocks) are added to the reference CLD. They are “Comprehension” and “Collaboration”. The links between the new elements and the existing elements in the reference CLD are determined by inspecting the ADH. The purpose-related functions linked to the new elements are scrutinised to determine their relationship to the existing reference CLD elements. For example, “Collaboration” is linked to “Develop situation awareness picture”, “Preventative action planning” and “Information dissemination” which in turn are linked to “Situation awareness” and “Information”. “Collaboration” is also linked to the functional purpose of “Initiate police response” in the top layer of the ADH. These links are therefore implemented in the CLD of Figure 74. This process is repeated for all the new variables. Logic and common sense are also applied to ensure that the CLD is useful to the stakeholders.

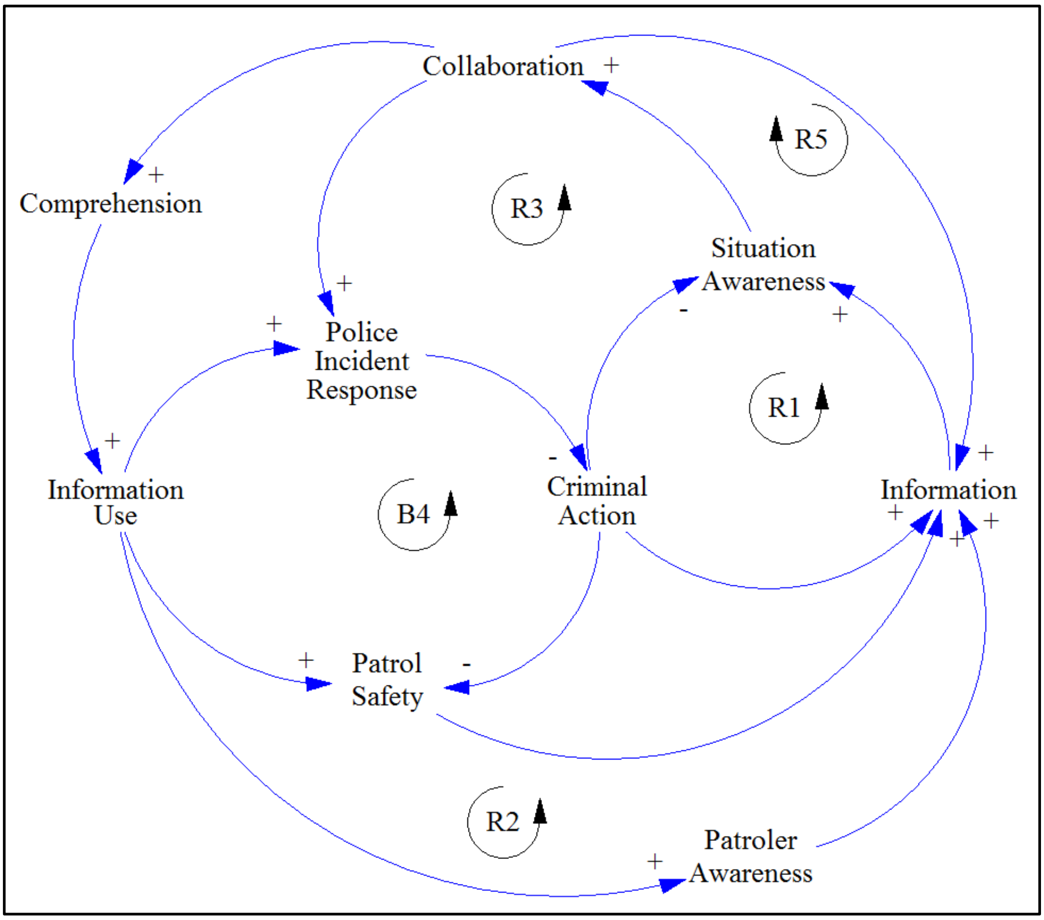

Figure 74: Causal Loop Diagram for Neighbourhood Watch with New Technology

The lessons learnt from Chapters 5 and 6 were used to improve the construction of the ADH (Figure 70), to ensure that the elements required for the CLD are present in the values and priority measures layer. Through this process, the ability of the WDA to support SD modelling is demonstrated. Care must be exercised not to make the model overly complex, as this will diminish its utility in supporting an improved understanding by the stakeholders.

The key contribution of Cmore, in addition to the initial loops from the reference model, is the collaboration loop, where the situation awareness is distributed to all participants to improve applying assets in response to an incident (R5). Cmore provides the ability to disseminate information and to coordinate the actions of the patrollers. The patrollers and shift coordinators subsequently have access to all the available information to develop a shared situation awareness of the crime situation. This makes the patrollers aware of what the trends of criminals are, and to report these, which further increases the richness of the pool of information.

7.3.4.3 Stock and Flow Diagram

The causal loop diagram (Figure 74), WDA (Figure 70) and physical system element diagram (Figure 72) are used to compile an SFD, as seen in Figure 75. This model is used to simulate the

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impact of the Cmore on the system. The dynamic hypothesis for the SD modelling and analysis in this case study is that Cmore will improve the coordination of patrols through disseminating information in support of a shared situation awareness. Therefore, the stock that flows through the model is “Information”. Information is gathered, distributed, processed and displayed to support planning and decision-making. These are related to the basic steps of the OODA loop. Variables are added to represent the external environment as well as to match its dimensions and units. The purpose of the SFD is to support simulations that assess the impact of the different technology's capabilities on the dynamic behaviour of the whole system.

The variable of situation awareness is not included in this diagram, as it is assumed to relate closely to the amount of information available and the use thereof, albeit only for the first level of perception from Endsley’s (2003) model. This forms the foundation of the measurements in the case study’s experiment. As different types of information have different contributions to the situation awareness, it is very difficult to be modelled with SD.

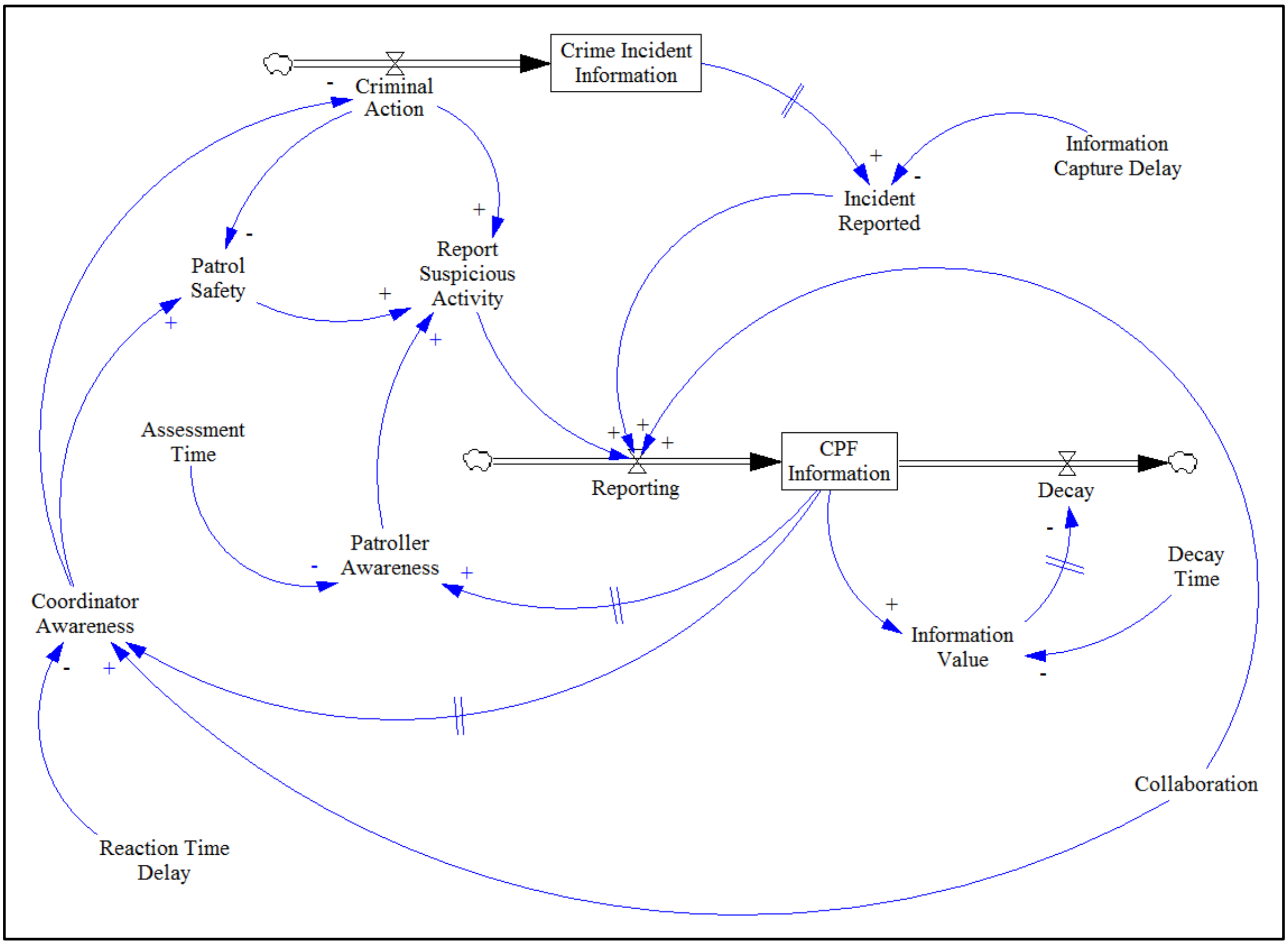

Figure 75: Neighbourhood Watch Stock and Flow Diagram with Collaboration Technology

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Criminal action leads to information on crime incidents, most of which are reported to the police. These are reported to the CPF after a time delay. The other main source of information is suspicious activity reported by patrols to the control room or management committee. Another important factor is that the value of information for effective action decays over time. The available CPF information leads to coordinator and patroller awareness in support of initiating a reaction from the police or of planning pre-emptive operations. These are aimed at preventing criminals from performing their activities.

This model achieves a reasonable approximation of the current situation experienced in a CPF system. However, the aim of modelling in this case study is to analyse the impact of the new collaboration technology on the STS. The main aspect included in the model is the effect of collaboration achieved with Cmore. Collaboration enhances the availability and use of information to support awareness of the patrol coordinators and CPF management.

7.3.5 Demonstrate Ability to Solve Problem Artefact in Context

7.3.5.1 Inputs

SD simulations with the SFD (Figure 75) are used to analyse the effect of the new technology on system behaviour. The equations applied in the SFD for the simulations are provided in Table 14. The main input from the external environment is criminal action in the neighbourhood. Despite the many aspects available in the NW system to investigate, these SD simulations centre on the impact of the collaboration capability of Cmore on the success of the overall system. Collaboration is viewed as a dimensionless constant, and is used with values of 1 and 2 to represent the degree of technological contribution in the simulation. The collaboration capability enables more information to be reported for situation awareness by the patrollers, as well as for information to be distributed for better coordination during patrols.

The values and assumptions in the model were derived from personal experience, the literature and the focus group inputs. This will suffice for the first round of simulations to determine whether the models and simulations produce sensible results. The simulations are used to ensure that model makes sense and that the factors (leverage points) in the system are understood. The initial results serve as an input to the second round of focus group discussions. Various forms of inputs can be utilised, although actual information from the environment is preferred.

In the simulations the criminal action input is assumed to be one per hour. The number of criminals available is not modelled, as it is assumed to be inexhaustible. It is assumed that contact with criminals reduces only their effective action, but does not reduce the number of attempts. Criminals often come from a remote area without detail knowledge of the area to attempt incidents. Patrols will however prevent them from actually performing criminal acts. This may however have long term effect on the system. The simulations were performed for a period of 100 hours.

Table 14: Variable Equations for Neighbourhood Watch System Dynamic Simulations

Variable	Equations	Explanation
Criminal action	(1-Coordinator Awareness/5)	One attempted incident occurs per hour. This is affected by the coordinator actions due to awareness, which prevents one in five attempts.
Report suspicious activity	(Criminal Action/3)+(Patrol Safety/3)+(Patroller Awareness/3)	Only one of three possible criminal activities is reported. This is improved by the safety experienced and awareness of the patrollers, which is a third each.
Patrol safety	Coordinator Awareness-Criminal Action	Patroller safety is increased by the awareness of the coordinator, and is decreased by criminal activity.
Incident reported	Fixed Delay ((Crime Incident Information/Information Capture Delay), Information Capture Delay , 0)	The crime incidents are reported to the police and may be received by the CPF after 24 hours. The value of the information is reduced due to a time delay.
Reporting	((Report Suspicious Activity)/2 + (Incident Reported)/2)*Collaboration	All sources of information are captured in the CPF information system. It is assumed that only half the available information is recorded. Effective collaboration improves the ability to report information.
Information value	Fixed Delay (CPF Information/Decay Time, Decay Time, 0)	Older information is of less value. The decay time is assumed to be two hours.
Patroller awareness	Fixed Delay (CPF Information/Assessment Time, Assessment Time, 0)	Patrollers may be aware of criminal trends in the neighbourhood, as derived from the available information. However, a delay of two hours can be assumed from the time that information is received.
Coordinator awareness	Fixed Delay ((CPF Information*Collaboration)/(Reaction Time Delay), Reaction Time Delay, 0)	The coordinators use the information gathered to request police assistance or plan pre-emptive operations. The delay reduces the situation awareness that can be gained from the available information. The collaboration capability enhances the effectiveness of patrols.

7.3.5.2 Criminal Action

The level of criminal action occurring in a neighbourhood, with the impact contributed by different levels of collaboration capability is shown in the graph of Figure 76. The number of criminal incidents without collaboration resembles the current state experienced in local neighbourhoods.

The graph shows that even with limited collaboration, the effectiveness of incident responses should be improved, resulting in fewer “successful” crime incidents. The big fall after 24 hours is mainly due to the time delay of crime reported to the police. When this information contributes to the awareness of coordinators and patrollers, criminal activities are curtailed.

7.3.5.3 Community Policing Forum Information

Information in support of crime prevention operations consists mainly of suspicious behaviour reported and actual incidents reported to the police. The reporting of suspicious activities is dependent on the effectiveness of the patrols, and is influenced by the level of safety experienced. The actual crime-related incidents that occur take longer to report. Not all behaviour that eventually results in a crime is detected and reported. Collaboration increases the ability of various participants to contribute to the gathering and instantaneous reporting of information, as seen in Figure 77. The oscillations during the initial stages are due to the delays in the feedback loops of the model.

7.3.5.4 Coordinator Awareness

The ability of coordinators to address criminal behaviour is mainly supported by the amount of information available for situation awareness, planning and decision-making. A minimum reaction time is required for the police to take action. However, collaboration assists the different resources in effectively reaching and taking action on the incident through shared situation awareness. The effect of collaboration to assist in addressing different incidents is shown in Figure 78. More incidents can be addressed given available, even limited, information. This means that collaboration enhances the ability to utilise fully the available information. The oscillations during the initial stages are due to the delays in the feedback loops of the model.

7.3.5.5 Patroller Awareness

The patrollers can also benefit from the situation awareness derived from the available information, as seen in Figure 79, despite also experiencing a time delay. Having awareness of the current situation in the neighbourhood will make them more sensitive and attentive to certain situations.

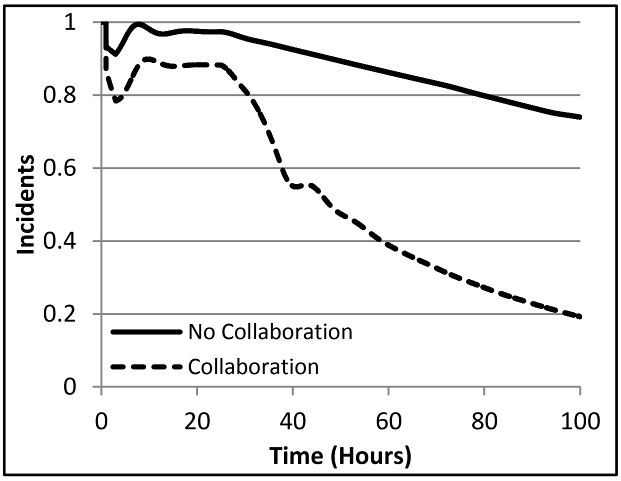

Figure 76: Criminal Action

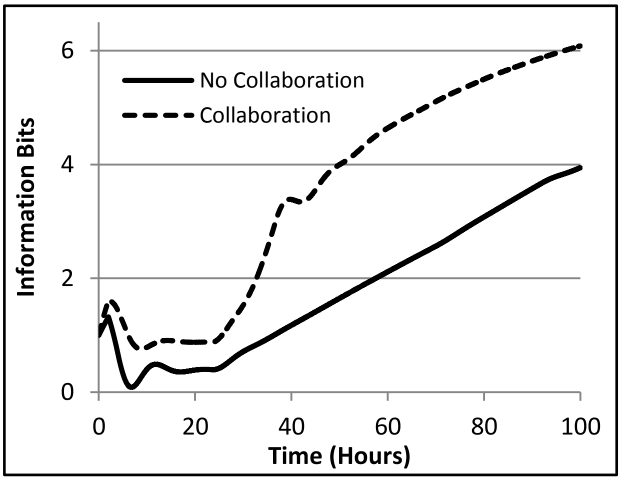

Figure 77: Level of CPF Information

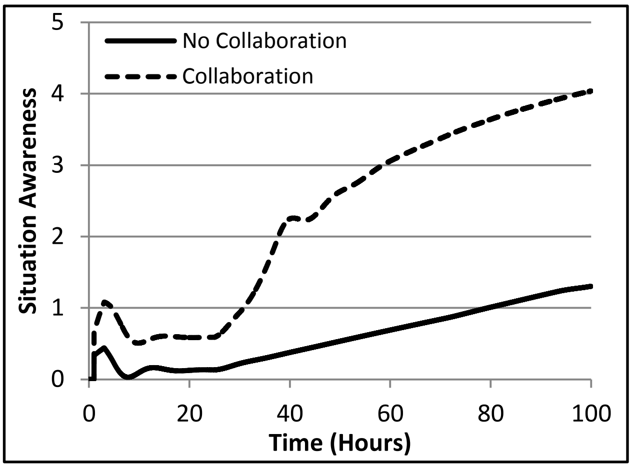

Figure 78: Level of Coordinator Awareness

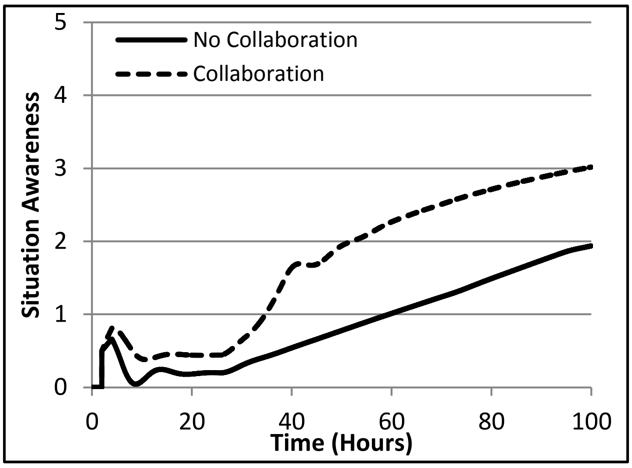

Figure 79: Level of Patroller Awareness

Again, the contribution of the collaboration technology to the whole system is visible. In this model it is assumed that the patrollers do not benefit directly from collaboration, and the resultant effect is visible in the graph. It is roughly at half the level of the coordinator awareness, as seen in Figure 78. This aspect can be measured during a field experiment. The oscillations during the initial stages are due to the delays in the feedback loops of the model.

7.3.5.6 Confirmatory Focus Group

The constructs, models and simulation outputs developed through the modelling methodology were discussed during a confirmatory focus group, consisting mainly of the same participants who participated in the exploratory focus group. The aim of the session was to make sense of the new technology in a NW system for CPF and to gain an understanding of how to derive the implementation requirements. This step supported the planning of field experiments.

Thirty minutes of the planned duration were used to present the models and the simulation results to the group. These served as topics for the discussions, and the focus group attendees were asked to comment on the various models and simulation output graphs. The details captured during the focus group discussions are provided in Appendix C.7. These inputs were used for improvements to the models. However, knowledge and experience gained from modelling Cmore in similar systems during the first two demonstrations resulted in higher-quality models that did not require many changes. Most of the issues were identified on the simulation output graphs. A brief summary of the key aspects derived from the focus group are as follows:

a) Cognitive Work Analysis. The confirmatory focus group participants felt that the ADH was adequate.

b) System Models. The confirmatory focus group participants felt that the system models were adequate.

c) System Dynamics Models. The following issues were identified with the elements in the CLD in Figure 74, and SFD in Figure 75:

  i) "Patrol safety" needs to affect the "Information" in the CLD.

  ii) Separate the variable of "Criminal activity" from the "Criminal action" flow in the SFD.

  iii) The reason and origin of the assumptions and initial conditions (values) need to be explained.

d) Simulation Graph Outputs. The following issues were identified with the simulation results of selected stocks and variables, as presented in Figure 76, Figure 77, Figure 78 and Figure 79:

  i) This results in the coefficients do change over time. This needs to be validated in the model.

  ii) If the graphs are considered over a longer period of time, oscillatory behaviour may result.

  iii) The collaboration should lead to a greater improvement in the patroller awareness.

  iv) Filters can be used to assess the data to determine the values of the parameters to provide the best parameter fit.

e) Corrective Actions. The following corrective actions were performed to update the models and simulations in preparation for possible experimentation:

  i) "Patrol safety" needs to affect the "Information" in the CLD.

  ii) Separate the variable of "Criminal activity" from the "Criminal action" flow in the SFD.

  iii) Update the names of the time delays, to be more representative and to assist in the empirical measurements.

  iv) Rerun the simulations to investigate the effect of coefficients that change over time, over a longer period.

Despite SD being an unfamiliar and specialised modelling approach, the output simulations enabled the focus group members to gain some understanding of the system's behaviour. This led to participants asking questions about assumptions and certain characteristics of the simulations. Discussions and comments helped to focus the analysis and modelling of the system in preparing field experiments.

7.3.5.7 Updates to Models

The updated CLD is shown in Figure 80. The variable "Patrol safety" was linked to the variable "Information" to bring the CLD more in line with the mental models of the system stakeholders. The updated SFD is shown in Figure 81. This change results in criminal activities being detected without patrollers getting involved with the criminals. The changes to the different models should assist in interpreting the model and understanding the simulation outputs.

7.3.5.8 Updates to Simulations

Implementing the initial changes to the models did not result in major changes in the simulation outputs. These were mainly to ensure that the structure of the models is representative of the stakeholders' mental models. The parametric outputs of the simulations are to be compared with the field experiment outputs to confirm the structure of the models before conducting more complex simulations. It was decided not to redo all the simulations with filters to investigate the effect of coefficients and time delays, but rather to conduct the field experiment first. The knowledge thus gained will improve the assumptions made in the model.

The simulation results from the updated models are only shown with feedback from the incorporated case study experiment. The case study assists in identifying possible values for variables.

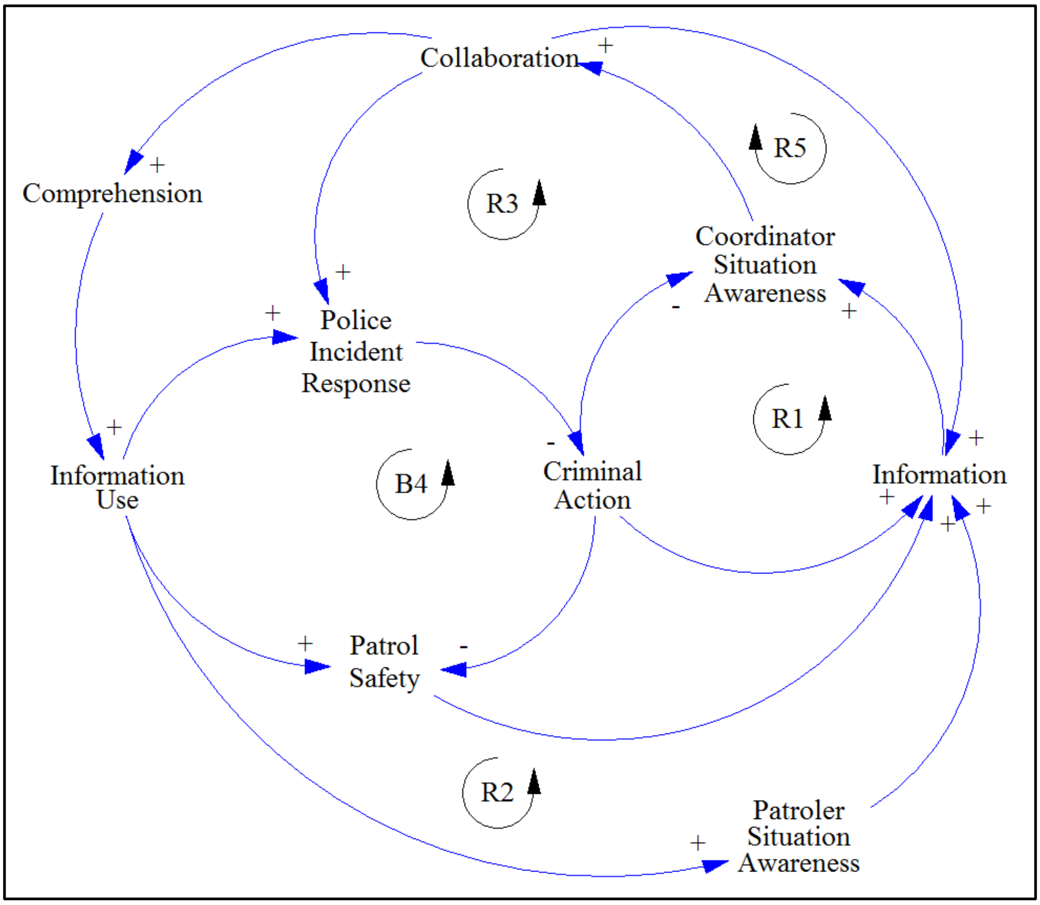

Figure 80: Updated Causal Loop Diagram for Neighbourhood Watch with New Technology

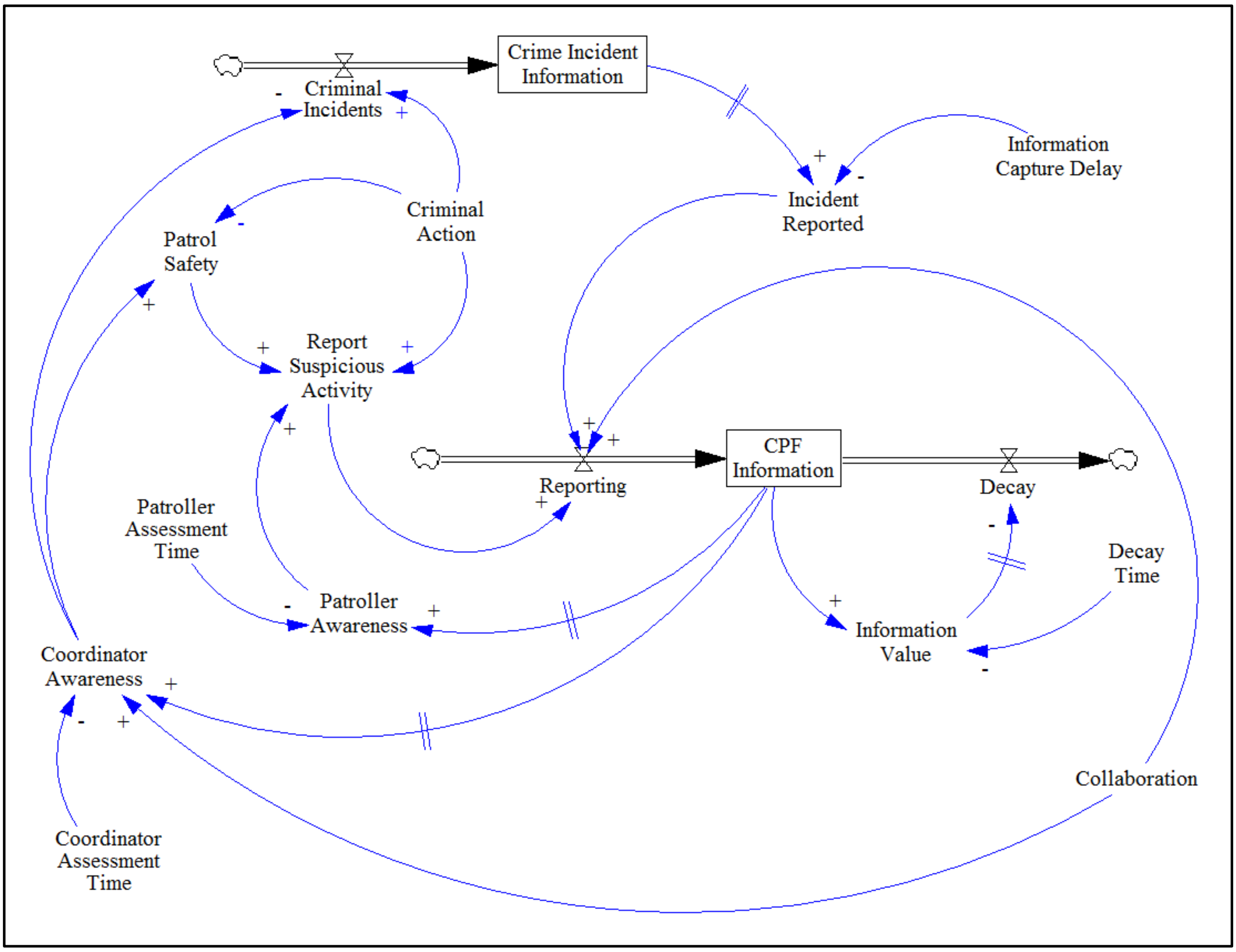

Figure 81: Updated Stock and Flow Diagram for Neighbourhood Watch with New Technology

7.3.5.9 Conclusion

The models on the system and technology implementation are not perfect representations of the system and its influence on the environment, but can still be used to learn about the influence of the variables on system behaviour. Effective collaboration between the patrollers, shift coordinators and the control room will increase the amount of information captured. With the new technology, more information on incidents can be recorded for input to the CPF system. The increase in information will improve situation awareness and resulting decisions. The awareness of the patrollers of what is unfolding will improve their ability to address criminal behaviour.

One clear output is showing the effect of delays on the stability of the system, as is predicted by the theory on C2. These exist from observing suspicious behaviour to reporting it, from the information being available to when it contributes to situation awareness, and from making a decision to taking action. These delays may lead to dynamic and oscillatory behaviour in the system. As patrols and other CPF activity operations become more effective, there could also be less information available from actual incidents for planning further operations. This effect in the

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system is somewhat counterintuitive and highlights the need to consider using less information that is available more effectively.

These aspects will serve as a guideline on what aspects to measure during experiments with the new technology. More data from experiments will improve models and simulations. The next section executes the case study and field experiment to investigate the impact of Cmore.

7.3.6 Evaluation to Determine Ability of Artefact to Solve the Problem

7.3.6.1 General

The final evaluation of the modelling methodology is in the form of an empirical case study. The aim of the case study is to evaluate the ability of the modelling methodology to support understanding the effect of a new technology on a complex STS. This was achieved through implementing a new technology into an existing complex STS to determine if the developed models provided insight into the observed behaviour.

As seen from modelling in the preceding sections of this chapter, the technology is a web-based collaboration tool, called Cmore, utilising smartphones. The complex STS is a CPF in a residential area of Pretoria (South Africa). The models provided insight on how the technology will be used in the complex STS and what its contribution will be to the system’s success. The SD models and simulation results guided planning the setup and measurements in the experiment. In an analysis, the experiment's results are compared with the models and simulation results, and are used to update the model. The purpose of the data is to assist in iterative model and simulation improvement, as part of a learning process.

The absolute accuracy of the data captured is not of critical importance, as the aim of this case study is to demonstrate that the complete modelling methodology can be executed. The data recorded during the case study is not to be used to prove or disprove a theory. The data has to be useful in helping stakeholders understand the problem situation and the possible contribution of the new technology. However, basic statistical tests will be performed on the data samples to confirm the identified hypotheses.

7.3.6.2 Case Study Design

The case study was executed through the deployment of Cmore in a CPF system. Empirical evidence was gathered on Cmore’s utilisation to confirm the modelling methodology’s ability to develop useful models. Empirical data were captured from users of Cmore through a survey in the form of structured interviews with questionnaires. This formed part of a pilot study to assess the use of Cmore in local CPFs. Because patrols often consist of rotating teams, the participants were exposed to Cmore only once during the experiment period.

The models, constructs and simulations developed through the modelling methodology identified the characteristics to be addressed in the interviews. The SD modelling and simulation provided insight into the structure of the system and the resulting dynamic behaviour. The main unit of analysis is the situation awareness developed from information captured during patrols and other sources. Structured interviews before and after introducing the new technology were used to capture the data on situation awareness with and without Cmore. However, the experiment captured "static" snapshots of the system status before and after introducing the technology.

As seen in Figure 82, the first step is for the participants, both coordinators and patrollers, to complete informed consent forms before completing the "before" questionnaire, provided and explained in Appendix A (Table 22). This is followed by a briefing on using the Cmore technology. The intuitive interface of Cmore enabled using it with limited experience and training. Each patroller was supplied with a smartphone with the required capability, airtime and software. The coordinators, who normally operate from their homes, were supplied with a laptop with the Cmore portal and Internet connectivity. The patrollers using the mobile version had to abide by the same rules as those using a mobile phone while driving a vehicle.

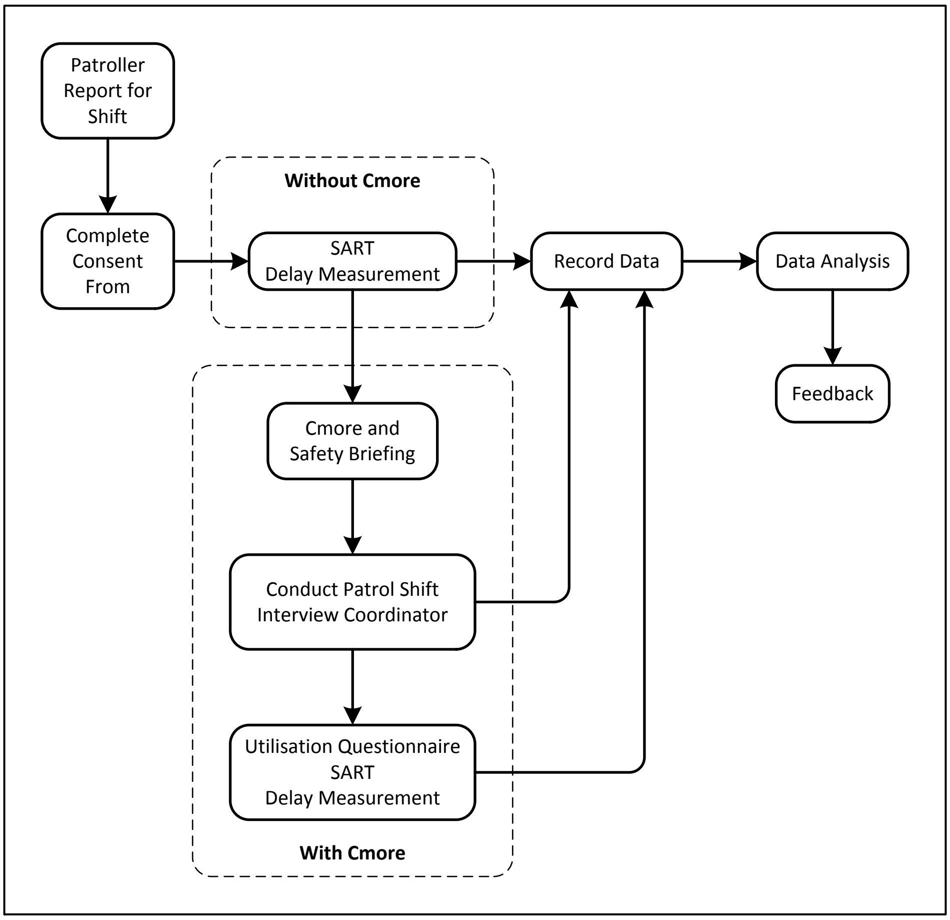

Figure 82: Case Study Execution Process

The only difference between the two situation awareness measurements is that the patrollers and coordinators were exposed to using Cmore while performing their activities. As the patrollers and coordinators work mostly on weekly rotations, they have a level of awareness of what to expect during the shift. After the two-hour shift, each patroller completed a questionnaire on using Cmore as well as a rating questionnaire on situation awareness, as seen in Table 23 in Appendix A.

The shift coordinator also completed the same questionnaires as the patrollers after at least one shift. Informal interviews were conducted with the coordinator, while the patrollers executed their shift, to discuss various aspects concerning the models. The aim was to confirm the time delays, information flow and other assumptions in the model.

7.3.6.3 Questionnaire Development

Empirical information in the case study is captured through a survey on the utility of the new technology and situation awareness gained. The survey uses structured interviews in the form of questionnaires to capture the data from the system users. Construction of the questionnaires was guided by the updated WDA (Figure 70) and CLD (Figure 80), which were populated from the literature and focus group inputs.

The empirical information had to confirm that the structure of the WDA correctly captured knowledge about Cmore in the STS. Since the users had to comment on the effect of Cmore on the way they performed their work, the evaluation focussed on the purpose-related functions and the supporting (enabling) object-related functions. This is used to compare the system and the problems experienced without the new technology to the utility provided by Cmore.

The issues listed in Table 20 and Table 21 were used to compile the questionnaires for use during the case study, as seen in Appendix A.2 and A.3. The technology application questions use a 5-point Likert scale (Vagias 2006, Vogt 1999), ranging from strongly disagreeing to strongly agreeing, to various statements on operation without the new technology. These relate to the assumptions made in modelling and simulating the system.

Because this case study investigates a “technology push” situation, most of the patrollers and coordinators would not be aware of the inherent shortcomings of the system and the possible contributions of a technology solution. Therefore, it was decided to complete the questionnaire on using the technology after demonstrating and allowing user experience of Cmore. Also, the time constraints on conducting the survey necessitated reducing the length of the questionnaires. The time before beginning a patrolling shift had to be divided between completing the questionnaires and providing instruction on using Cmore.

The situation awareness rating technique (SART), as described in section Chapter 2, was used in this case study to measure the difference in situation awareness with and without the new technology. The SART measures general situation awareness constructs and relies on an understanding of the situation of the operators in making decisions. This understanding is often conscious, explicit and quantifiable. This situation awareness measurement is useful for both field and laboratory settings (Salmon et al. 2006, Taylor 1990). Generally, the patrollers and coordinators have some level of experience in patrolling to in order to comment effectively on their level of situation awareness. The overall situation awareness rating or score, which is useful for comparison, is calculated by the following equation (Taylor 1990):

$$\textit{Situation Awareness} = \textit{Understanding} - (\textit{Demand} - \textit{Supply})$$

As the SART was initially developed for situation awareness measurements of pilots during various missions, the questions needed minor adjustments to make them understandable and relevant for the patrollers and coordinators of the CPF environment, as seen in Table 22 and Table 23 in Appendix A.3 (Taylor 1990). Despite a change in the wording and scenario descriptions, the key variable measured per question was retained.

The first SART questionnaires would be completed before exposure to Cmore. Questionnaires on the SART and the effect on work in the system would also be completed after being exposed to and using Cmore. The same sheets were used for patrollers and coordinators. The questionnaires were simplified and condensed to fit one A4 sheet. Interviews had to be completed in less than 10 minutes, as the patrollers (volunteer) wanted to return home after their shift (most of the interviews were conducted late at night).

7.3.6.4 Case Study Execution

The case study was completed over two weeks in October 2014. A total of 20 patrollers and 14 shift coordinators from two different neighbourhoods in the East of Pretoria (South Africa) were interviewed. Before evaluating a specific patrol team, coordinators were contacted for their consent, and to make arrangements for engaging the patrollers. Before deployment of the Cmore base station with the coordinators, the initial questionnaire was completed. With the system operational, informal interviews were conducted while coordinators were monitoring their patrollers. At the end of the interviews, the after questionnaire was completed. The main purpose of the interview was to determine the accuracy of the assumptions and time delays in the models.

The number of respondents was increased with four co-workers at the CSIR from other regions of Pretoria, who also participate in NW patrols in their own residential areas. They were given a demonstration of the technology before having to complete the questionnaires from the perspective of their specific neighbourhood. This is supplementary to the field experiments. The advantage is that the technology's utility was exposed to a larger geographical area with the other regions' specific modus operandi and operational constraints.

A summary of the completed questionnaires and recorded data is provided in Appendix E. The main shortcomings and problems experienced during the case study were the following:

a) Very few incidents were recorded during the night, as the smartphone cameras with limited flash functionality did not work very well.

b) The novelty of the new technology may provide a skew measurement, as most patrollers were excited to be assisted in this way.

c) Different age groups had varying opinions of the new technology. Many of the older respondents are not used to using smartphones and could not effectively capture information during their shifts.

d) The limited exposure to the utility of the technology may also have resulted in skewing the opinions and ratings in the questionnaires.

e) Questionnaires completed at late hours did not always receive the same attention as those completed during daytime hours.

f) Since the experiment started with a blank system without information having been captured, understanding the value of the technology was hampered. This was rectified through the manual input of historic incidents from the past month. Also, as the experiment progressed, more incidents were captured by the patrollers with the smartphones.

g) It was difficult to get a bigger sample, especially of the coordinators, as they are normally in a ratio of 1 to every 10 patrollers.

Despite the difficulties, adequate data was captured over the experiment period for the intended purpose of qualitative, and to some extent quantitative assessment. This was analysed to improve the models and simulations on the impact of Cmore on the CPF system.

7.3.6.5 Case Study Analysis

7.3.6.5.1 General

The previous steps of the modelling methodology investigated how the new technology contributes to the success of the complex STS as well as how it affects the way work is done. The data analysis subsequently has to determine how well the system models and simulations, CWA and SD, correspond to the empirical evidence. The questionnaires focussed on the possible improvement of situation awareness levels and utilisation of the system. The information captured during the interviews has to be related to the models and simulation results from the modelling methodology to verify the understanding gained on system behaviour.

The SART results, captured before and after introducing Cmore, were analysed in terms of the three main variables (demand, supply and understanding) as well as the resulting calculated situation awareness. Box and whisker plots were used to present and interpret the recorded data, as it enables the researcher to reason about information in complex tables. These plots provide an exploratory analysis of patterns regarding the shape, variability, and median of a statistical data set, through a graphical summary. The metrics include the median, quartiles and the lowest and highest data points, to present the symmetry, spread, and level of a distribution of data values (Williamson et al. 1989).

Due to the small sample size, visually inspecting the graphs is the main method of analysis of the outputs. However, limited statistical analysis is used to assess the quality of the data sample. Categorical frequency (count) data is captured during the SART and utilisation questions. The Chi squared test (χ^2) is used to test the sample distribution for the case when the null hypothesis is true and test the association between two variables. The null hypothesis of the case study is that the SART test before and after introducing the new technology will be the same (Wackerly et al. 2007).

As the sample size in the case study is rather small, many of the expected values ended up smaller than five. In reality this called for Fisher's Exact Test with a 2 x 2 matrix. Since the analysis of before and after SART data on implementing Cmore requires a 2 x 7 matrix, this option was rejected. As the SART calculates the situation awareness through summing and subtracting 10 variables grouped in three categories, the values for the variables (the 10 questions) per category (demand, supply and understanding) were combined. This reduced the number of counts with a value less than 5 to enable calculating acceptable p values. Due to the small sample size, the value $\alpha = 0.1$ is used for comparison with p to reject the null hypothesis (Wackerly et al. 2007). A summary of the p values is provided in Table 15. From these p-values, the null hypothesis can only be rejected for the Understand category of the SART test for both the patrollers and coordinators.

Table 15: SART Data p-Values

	Demand	**Supply**	**Understand**
Patrollers	0.944	0.907	0.04
Coordinators	0.860	0.754	0.0001

7.3.6.5.2 Patrollers

The distributions of the data on the different SART variable categories for the patrollers are presented through the box and whisker plots in Figure 83. These categories are the same as used during the chi-square test.

The first three SART questions focus on the demand of the environmental conditions, and should be the same for both before and after measurements. This is correct, as Cmore does not change the complexity existing in the environment. This can be seen as a limited way of validating the questionnaire before and after using Cmore. With p = 0.944 (Table 15), the null hypothesis cannot be rejected on these variables, as Cmore does not affect the situation awareness demand on the CPF system.

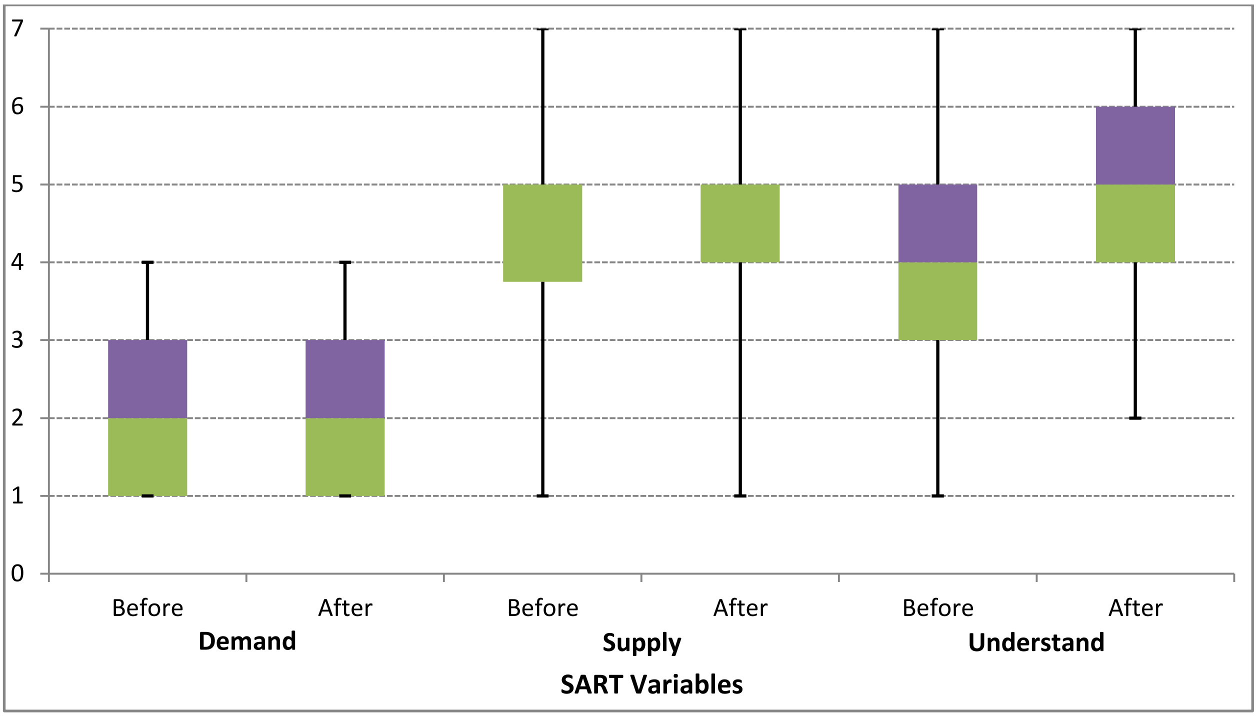

Figure 83: **Patrollers SART Variable Categories**

The next four SART questions focus on the variables required for the supply of elements required for situation awareness by the patrollers. Also with p = 0.907 (Table 15), the null hypothesis cannot be rejected on these variables. Cmore does not benefit the patrollers a great deal, as patrollers do not often operate the smartphones when patrolling, which is their interface to Cmore. Their eyes are on the road to look for suspicious elements or behaviour. The smartphones are mostly used for recording an incident after it has been detected.

The final three SART questions focus on the variables required for understanding the situation through the available information in support of patroller situation awareness. In contrast with the first two sets of variables, a slight increase is observed between the measurements without Cmore and those with the new technology. Cmore does provide the patrollers access to the available information through the web browser on the smartphone. Also, the contextual information on the incidents, the quality of information, is increased through the smartphone capability, as opposed to radio messages. This leads to improved identification and classification of the situation to determine the required course of action. With p = 0.04 (Table 15), the null hypothesis can be rejected on these variables, and a limited contribution of Cmore to patrollers accepted.

The final graph for the SART is the calculated situation awareness, as seen in Figure 84. This is calculated from the variables listed in the graphs above. According to the graph, using Cmore should result in an increase of the median value of the situation awareness from 23 to 26.5. This represents a small increase in performance, which is mainly due to the information on incidents, and tracks the CPF being available in the smartphone.

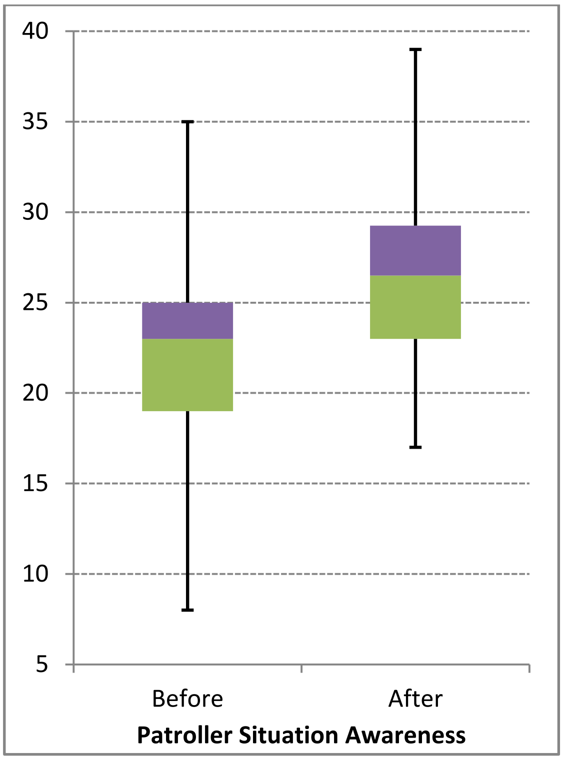

Figure 84: Situation Awareness of Patrollers

The SART evaluation on using Cmore for patrollers alone is not conclusive, and does not promote a widespread implementation. From the empirical data analysis, it can be deduced that the patrollers do not require a smartphone in the vehicle or the web-based access to information for improved situation awareness. They are active for only two hours and need eyes on the road to detect suspicious behaviour or other incidents. The smartphones do however afford them the ability to capture and distribute information for the coordinators to apply.

7.3.6.5.3 Coordinators

The distributions of the data on the different SART variable categories for the coordinators are presented in the box and whisker plots in Figure 85. These categories are the same as those used during the chi-square test.

The questions on the demand of the environmental conditions did not change between the two measurements. This is correct, as Cmore does not change the complexity existing in the environment. This can be seen as a limited way of validating the questionnaire before and after using Cmore. With p = 0.860 (Table 15), the null hypothesis cannot be rejected on these variables.

The supply category for coordinators also remains the same. Despite having access to information, the Cmore portal does not affect the coordinators' level of alertness, concentration, attention and demands on mental capacity. The graphical display of incidents and contextual information also reduces the load on their concentration when interpreting incidents.

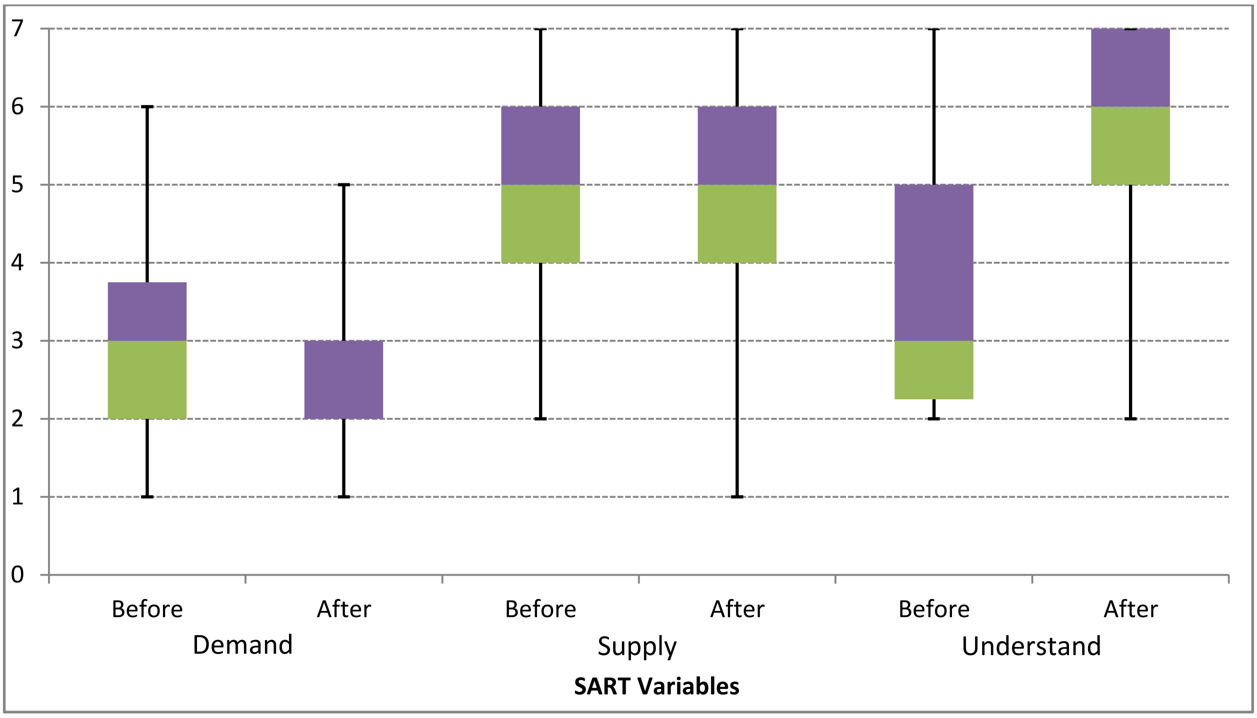

Figure 85: Coordinator SART Variable Categories

The NW environment provides for a low-intensity environment with long periods of nothing happening, possibly interrupted by a few, and sudden incidents. Again, with p = 0.754 (Table 15), the null hypothesis cannot be rejected on these variables.

The final SART category on understanding the situation considers the available information in support of coordinator situation awareness. In contrast with the first two sets of variables, a clear increase is observed between the measurements without Cmore and those with the new technology. Cmore does provide the coordinators access to the available information, past and present, through the web-based portal. With p = 0.0001 (Table 15), the null hypothesis can be rejected on these variables and the contribution of Cmore to coordinators accepted.

The SART situation awareness graph for the coordinators calculated from the variables listed in the graphs above is provided in Figure 86. According to the graph, using Cmore should result in an increase of the median value of the situation awareness from 22 to 30.5. This definite increase in the performance of the coordinators is mainly the result of information on incidents, and tracks the CPF being available. The SART evaluation of the use of Cmore for coordinators does promote a widespread implementation.

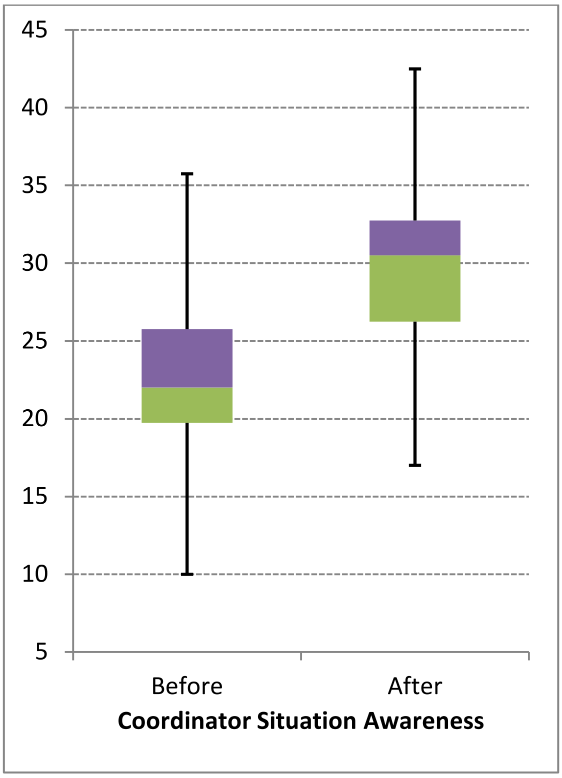

Figure 86: Situation Awareness of Coordinators

7.3.6.5.4 Technology Utilisation

Again, visually inspecting box-and-whisker graphs is the main way of analysing the evidence on utilising the technology captured during the experiment. Limited statistical analysis is performed to support the deductions made. As discussed before, it was decided to complete the utilisation questionnaire only after exposure to Cmore, due to time constraints as well as a lack of knowledge on the current system's deficiencies and the capability of possible solution technologies.

The way the questions were constructed was aimed at supporting a hypothesis that Cmore would provide a contribution to the work performed in the system. Therefore, the chi-square test can compare the actual Likert-scale results to presumed negative and uncertain responses for the case of "before" Cmore introduction. To generate "before" data for comparison in the chi-squared test, the Likert-scale categories (1 to 5) were distributed evenly across the total data set. Values of 1 to 5 were each assigned to 6 data points in the total population, making the average of the test sample 3. This represents a population that is uncertain about what the problems are and what the solution should do. Despite this, the p-values clearly rejected the null hypothesis that Cmore would not contribute to using the system, as seen in Table 16.

Table 16: System Utilisation Data (p-Values)

	Ease of Report	What to Report	More Info	Utilise	Coordinate	Safety	Effectiveness
System Use	0.00052	6.6E-05	5.3E-05	0.00097	0.0022	0.0052	0.00025

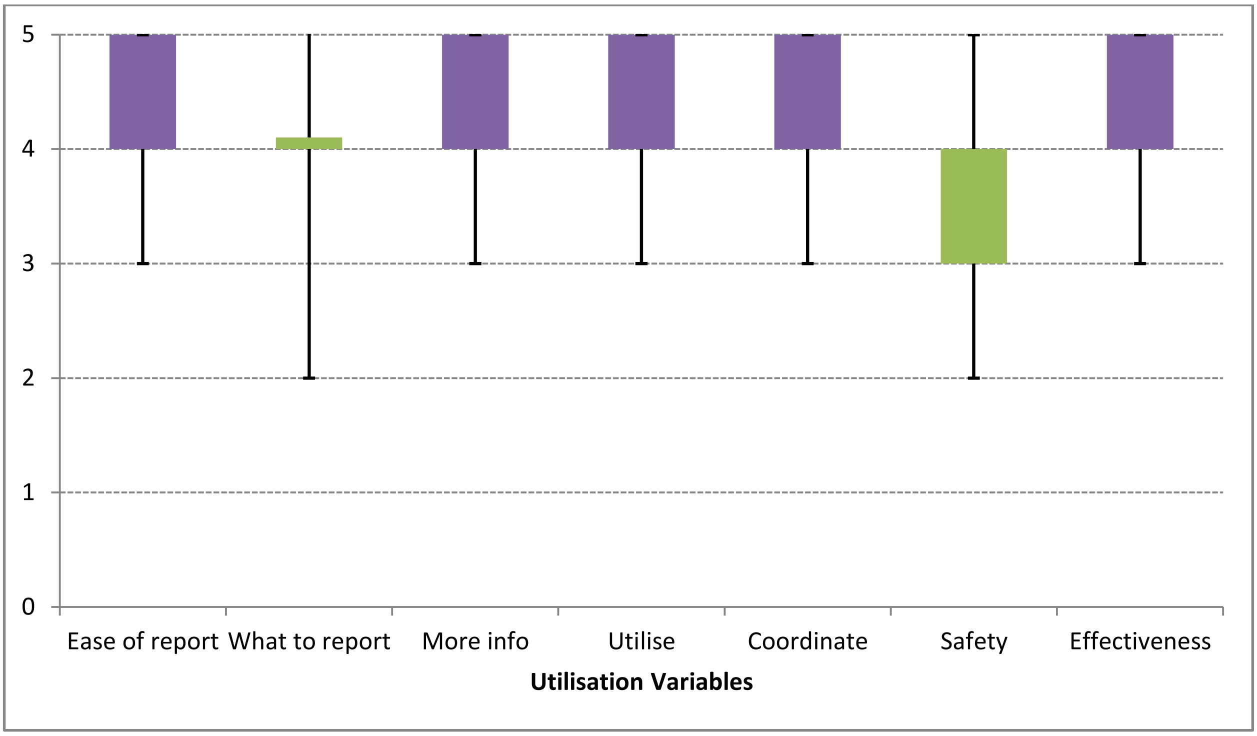

Figure 87: Discriminated Effect of Technology on Work

The results from the effect of the technology on performing work in the system is summarised in Figure 87 with box and whiskers plots. The graph shows that the respondents agree with the structure of the WDA and the CLD modelling artefacts.

7.3.6.6 Case Study Results Discussion and Implementation

The first iteration of the modelling methodology focussed on the parametric issues of the models on the problem and solution space. This supported the capturing of actual empirical data during a field experiment with the solution technology (Cmore) in a complex STS. The SD simulations indicated that Cmore should contribute to the level of information in the system and the resulting awareness of the participants. The empirical evidence also highlighted the value of information available to (especially) the coordinators in achieving situation awareness, as seen in Figure 85. However, these measurements achieved a snapshot view of the system, and do not consider the dynamic behaviour in the system.

The insight gained during the informal interviews was also used to update the SD, specifically SFD, models for improved simulations. This knowledge, based on actual data, was used to improve the models for another iteration of modelling and simulation.

7.3.7 Final Modelling Methodology Iteration

7.3.7.1 Introduction

In this section the knowledge gained from the experiment is used to update the models and simulations to improve the learning about the problem and solution space.

7.3.7.2 Model Updates

This is the third and last iteration in the modelling methodology from Figure 69, which focuses on the effect of delays on the dynamic behaviour of the system. The first iteration confirmed the structure of the system models and the contribution of the technology to the coordinator situation awareness (Section 7.3.2 to 7.3.5). Since the data on using Cmore in the system has confirmed the structure of the models, no changes to the ADH and the functional diagrams were required. The case study experience and analysis of the data indicated that the variable "Situation awareness" in the CLD of Figure 80 relates almost entirely to the coordinator. This is fixed, as seen in Figure 88, by separating coordinator situation awareness and patroller situation awareness. The patroller will only gain situation awareness from how the coordinator collaborates and utilises the available information. This will affect the way the SFD is constructed and interpreted.

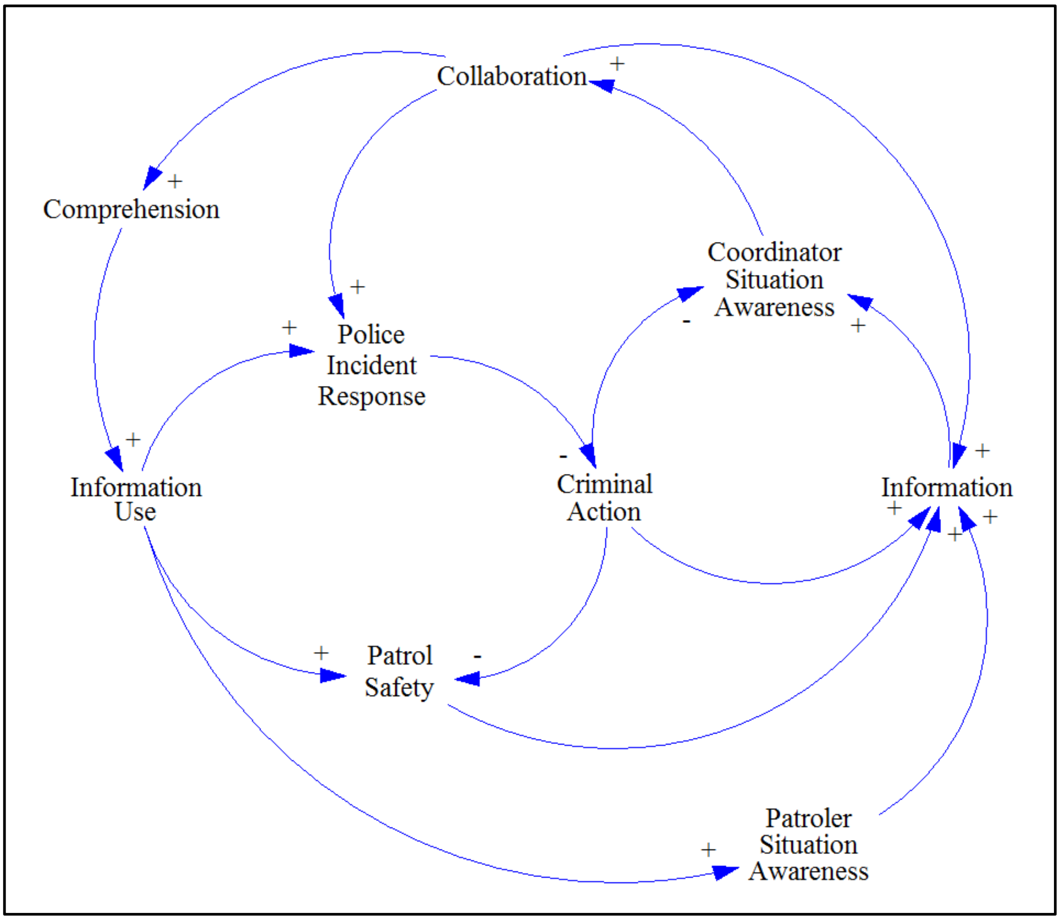

Figure 88: Final Update of Causal Loop Diagram for Neighbourhood Watch with New Technology

With the structure of the models confirmed, a parametric assessment and "snapshot" of empirical evidence, the focus subsequently shifts to the dynamic behaviour of the complex STS. Informal interviews during the experiment with the coordinator respondents were used to gather information on the time delays in the system, and the effect thereof on performing work. Lessons learnt from the previous simulations and the field experiment, including the informal interviews, were used to update the SFD from Figure 81 to what is seen in Figure 89. The variable equations for the SD simulations were updated as seen in Table 17. The main changes implemented are the following:

a) From the empirical data, it was determined that Cmore does not contribute to the situation awareness of patrollers, only to coordinators. However, the coordinator will communicate this to the patrollers in terms of lookouts and requests for focus on certain areas.

b) Every two hours a new patroller starts a shift without situation awareness; this has to be updated again if the coordinator is available.

c) As not all incidents are prevented during patrols, a variable of "Patrol effectiveness" was added.

d) The input patterns were updated.

e) The delays as derived from the purposive sampling were implemented.

f) Due to the size of delays, the sampling rate of the simulations was changed from hours down to minutes.

g) The effect of coordinator awareness and patrol effectiveness on the ability of criminal actions to create incidents were included.

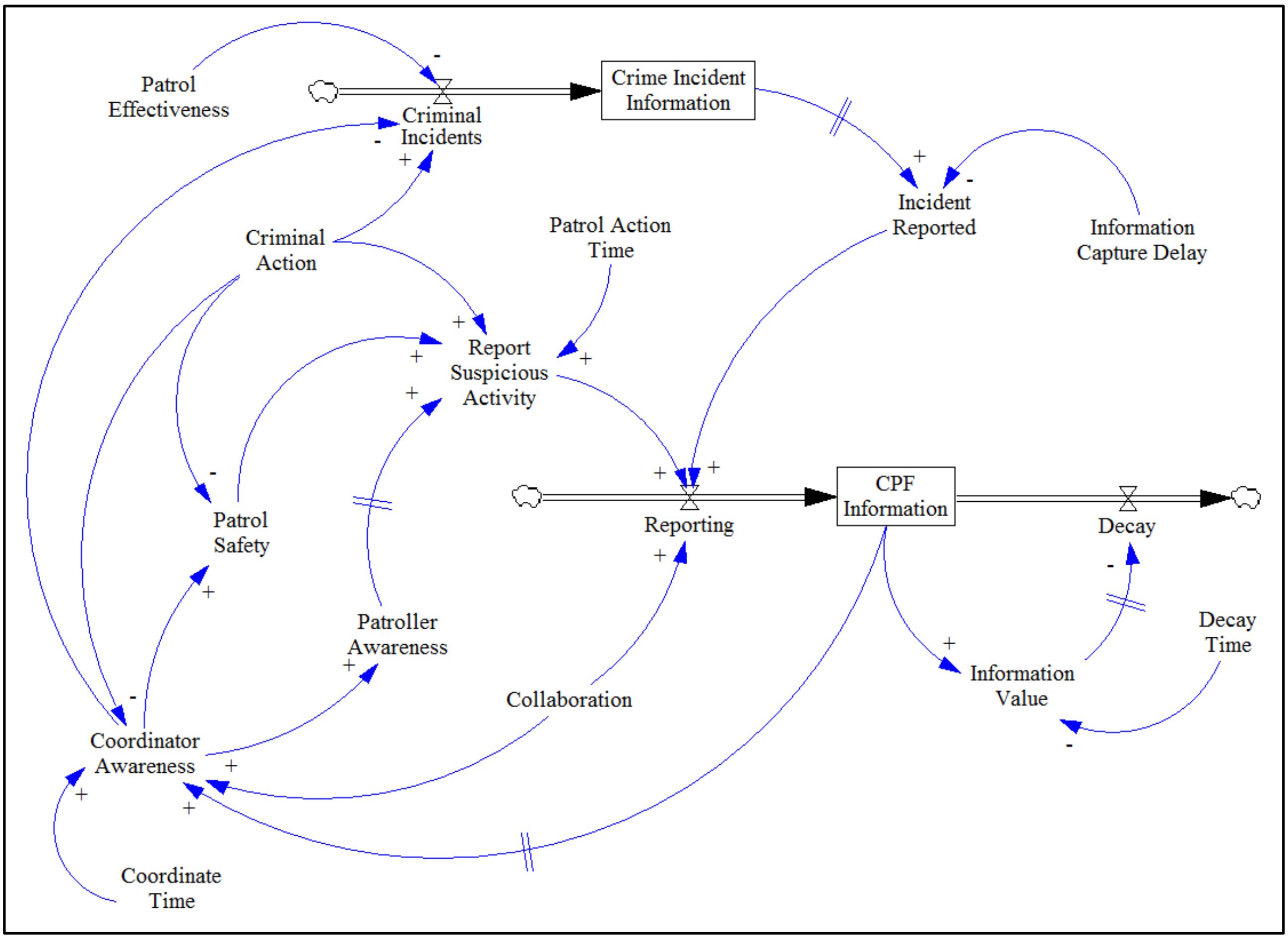

Figure 89: Final Update of Stock and flow Diagram for Neighbourhood Watch with New Technology

Table 17: Updated Variable Formulae for System Dynamics Simulations

Variable	Formula	Explanation
Criminal incidents	MAX(0, Criminal Action-Coordinator Awareness/Patrol Effectiveness)	Incidents are the result of criminal action, which is affected by the coordinator's actions due to awareness; in turn, these are affected by the effectiveness of the patrol. This cannot go below zero.
Report suspicious activity	DELAY FIXED (MIN((Criminal Action+Patrol Safety+Patroller Awareness), Criminal Action), Patrol Action Time, 0)	Patrollers report criminal actions, which is improved by patroller safety and awareness. Nothing will be reported if there is no criminal action. Reports are delayed due to the duration of the patrol shift.
Patrol safety	MAX(Coordinator Awareness-Criminal Action, 0)	Patroller safety is increased by the awareness of the coordinator and decreased by criminal activity. It cannot go negative.
Incident reported	DELAY FIXED ((Crime Incident Information/Information Capture Delay), Information Capture Delay , 0)	The crime incidents are reported to the police and may be received by the CPF after a delay. The value of the information is reduced due the capturing time delay.
Reporting	MAX((Report Suspicious Activity + Incident Reported)*Collaboration, 0)	All sources of information are captured in the CPF information system. Effective collaboration will improve the ability to report information. Information reporting cannot go negative.
Information value	DELAY FIXED(CPF Information/Decay Time, Decay Time, 0)	Older information is of less value. The decay time is assumed to be two hours.
Patroller awareness	Coordinator Awareness	Patrollers may be aware of criminal trends in the neighbourhood, as received from the coordinators.
Coordinator awareness	DELAY FIXED (((CPF Information* Collaboration)/(Coordinate Time))-Criminal Action*2, Coordinate Time, 0)	The coordinators use the accumulated information to request police assistance or plan pre-emptive operations. The information assessment delay reduces the situation awareness that can be gained from the available information.

7.3.7.3 Simulation Outputs

To assess the dynamic behaviour of the system, parametric and Monte Carlo multivariate simulations were performed. The updated SFD presented S-Shaped growth with overshoot mode of dynamic behaviour, as seen in Figure 90 and Figure 91, to accumulate information and to convert it to situation awareness. The S-Shaped curve presents initial exponential growth followed by goal-seeking to an equilibrium level. This is a result of the carrying capacity of the system and its environment. S-Shaped growth exists if the nonlinear positive and negative feedback loops do not have significant delays, and the carrying capacity must be fixed. The overshoot in S-Shaped growth is a result of delays in the feedback loops, causing an oscillation around the carrying capacity of the system, as determined by the available information on criminal activities (Sterman 2000, Meadows 2008).

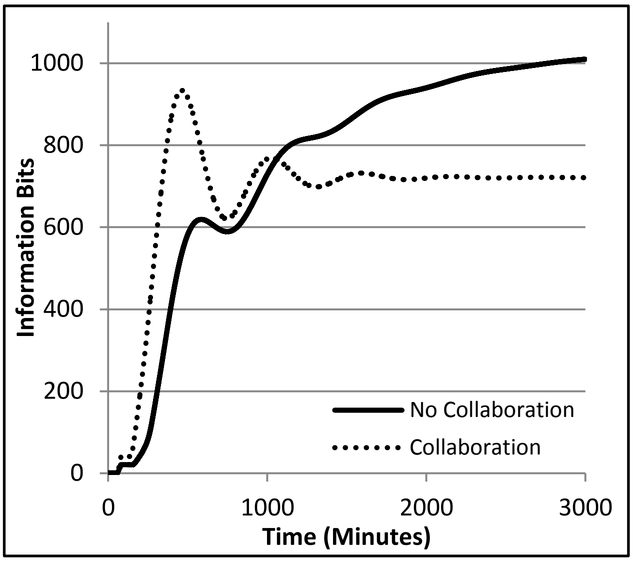

Figure 90: Level of CPF Information

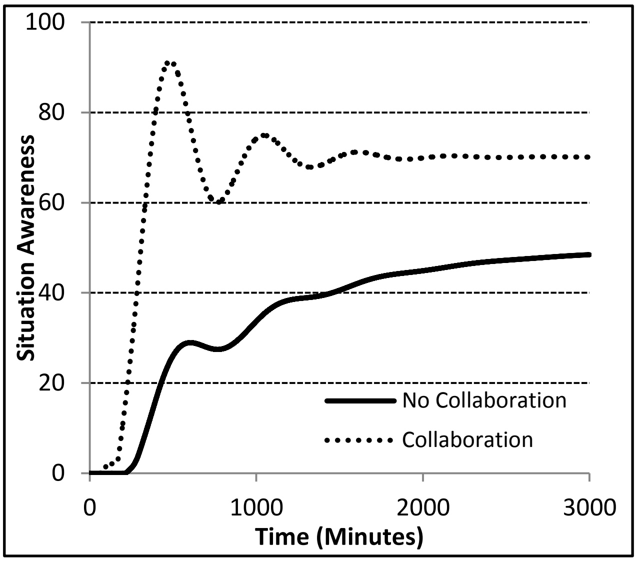

Figure 91: Level of Coordinator Awareness

The steady state of the coordinator situation awareness in Figure 91 is higher than without the technology, which relates to the empirical evidence. The steady state is achieved only after a long period, as the users of the system first have to learn how to use the technology. This is also complicated by the delays in the system. The oscillations in the initial stages of the graph requires deeper analysis, as the fluctuating levels of situation awareness may cause the coordinators to lose faith in the technology, and thus hamper its acceptance in the STS. Another interesting observation is the ability of Cmore to enhance the level of coordinator situation awareness relative to the available information.

7.3.7.4 Sensitivity Analysis

The SD models are also useful to investigate the uncertainties in the system models as well as possible variables that can be managed through policy or other user guidelines (Sterman 2000, Meadows 2008). The variables from the SFD in Figure 89, chosen for sensitivity analysis are "Patrol effectiveness", "Coordinate time" and "Criminal action". These affect the coordinator awareness and the criminal incidents occurring, which are important variables identified through the modelling process.

The Monte Carlo facility in Vensim was used to investigate the effect of uncertain variations of the chosen variables on the key parameters in the model. Normal distributions were used for the variations in all the chosen variables. A summary of the variations selected in Vensim is provided in Table 18. The simulations were only performed for the system with the new technology implemented. The results of the sensitivity analysis for coordinator awareness are provided in the combined views of the graphs in Figure 92.

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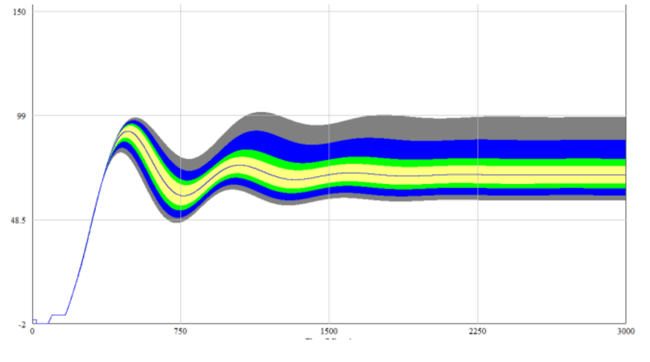
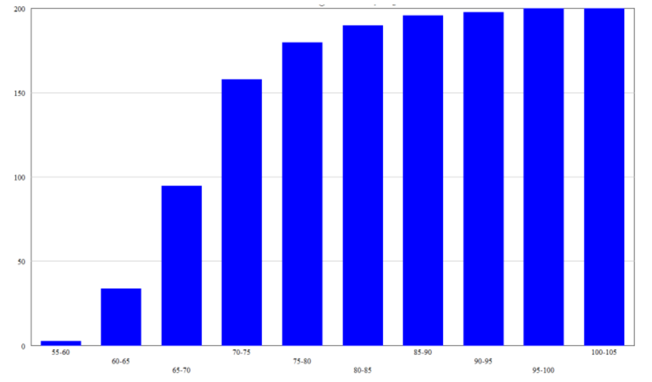
<tr><td>
</td><td>
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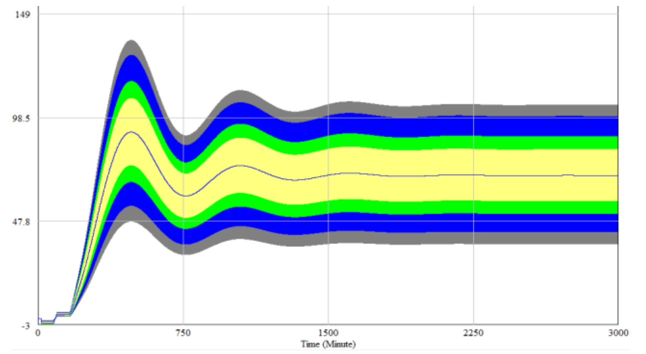
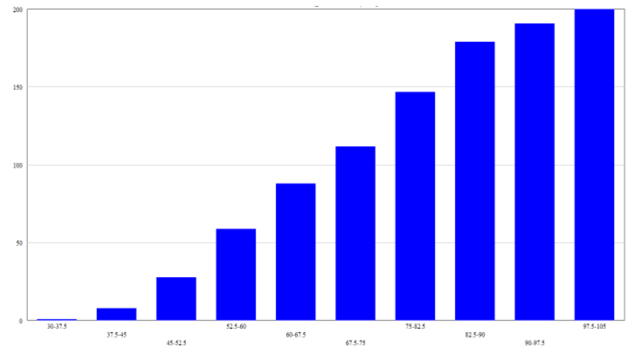
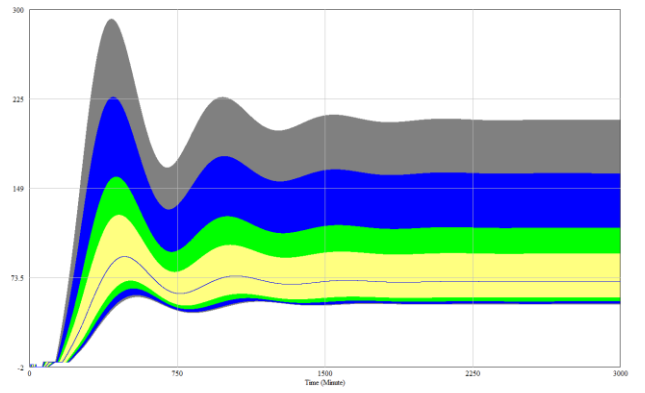
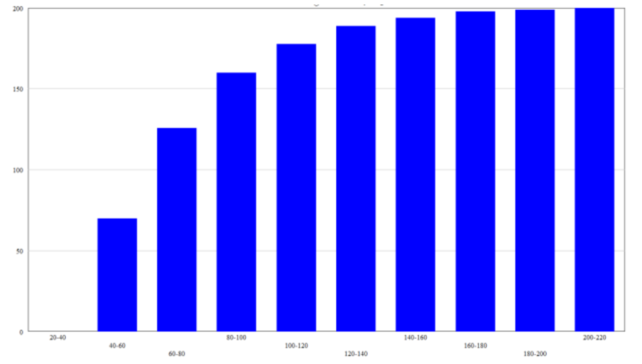
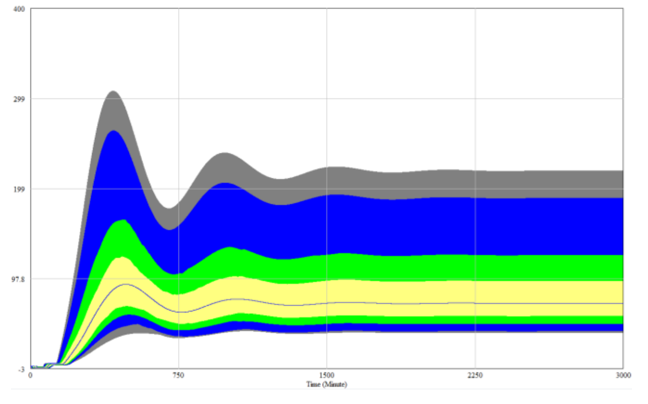
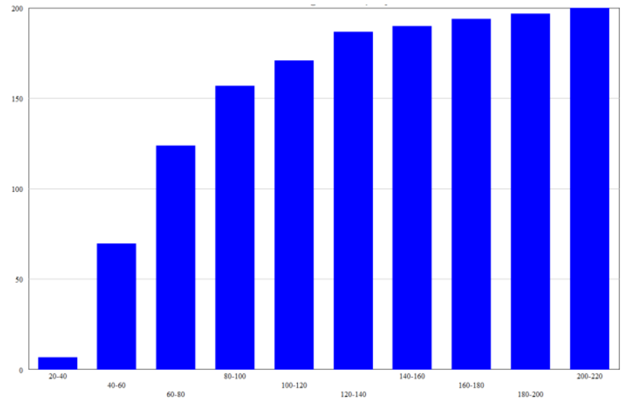
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">Criminal Action</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">Coordinate Time</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">Combined Influence</td></tr>
</table>

Figure 92: Monte Carlo Output for Coordinator Awareness

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Table 18: Normal Distribution Settings

Variable	Value	Minimum	Maximum	Mean	Standard Deviation
Patrol effectiveness	50	10	100	40	20
Coordinate time	1	0.5	1.5	1	0.25
Criminal action	20	5	35	10	10
Information capture delay	120	20	200	120	30
Decay time	120	20	200	120	30
Patrol action	60	20	100	60	20

The sensitivity analysis of the effect of the various variables on the coordinator situation awareness indicates that the model is robust. The same oscillatory behaviour is present in the analysis of all the variables individually as in a combined simulation. Also, the end state of all the outputs reflects the similar steady state conditions. The histograms are also consistent, and reflect the cumulative effect of a normal distribution of uncertainty in parameters.

The Monte Carlo facility in Vensim was also used to investigate the effect of variations of the delay times on the key parameters in the model. These are the main reason for the oscillatory behaviour of the system. The values chosen for the time delays were derived from coordinator inputs during the informal interview in the case study. Since they were generally uncertain about the values, normal distributions were used for the variations in all the chosen variables. A summary of the variations selected in Vensim is provided in Table 18. The simulations were only performed for the system with the new technology implemented.

The results of the sensitivity analysis for coordinator awareness are provided in the combined views of the graphs in Figure 93. These graphs present more variation than the graphs for the first sensitivity analysis in Figure 92. This highlights the effect of time delays in C2-type systems. Especially the combined effect of all the time delay variations together that effectively ‘pushes the envelope’ of the system model's robustness. Management of time delays in the system will be a leveraging point for policy to focus on. This needs to receive special consideration during technology implementation in the complex STS.

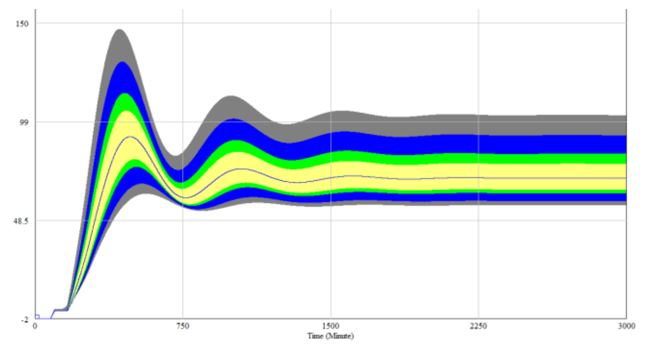
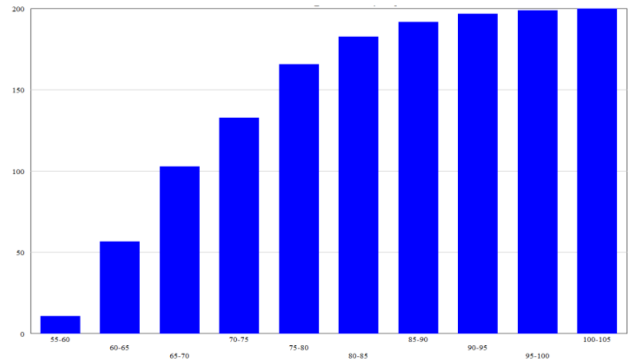
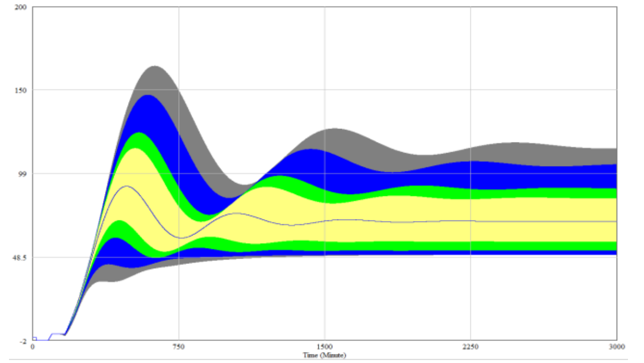
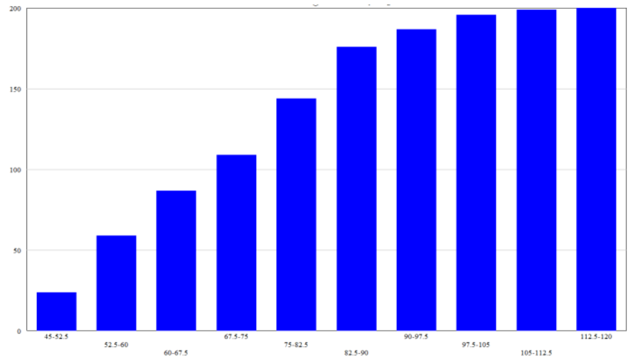
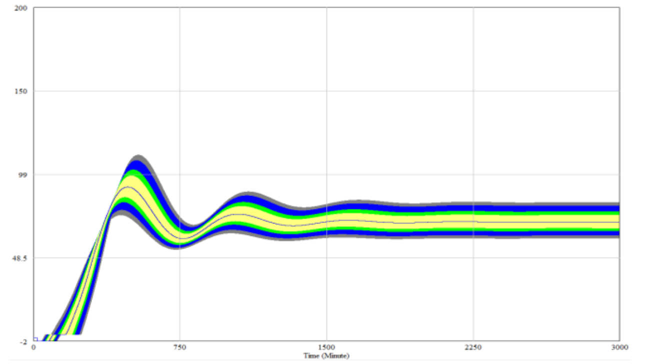
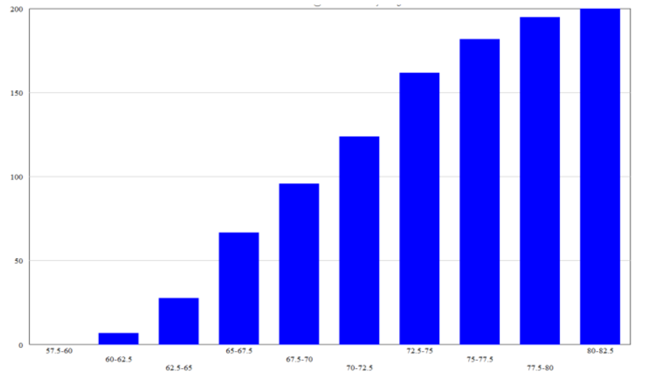
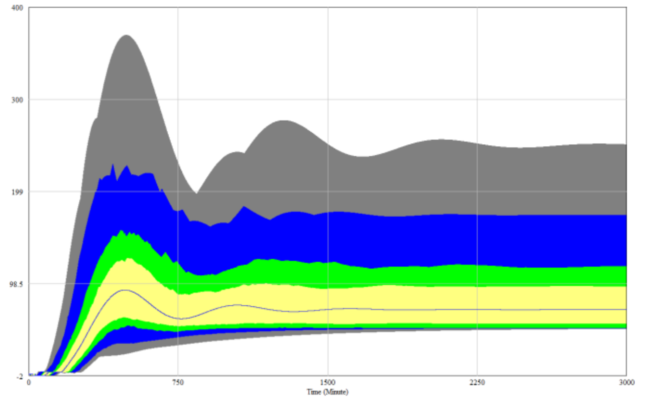
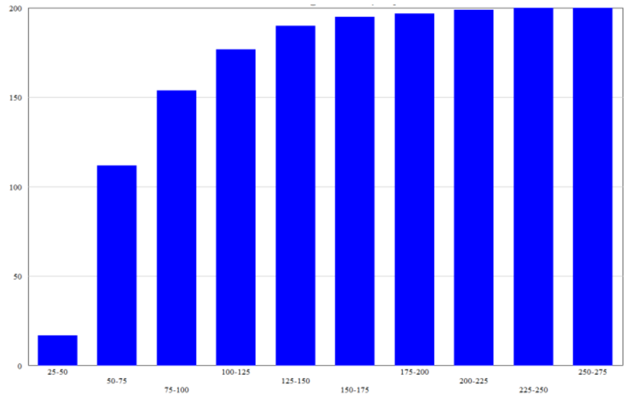
Sensitivity Graph	**Histogram**
	
Information Capture Delay	
	
Decay Time	
	
Patrol Action	
	
Combined Influence	

Figure 93: Monte Carlo Output for Effect of Time Delay on Coordinator Awareness

7.3.7.5 Stakeholder Requirements

The purpose of modelling the technology in the complex STS is to gain an understanding of its impact on the system's behaviour. This chapter has investigated the impact of web-based technology integrated with smartphones for NW patrols in a CPF. The process of modelling, simulation and field experimentation enabled learning about the problem space and the impact of the solution. This supports identifying key aspects to capture in the requirements for implementing and operating the system. A few quick examples on the STS side of the implementation include the following:

a) Implementing Cmore in a CPF firstly has to focus on the coordinators to assemble and analyse the information. Their gain in situation awareness is better than for the patrollers. As the patrollers become aware of the advantages, their enthusiasm rises to fully use the smartphones to capture more information.

b) Coordinator use of Cmore may be initiated by manually capturing reported incidents in the system. This places a requirement on Cmore to export and print the incidents captured in the database.

c) The implementation plan needs to cater for change management from the old way of doing things to the new possibilities presented by Cmore. This needs to consider the oscillatory behaviour during the initial stages of the implementation, as the operators learn to apply the technology. Operators need to be aware of the time delays in the system for effective reaction to incidents (Rodrigues et al. 2006, Reddi & Moon 2011).

d) Management of information in support of analysis and situation awareness is required. As incidents reduce, available information for situation awareness and planning actions reduces. This requires additional intelligence analysis tools to utilise the smaller volume of information.

e) Effective training of Cmore operators to optimally use the system. This may prevent bad experiences due to unrealistic expectations, loss of confidence in the technology and limited adoption.

7.4 Conclusion

This Chapter provides the third demonstration of the modelling methodology for complex STS using a complete case study. Careful modelling and analysis are required to assist in developing a complex STS. This is applicable where people, especially volunteers, participate in a C2-type system that requires technology for decision support and to communicate information. Effective modelling can support experimentation to gain an understanding of the system requirements under diverse conditions.

At the outset of this case study, no existing models could be found to support the SE process on C2 in CPF and NW patrols. The CWA was used to analyse the work performed with the new technology in the system. The SD modelling and simulation are built onto this to identify the leverage points in the system. The simulations highlighted some counterintuitive behaviour that designers and developers of the C2 system should consider. This can be used to guide allocating development priorities as well as planning improved measurements during field experiments. Despite applying the same technology – Cmore, as in Chapter 5 and 6 – here, in a different environment, other issues could be identified and investigated. The same methodology leads to considerably different constructs and models, which would appear to be contingent on the application and assumptions adopted. It also highlights other possibilities, uses and applications of the new technology in the environment.

The initial modelling of outcomes and simulation results was verified using a confirmatory focus group. The least number of changes of the three demonstrations were required for this case study, mainly due to the lessons learnt from the first two demonstrations already having been implemented. This demonstrated that the models and constructs developed using the proposed methodology can assist in eliciting information from the stakeholders, on the problem situation and the environment. Even if the models and simulation include flaws, their value is in eliciting further information from stakeholders, to improve the knowledge of the problems faced by the system. The SD models and information gained from them can subsequently be used to support decisions on the choice of technology or policy to improve an aspect of the system.

The knowledge gained from the modelling and simulation was applied in planning and executing an empirical field study to capture data on applying the new technology in a CPF. The CWA and SD constructs were used to develop questionnaires to capture information during the experiment. The hypothesis developed for this research is that a modelling methodology that addresses human work and dynamic interaction will support understanding the effect of new technology on complex STSs. The insight gained into the complex behaviour of the system in this demonstration supports the hypothesis of this research. No examples exist in the literature where the dynamic interaction between humans and a new technology for CPF has been modelled, simulated and verified. This is another novel contribution of this research.

There is good correlation between the experiment and the initial behaviour modelled, reinforcing the utility of the methodology. The field experiment demonstrated a clear gain in situation awareness for coordinators, but not for the patrollers. These could be explained by considering the patrollers' roles, priorities and their way of performing work. They might also been reluctant to adopt a new technology for a task they don’t think necessary. Also as patrols often occur during the dead of night when energy levels to try something new is low.

The knowledge gained from the field study was used to the update the models for improved simulations. The final simulations, which were evaluated through sensitivity analysis, highlighted some critical aspects for consideration while implementing Cmore into the CPF system. From these, some system implementation issues and requirements were identified to support an SE project. These add to the novel contributions of the research, described in this thesis. Experience gained while applying the methodology in Chapters 5 and 6 also contributed to improved modelling and simulation results in this chapter.

The next two chapters conclude this thesis by highlighting the gains and novel contributions from this research, resolving the hypothesis and identifying future work.

8 METHODOLOGY EVALUATION

8.1 Introduction

The aim of this chapter is to summarise and assess the ability of the modelling methodology to model complex sociotechnical system (STS). As per the research design, this chapter forms the final step in the second stage, as seen Figure 94. It captures all the results and lessons learnt in the previous three chapters to update the artefact developed in this research. The methodology implementation and demonstration outputs are compared with the initial requirements established for the modelling methodology. If required, the problem (gap) definition, requirements for the modelling methodology or the modelling methodology itself can be improved.

In the previous three chapters, the modelling methodology was applied to model and assess the impact of a new technology to be implemented in different complex STSs. Despite being the same web-based collaboration technology, called Cmore, introduced into a command and control (C2) related system, different aspects could be investigated.

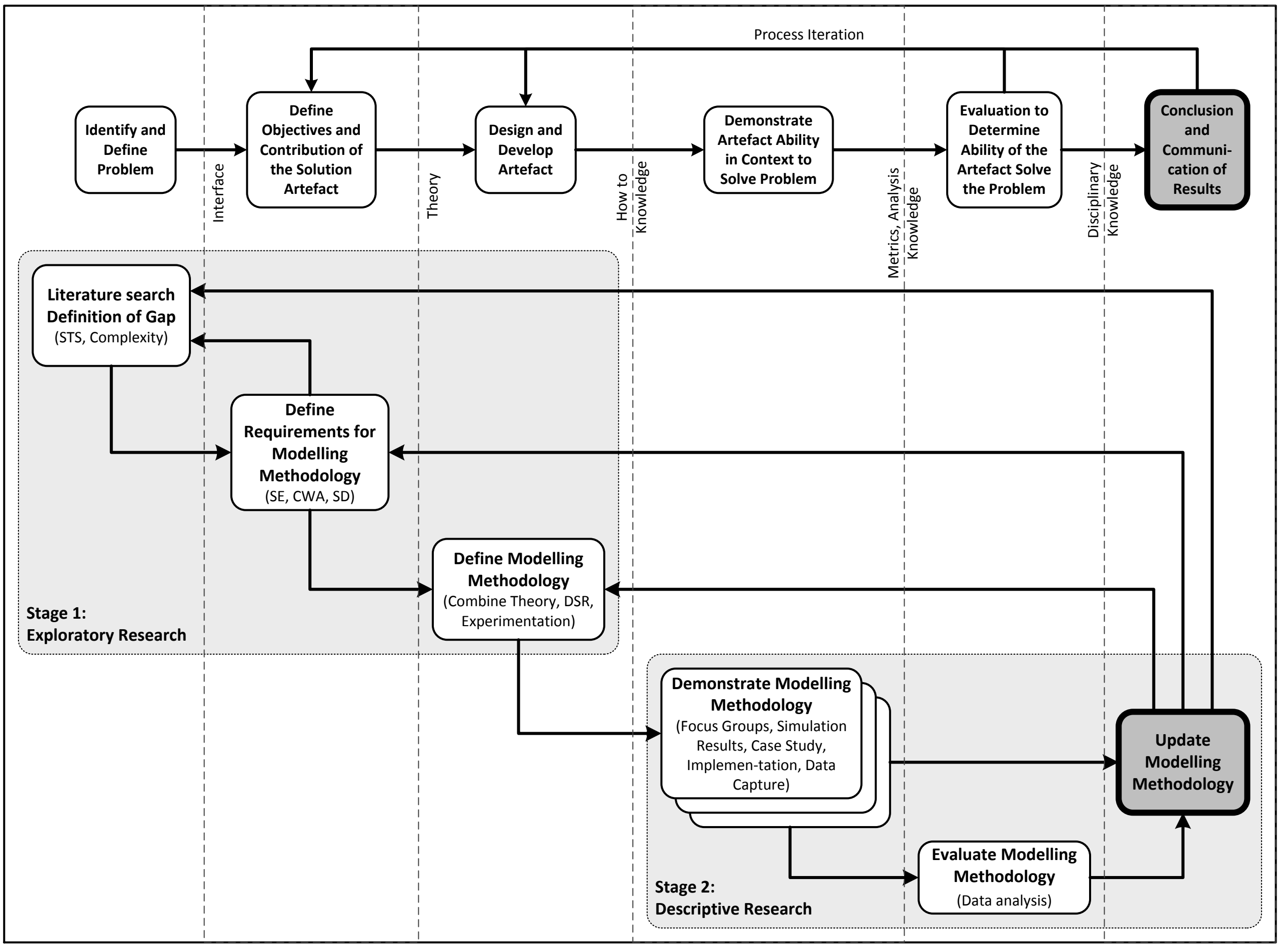


Figure 94: Research Design

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The models did exhibit similarities, but different questions could be answered and different issues investigated. The main source of the differences is the context (constraints) of the operational environment and the situated use of the system.

8.2 Modelling Method Successes

In short, the modelling methodology, as seen in Figure 95, consists of the cognitive work analysis (CWA), specifically the work domain analysis (WDA) and systems dynamics (SD) frameworks integrated in a design science research (DSR) methodology. The aim is to develop models that represent the structure and dynamic behaviour of the complex STS in support of experimentation and learning about the system. This knowledge is required to help initiate the systems engineering (SE) process. The methodology also applies focus group discussions with subject matter experts (SMEs) to supplement the system and problem information derived from documentation and the literature. The SMEs are also used to assess and comment on the utility and accuracy of the models and simulation outputs.

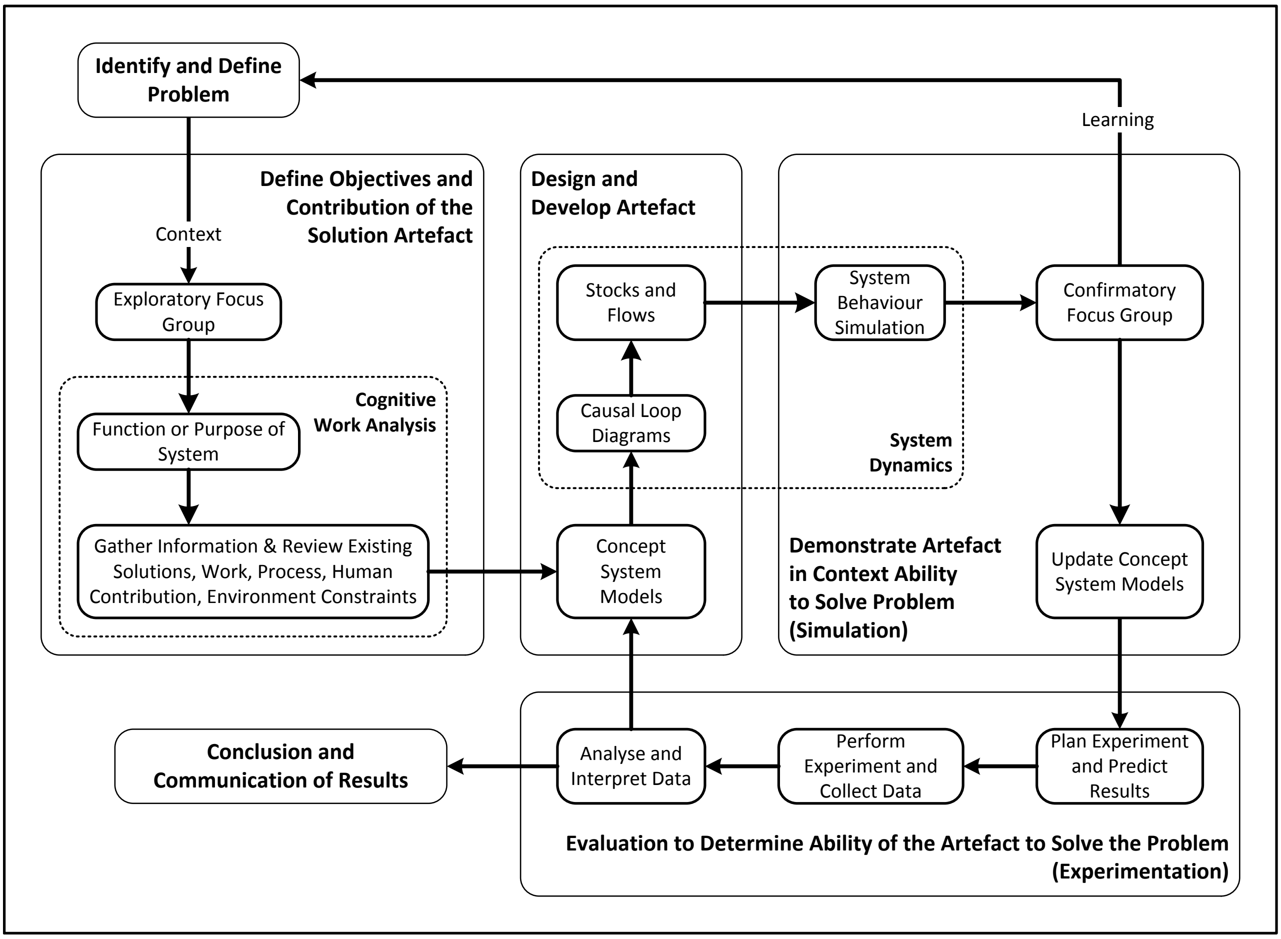

Figure 95: Modelling Methodology

The modelling methodology for modelling and assessing the impact of a new technology in different complex STSs was demonstrated in three case studies. The same web-based collaboration technology, called Cmore, is introduced into the three different C2-related systems. The three case studies included C2 during border safeguarding operations (BSO), anti-poaching operations (APO) and community policing forums (CPF). A technology can affect different systems in various ways. Even similar systems may in different contextual situations result in diverse behaviour and issues to be investigated. The requirements for modelling complex STSs, as set out in Table 4 from section 4.3.3 and summarised in Table 19, are compared with the outcomes and results of the three demonstrations.

These are not the only characteristics and advantages of the modelling methodology. The other spin-off contributions of the modelling methodology include the following:

a) CWA and SD are extremely useful to develop evaluation templates during the planning of experiments. These methodologies identified the issues concerning the system to be covered in the questionnaires, as seen in section 7.3.6.3 and Appendix A.2.

b) CWA helps SD to identify variables through the different abstraction and decomposition levels of the ADH. This helps to comprehend the human and dynamic complexity of the system to be captured in the SD models. This was shown in each of the three demonstrations (sections 5.3.4.2, 6.3.4.2 and 7.3.4.2).

c) This methodology is useful to start identifying the leverage points in the system where the new technology can make a difference. These can be used to prioritise the requirements of the new technology in the system, in order to enable making a selection among different types of technologies (section 7.3.7.5).

d) SD modelling is useful for learning about STS, as complex dynamic behaviour is difficult to record empirically (Harrison 2007). This was shown in each of the three demonstrations (sections 5.3.6, 6.3.6, 7.3.5 and 7.3.7).

e) The ability of research principles to support structuring, modelling and assessing the problem to be solved by SE has been demonstrated. The DSR framework supports developing abstract artefacts, and is useful for developing complex STSs, as proposed in section 4.4.6.

f) Implementing focus groups as part of the SE process provided a useful approach for capturing diverse views on the problem from the stakeholders. The formal and structured approach provided by the modelling methodology enabled the modellers to extract maximum value from the SME participation in a relatively short period. This is illustrated in sections 5.3.3.1, 5.3.6.1, 6.3.3.1, 6.3.6.1, 7.3.3.1 and 7.3.5.6.

Table 19: Complex Sociotechnical System Modelling Requirements

No	Complex STS Requirement	Comment
1	Present the structure and behaviour of human work in the system.	The structure of the problem situation and system under investigation are captured through CWA, system modelling and SD modelling. The system's behaviour is displayed using the SD simulations. The functional modelling of the system also provides insight into the behaviour of the system.
2	Capture the mental models and domain knowledge of stakeholders and SMEs.	Using focus group discussions proved very useful in capturing the mental models of the system's stakeholders. The models built from the literature and other documents were presented to the SMEs in the focus groups, and often resulted in significant changes, as the literature did not provide all of the information.
3	Support experimentation with knowledge on the problem.	The methodology support experimentation with simulation as well as field experiments. The knowledge gained through simulation was demonstrated with BSO and APO. The ability to support designing, planning and executing the field experiments was demonstrated with the CPF. The main contributor here is the DSR framework, which integrates the CWA and SD approaches.
4	Guide identifying the elements that cause complexity to support the design. This includes the constraints of complex work domains and operating environments.	The analysis of means-to-ends relationships may identify elements in the model that may result in complex behaviour. As seen with the CPF demonstration, the SD simulations are used to identify leverage points in the system. These are investigated with sensitivity and policy analyses.
5	Support the qualitative and quantitative analysis of a large system.	The CWA and SD modelling addressed the qualitative aspects of the system. The SD simulations and actual data captured during the CPF experiment resulted in quantitative results.
6	Use scenarios to assess the effects and goals of cognitive work in context, which includes situation awareness, sense-making and decision-making in the system.	This was partially addressed in the WDA part of the CWA as well as during SD modelling and the experiments. It may be captured in the other steps of the CWA not addressed in the current modelling methodology.
7	Consider open systems and information exchanges.	The fact that the WDA and SD focus is more on modelling the problem than only the actual technical system ensures that the ecological environment is addressed.
8	Address the complex relationships between the social and cognitive humans, business processes (organisation) and technical means, in unison.	The main purpose of CWA is to address these aspects. The dynamic interaction between the various elements are addressed through SD modelling and simulation.
9	Use work and task principles to define activities and ensure that all functions can be identified and allocated.	This requirement is covered through CWA modelling, which leads to functional and structural system models.
10	Understand the relationship between the system as a whole and its parts, as well as the possible emergent properties, to ensure an effective and efficient design.	CWA supports both a top-down and a bottom-up approach to the modelling and system analysis, while the SD approach provides a top-down modelling and simulation capability.

g) Some texts allude to using SD in C2 modelling, but successful implementations are few, as seen for example in Hallberg et al. (2010). This issue has been investigated and demonstrated in this thesis, in sections 5.3.4, 6.3.4 and 7.3.4. However, there will never be a single implementation of SD for C2. This is because the implementation depends on the questions requiring answers and the ensuing level of modelling. SD modelling tends to focus at the highest level (strategic), where the impact of policy or doctrine can be investigated.

8.3 Updates to the Modelling Methodology

The aim of this chapter, following the research design, is to identify and implement updates or changes to the research artefact, the modelling methodology. Despite all the advantages identified in the previous section, the modelling methodology as developed in this thesis does have some shortcomings, as the demonstrations highlighted. The following improvements can be made to the modelling methodology, which will form part of future research:

a) Literature Search and Gap Definition. The different SMEs participating in the focus groups have different mental models of the problem situation and the ability of the new technology to improve the system. The focus group method may be enhanced with a morphological analysis to investigate complex and abstract issues in the problem situation.

b) Modelling Methodology Requirements. More iterations in the modelling methodology are required to implement (model) and then verify stakeholder inputs on the models. The SD modelling and simulation outputs may also lead to many additional aspects being identified, which need to be included in the model, as demonstrated with the CPF. However, this cannot continue indefinitely, and the optimum point at which to stop iterations and proceed to the next step needs to be determined.

c) Modelling Methodology Updates. From the knowledge gained through the demonstrations, the importance of iterative feedback from the confirmatory focus group concerning the modelling and simulation steps is required. As seen in Figure 96, a line back to the concept models is added. Other possible improvements could be suggested to the details on the modelling taking place in each step, these are:

    i) Implementing more steps for the CWA, not only the WDA, for deeper insight into the human work in the system. This would allow social aspects (such as trust, culture and norms of behaviour) to be investigated in greater detail.

    ii) Deeper and more involved SD modelling to validate the models and to investigate different non-linear variations in the variables. Further simulations may be used to investigate leverage points and tipping points in the models. Simulations over longer

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time spans of the system may expose high-level and long-term problem and system oscillatory behaviour.

iii) The level and focus of the modelling effort must be carefully monitored. SMEs have a tendency to get lost in the details of the system and the problems. The focus group discussions need to be bounded and carefully planned, with fewer and more concise questions.

However, the only possible immediate update to the model is a feedback link for an iterative loop between the SD updates from the updated concept system models to the design and develop artefact phase, for more SD modelling and simulation, as seen in Figure 96. In the initial model (Figure 95), this step was not clear, despite turning out this way through the modelling methodology implementation.

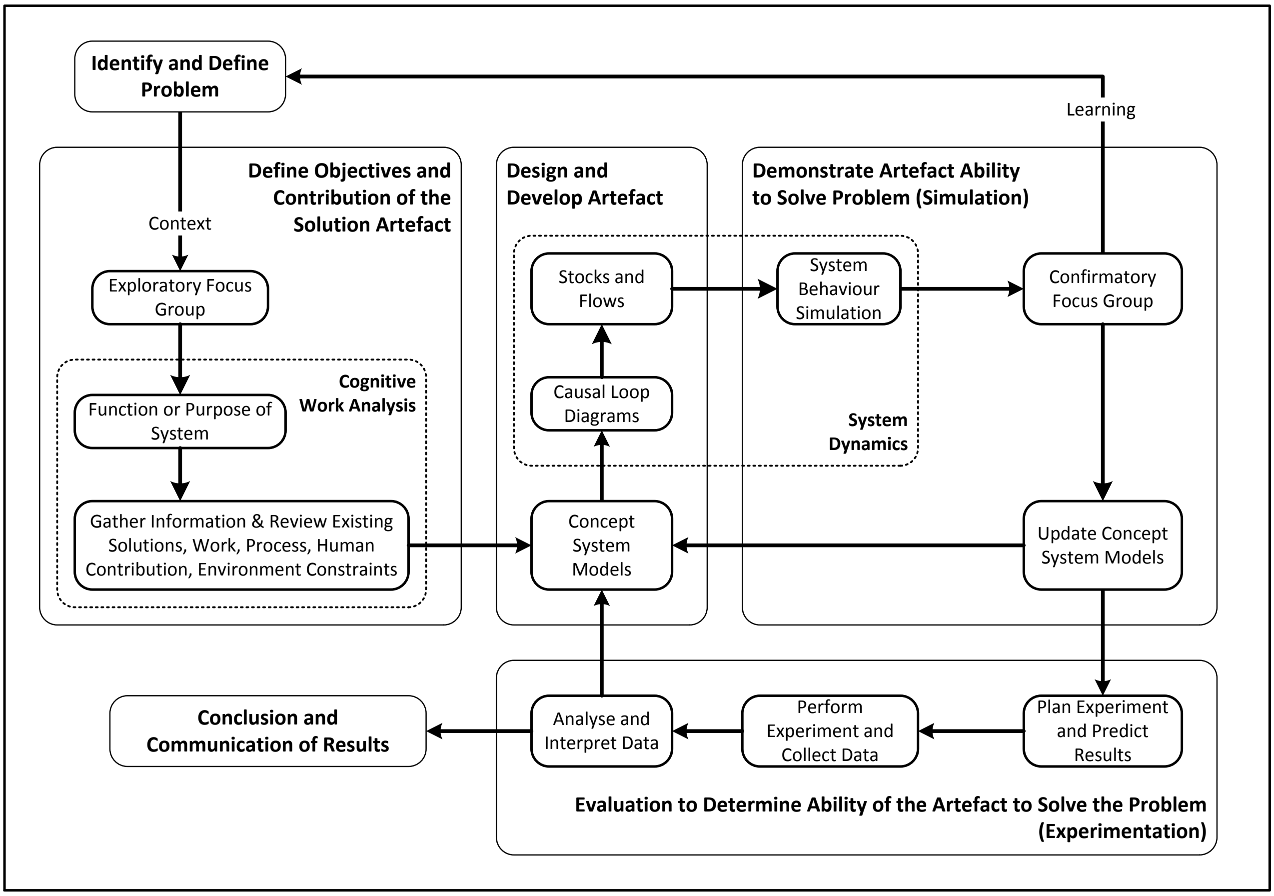

Figure 96: Updated Modelling Methodology

8.4 Conclusion

This chapter concludes the steps defined in the research design. It closes the research rigour cycle and updates the artefact with knowledge gained through the research process. The success of the modelling methodology is demonstrated to capture and model the dynamic behaviour of the complex STS system in the complex problem. Additional successes of the artefact are also highlighted.

Some modifications to the methodology are suggested, focussing on the details of the different steps. The main structure of the modelling methodology does not require major updates. The only changes involve a deeper application of the different modelling approaches using more and smaller iterations.

The next chapter concludes this thesis study to address the research questions and hypotheses, as well as to capture the contributions of this study and to identify future work.

9 CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

9.1 Introduction

The aim of this chapter is to conclude the research of this thesis. This is achieved through comparing the outcomes of the research with the hypothesis and research questions identified in the first chapter. Other aspects include defining the novel contribution of the research, listing limitations on the study and providing guidelines for future research in this field.

9.2 Research Questions

The aim of this thesis is to answer the research questions defined in Chapter 1. These are based on the hypothesis that a modelling methodology that addresses human work and dynamic interaction will support understanding the effect of new technology on complex sociotechnical systems (STS). The problem and solution domain of systems engineering (SE) projects includes the impact of new technology on a complex STS. Typical new technology for a complex STS can consist of new communications, displays, decision support systems, or even a new process. The research questions addressed in this research include the following:

a) Difficulty of Developing Complex STS. The problems experienced during the modelling of complex STSs have been discussed in sections 3.5 and 3.6 with information from the literature. In summary, capturing the complexities of the situated work of complex and social humans with new technology in a complex environment is difficult. Even more so representing it in requirements or supporting models.

b) Role of Modelling in SE. The importance and role of modelling in SE is derived from the literature, as provided in section 4.3. Modelling captures the mental models of system stakeholders to support analysis based on systems thinking.

c) Characteristics of Complex STS that make Modelling and Analysis Problematic. The requirements for a modelling approach to complex STSs are listed and discussed in section 4.3.3. These represent the requirements for developing the modelling methodology.

d) Modelling Methodologies for Complex STS. The cognitive work analysis (CWA) and system dynamics (SD) methodologies have been identified and discussed in section 4.4 as possible candidates to support the modelling of complex STSs. These are related to the approach provided in a soft systems methodology. The comparison indicated that a framework employing both CWA and SD can address the modelling characteristics of complex STS. CWA address the work system operating within real-world constraints, while SD focuses on the system's behaviour within the context of decision rules and policies. CWA does not address the dynamic behaviour and interaction among subsystems, while SD does not cater for the impact of technologies on human work. SD focus on the macro-level behaviour of the system, while CWA addresses the lower-level functions and the role of technology. The aspects addressed by SSM are also covered by combinations of CWA and SD. Although not explicitly present in the methodology and table, the principles of SSM are addressed by CWA and SD.

e) Framework to Support Modelling of Complex STS. Since the modelling methodology entails "designing" a model for complex STSs where the supporting information is complex and qualitative, the design science research (DSR) framework is implemented. The DSR framework can seamlessly integrate the modelling methodologies of CWA and SD, despite their differences in focus and level of analysis (modelling).

f) Ability of the Modelling Methodology to Identify Key Parameters and Variables. The ability of the modelling methodology to develop models of complex STS and to identify key parameters is demonstrated in three cases. The ability to model and compare the contribution of the same technology in three different applications is a novel contribution.

g) Utility of the Complex STS Models to Support Understanding Internal and External Constraints. The ability of the modelling methodology to support understanding the solution and problem space is demonstrated in all three applications. The effect of the identified variables could be simulated with SD to guide planning an experiment with the technology in the real world, with an actual complex STS. This was clearly demonstrated by implementing a new technology in a CPF.

h) Ability of the Modelling Methodology to Support Engineering of Complex Systems. The outputs of the simulations lead to identifying some requirements for initiating the SE process in the final demonstration, in section 7.3.7.

9.3 Resolution of Hypotheses

This thesis attempted to aid system engineers in structuring and understanding through modelling the problem space and the effect a solution technology might have on it. The intent of the research is to test the hypothesis, at least initially, and to speculate on its validity (Robinson 2009). The hypothesis developed for this research is that a modelling methodology that addresses human work and dynamic interaction will support understanding the effect of new technology on complex STS. This is demonstrated qualitatively in the first two cases, despite the absence of quantitative evidence. The final demonstration, in Chapter 7, also provides empirically qualitative and quantitative evidence of the utility of the modelling methodology.

9.4 Contribution of this Research

The problem addressed in this research is the difficulty of modelling and assessing the problem and solution domain of complex STSs as part of the SE process. This thesis researched the design and development of complex STSs that operate in complex environments. Successful implementation projects require an understanding of the problem, complex environment and dynamic interaction between these elements. Building models from knowledge of the system, documentation, the literature and subject matter experts (SMEs), and experimenting with them increases understanding the structure and behaviour of humans, organisations (structure), work (processes) and technology.

The modelling methodology developed and investigated in this thesis has not been published previously as far as could be ascertained through extensive literature reviews. The thesis demonstrates the ability of the modelling methodology in a real operational environment with different implementations of a command and control (C2) system. The methodology is flexible enough to support a technology – initially intended for a formal and structured military C2 system – in semiformal (anti-poaching operations) and informal implementations (community policing forums). These implementations also have to cope with different operational constraints.

The methodology will be a useful tool for systems engineers and researchers involved in the design, assessment and development of complex STSs with a focus on operational management systems. They may be situated in related industry or research organisations. Specific contributions of this research are the following:

a) The research in this thesis developed and demonstrated a modelling methodology to assess complex problems in support of SE. The modelling methodology is tested with representative case studies in different operational contexts, which will contribute to the SE body of knowledge.

b) Focus groups were introduced to capture information and mental models from stakeholders during the demonstrations of the modelling methodology. These proved extremely useful and should feature more prominently in SE projects.

c) A difficult aspect of SD is constructing the subsystem diagram, especially for complex STS. It is here that CWA assists the SD process to incorporate the human aspect in models in support of CLD and SFD.

d) Applying CWA and SD in a complementary fashion enhances the field of SD modelling, and simulating a complex system. SD modelling and simulation are difficult in heterogeneous environments where the focus is in the micro level (Borshchev & Filippov 2004). Applying CWA will assist in understanding the impact of humans at a micro level, to derive macro-level system behaviour. The two methodologies have been applied separately to similar problems in the past, but this thesis demonstrates their synergetic combination, despite fundamental differences.

e) This research developed a generic SD model for assessing new technological artefacts in C2. Many authors have alluded to applying SD in operational management systems, such as C2, but its true application has not yet been comprehensively demonstrated.

f) This thesis provides an enhanced understanding of the requirements of C2, based on military theory within the context of complex STS. The research design in this thesis also serves as a roadmap for research into the contribution of collaboration technology in C2.

g) The constructs and model outputs of the modelling methodology support planning experiments and measurement tools to be used in the experiments. This is normally a difficult task with complex STS, but the modelling construct enabled the author to identify and relate variables in the system and operational environment.

h) The process of modelling and its iterative improvement using the methodology is demonstrated in three real-world case studies. In Chapters 5, 6 and 7, the modelling methodology is applied to modelling and assessing the impact of a new technology to be implemented in different complex STSs, despite it being the same web-based collaboration technology. The ability to model the three problem types, in three cases, in three contexts is a novel contribution in itself.

i) A specific real-world insight generated from the second case study was that as anti-poaching operations become more effective and more poachers apprehended, there will be less information available from tracks, shots or carcasses to plan further operations. This effect in the system is somewhat counterintuitive and highlights the need to consider using less information that is available more effectively.

9.5 Limitations of the Study

Any honest dissertation will not only present the positive and encouraging research results, but also address the less successful ones. Researchers embarking on similar ventures will benefit more from the knowledge of possible pitfalls. This thesis successfully demonstrates the utility of the modelling methodology to investigate the impact of a new technology on a complex STS. The methodology effectively supports structuring and understanding the problem, to initiate an SE process to develop or improve a complex STS through implementing a new technology. However, the following issues are not addressed in this thesis:

a) Modelling Precision. Models at this stage of the system life cycle are used to investigate concepts. This serves as an input for discussions between stakeholders on the behaviour of the system, in support of understanding the problem to be solved as well as the impact of different variables and technologies. The idea is to build simple models that are easy to convey, and to stimulate discussions among the stakeholders and SMEs. Only when the system is being designed and specified are high-fidelity system models required.

b) Change Management. Change management is identified as a critical requirement to enable implementing a new technology in a system. This is not addressed in this research, as the focus is on structuring and understanding the problem and the impact of a new technology on a complex STS. However, the models are demonstrated to assist in identifying the implementation issues, in support of planning change management (Rodrigues et al. 2006, Reddi & Moon 2011).

c) System Dynamics Modelling. New technology in a complex STS may afford different ways of performing the work. SD may be used to investigate the effect of new procedures, doctrines and policies on operating the system. This thesis does not utilise all the capabilities of SD modelling and simulation, which can be investigated in future work. Basic validation and verification are performed, and the variable values support simulation in the context of the assessment. Despite developing lower fidelity models than what is possible with SD, they still serve as a useful vehicle to stimulate discussion and extract inputs from SMEs. In the context of this thesis, simple SD models were easier for the SMEs to understand, to stimulate discussions in the focus groups and to learn about the dynamic behaviour of the system. More is gained from simple SD models focussing on key variables in the model than from complex models with many interacting variables.

d) Systems Engineering. The complete body of knowledge of SE is not applied. The process and sequence of identifying functions, states and modes, and requirements are not followed. The methodology in this thesis focuses on structuring and identifying the problem to be solved with the SE approach.

e) Level of Effort. The simulation and modelling (methodology) performed in this thesis was done by one person over a period of a few months. In reality, this has to be performed by a team of experts (systems engineers) over a longer period to increase fidelity as well as to measure outcomes. However, valuable knowledge was gained from the modelling effort.

f) Ergonomics. The effect of ergonomics and the ease of use on the situation awareness gained from using Cmore was not considered in this study. It was assumed that since the intuitive design interface makes learning to use it very easy, this would not affect the outcome of the models too much.

g) Systems Dynamics Experience. The stakeholders and SMEs participating in the modelling effort require a working knowledge of CWA and SD to contribute effectively. This is not always possible, and some form of induction to the modelling approaches needed to be provided to participants. This was not addressed in this research and limited the effectiveness of contributions received from the focus groups. The focus was on keeping the SD models as simple as possible, which also may have limited the possible utility and insight gained. Scenarios and story-line discussions were also used to explain the behaviour in simulation output graphs.

9.6 Future Work

This thesis has developed and demonstrated a modelling methodology for complex STS. It has also identified related aspects available for future research, which include the following:

a) In this research only the first step of the CWA, the WDA, was performed. The other four steps of the CWA may provide deeper understanding of the way in which human work is performed in the cognitive system. This should enhance the utility to the modelling methodology, and requires further research.

b) Further research into applying SD modelling and simulating complex STS is required. Validity and Monte Carlo simulations with the SD models may add deeper insight into the complex behaviour of the complex STS. This was addressed only at a limited scale in this thesis.

c) The mechanics and interactions in the complex STS – which lead to distributed situation awareness, sense-making, decision-making and trust – have unique modelling and simulation requirements. This opens a completely new research field of modelling and developing distributed systems. Deeper investigation into the capabilities of SD and CWA may provide the basis for this.

d) The effect of the quantity and quality of different information types on situation awareness, sense-making and decision-making, with different quality and quantity characteristics, requires further detailed investigation.

e) The impact of distributing the Cmore mobile application to the public in complex STSs, as a form of crowd sourcing, requires further research. This may be required for civilians living in border areas, for border safeguarding operations; tourists in a reserve, for anti-poaching operations; and residents in neighbourhoods, for the community policing forum. This will place additional requirements on information management, analysis and security.

f) The first step in addressing complex systems is to identify them as such and to know when to apply different SE approaches and techniques. The tables (Table 8, Table 10 and Table 13) used to assess the complexity of STSs may be further developed into a useful tool.

g) A method for performing risk analysis on implementing the new technology in a complex STS also requires deeper and longer-term investigation. This may focus on the resistance to change by the people in the system as well as the possible role and contribution of a champion for the technology in this regard.

h) The proposed modelling methodology can be applied to other technology applications in different industrial sectors.

9.7 Conclusion

This thesis develops and demonstrates a modelling methodology for complex STSs, based on the hypothesis that addressing human work and their dynamic interaction with the technology, the environment and among themselves in system models will support understanding the solution and problem space. The research led to the novel contribution of the methodology, which will assist SE projects to investigate the dynamic behaviour of the complex STS. This was achieved through addressing the research questions identified in the first chapter.

The modelling methodology is based on integrating CWA and SD. Although both are based on systems thinking, major obstacles exist in terms of abstraction level and time span differences. However, this was overcome through the DSR framework, which enhanced the strong points of the two modelling approaches. The methodology was demonstrated through modelling the implications of a new C2 technology in three operational environments, to develop concepts as well as to derive stakeholder and system requirements.

The modelling methodology was demonstrated through modelling the impact of a new collaboration technology on a C2 system for the diverse operational environments of border safeguarding, anti-poaching operations and community policing forums. The output models and simulation results of the system’s dynamic behaviour enable system developers to identify requirements, policy issues and tipping points. These may be further investigated through “what if” analyses. The models improved each time, as the methodology and the frameworks were better understood.

The research has also opened the door for multiple opportunities to improve the modelling and simulating of complex STSs through future research.

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Appendix A QUESTIONNAIRES AND CONSENT FORMS

A.1 Consent Form

Informed consent form for Evaluation of Cmore in Anti-Poaching Operations

1 **Title of Research Project**: Modelling Methodology for Complex Sociotechnical Systems

2 I …………………………………………… hereby voluntarily grant my permission for participation in the project as explained to me by Rudolph Oosthuizen.

3 The nature, objective, possible safety and health implications have been explained to me and I understand them.

4 I understand my right to choose whether to participate in the 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 publication.

5 I am aware that all audio recordings will be made of the focus group discussions.

6 Upon signature of this form, you will be provided with a copy.

Signed: ___________________________ Date: ________________

Witness: ___________________________ Date: ________________

Researcher: ___________________________ Date: ________________

A.2 Questionnaires Inputs

The analysis focused on the critical parameters identified in the CLD and SFD. Here, specific incidents illustrating the utility of the technology may be highlighted. The analysis results have to be linked to the assumptions in the CLD and SFD as well as outputs of the SD simulations performed in preparation to the experiment. Table 20 provides typical questions derived from the CLD.

Table 20: Questions Derived from System Dynamics

Factor	Information	Analysis
Contribution of information to situation awareness	Incidents Tracks	Number of incidents recorded
Contribution of situation awareness to information use	Incidents Time	Situation awareness measurement
Contribution of information use to incident response	Incidents Tracks	Situation awareness measurement
Effect of new criminal action on situation awareness	Incidents Time	Situation awareness measurement
Effect of patroller safety on incident response	Incidents Time	Number of incidents covered Reaction Time
Effect of collaboration on patroller safety		Questionnaire

Table 21 provides the set of source questions and issues identified from the WDA to be addressed during this part of the evaluation.

Table 21: Questions Derived from Work Domain Analysis

Functions	Issues	Current	With Cmore
Sensing Data and Information	Type of information captured	Any	Any
	Method of information capture	Paper and radio (voice)	Digital (Text and photo)
	Ease of information capture	Tedious	Easy
	Time taken to capture information	Long	Quick
	Information reporting	Paper and radio	Digital with images
Analyse Information	Method of situation assessment	Memory	Cmore display & tools
	Information used in assessment	Paper and reports	Digital reports, positions, history
	Level of situation awareness	Low	High
Plan Actions and Make Decisions (Coordinate and Control Patrols)	Method of coordination and control	Voice	Text and line on map
	Coordination and control effectiveness	Low	High
	Situation awareness contribution to coordination and control	Limited	High
	Patroller safety	Low	High
Control Patroller Response to Incidents	Source of patroller situation awareness when attending to incident	Memory	Map display
	Level of patroller situation awareness when attending to incident	Low	High
Generate Intelligence	Source of information for intelligence generation	Paper and voice reports	Digital reports, positions, history
	Level of intelligence generation	Low	High
	Process for intelligence analysis	Memory	Filtering, heat maps,
Develop Situation Awareness Picture	Method of information display.	Paper Map	Big screen
	Responsiveness of display (up to date)	Daily	Instantaneous
Disseminate Information	Method of information sharing	Voice	Chat and other visual applications
Delays	Crime Information Reporting	Long	Short
	Information Decay Delay	Long	Short
	Assessment Delay (Coordinator and Patroller)	Long	Short

A.3 Generic Interview Questionnaire Form

A.3.1 Questionnaires

The first questionnaire for the case study is provided in Table 22. The aim of this questionnaire is to measure the situation awareness achieved in the system with the current equipment before the introduction of the new technology. It will also provide insight into the typical delays experienced in the system, which are the main factors that may lead to complex dynamic behaviour.

The second questionnaire for the case study is provided in Table 23. The aim of this questionnaire is to measure the situation awareness achieved in the system with the new technology introduced. It will also provide insight into the effect of the new technology on performing work in the system.

A.3.2 Situation Awareness Measurement

The Situational Awareness Rating Technique (SART) methodology is used to measure the situation awareness of the Neighbourhood Watch (NW) participants, which include both the patrollers and coordinators. The meanings of the questions are as follows:

a) How often do Incidents Occur during Patrols? This refers to the level of instability experienced in the situation, meaning how often does something happen or the current situation change (Demand).

b) How Complex is the Incident? This refers to the level of complexity experienced in the situation, meaning the difficulty to understand (interpret) the current events (Demand).

c) How many Things are changing during the Incident? This refers to the number of variables changing in the situation that need to be monitored for clues on what action to take (Demand).

d) How Alert and Ready for Incidents are you during Patrols? This refers to the degree of alertness or readiness for action, meaning the preparedness to take action immediately when required (Supply).

e) How much are you Concentrating during Patrols? This refers to the degree to which thoughts are brought to bear, meaning the level of concentration required to be able to identify an incident and to take immediate action (Supply).

f) How much of your Attention is Divided in during Patrols? This refers to the number of variables requiring a distribution and spread of focus, meaning the difficulty to focus on many different things simultaneously (Supply).

g) How much Mental Capacity do you have to Spare during Patrols? This refers to the mental ability available to comprehend new variables changing during an incident, meaning the difficulty to detect and interpret new information (Supply).

Table 22: Questionnaire for Before Technology Introduction

Call Sign:		**Role:**	**Experience:**						
	No.	**Questions**	**Rating**						
			Insignificant						**Substantial**
Situation Awareness	1	How often do incidents occur during patrols?	1	2	3	4	5	6	7
	2	How complex is the incident?	1	2	3	4	5	6	7
	3	How many things are changing during the incident?	1	2	3	4	5	6	7
	4	How alert and ready for incidents are you during patrols?	1	2	3	4	5	6	7
	5	How much are you concentrating during patrols?	1	2	3	4	5	6	7
	6	How much of your attention is divided in during patrols?	1	2	3	4	5	6	7
	7	How much mental capacity do you have to spare during patrols?	1	2	3	4	5	6	7
	8	How much information is available during patrols?	1	2	3	4	5	6	7
	9	How good or relevant is the information have you gained about the patrols?	1	2	3	4	5	6	7
	10	How experienced are you for handling incidents that occur during patrols?	1	2	3	4	5	6	7

h) How much Information is Available during Patrols? This refers to quantity of information for interpreting a situation, meaning the amount of knowledge received and understood (Understanding).

i) How Good or Relevant is the Information have you Gained about the Patrol? This refers to quality of information for interpreting a situation, meaning the accuracy and value of knowledge communicated (Understanding).

a) How Experienced are you for Handling Incidents that Occur during Patrols? This refers to familiarity with the incident that needs to be interpreted, meaning the degree of prior experience and knowledge in the situation (Understanding).

Table 23: Questionnaire for After Technology Introduction

Call Sign:		**Role:**	**Experience:**						
	No.	**Questions**	**Rating**						
			Insignificant						**Substantial**
Situation Awareness	1	How often do incidents occur during patrols?	1	2	3	4	5	6	7
	2	How complex is the incident?	1	2	3	4	5	6	7
	3	How many things are changing during the incident?	1	2	3	4	5	6	7
	4	How alert and ready for incidents are you during patrols?	1	2	3	4	5	6	7
	5	How much are you concentrating during patrols?	1	2	3	4	5	6	7
	6	How much of your attention is divided in during patrols?	1	2	3	4	5	6	7
	7	How much mental capacity do you have to spare during?	1	2	3	4	5	6	7
	8	How much information is available during patrols?	1	2	3	4	5	6	7
	9	How good or relevant is the information have you gained about the patrols?	1	2	3	4	5	6	7
	10	How experienced are you for handling incidents that occur during patrols?	1	2	3	4	5	6	7

Consider the work performed with the new technology							
			Strongly disagree	**Disagree**	**Uncertain**	**Agree**	**Strongly agree**
System Utilisation	11	It is easier to capture information	1	2	3	4	5
	12	A patroller is aware of what needs to be reported	1	2	3	4	5
	13	More information will be captured	1	2	3	4	5
	14	Information will be better utilised	1	2	3	4	5
	15	It is easier to coordinate patrols	1	2	3	4	5
	16	Safety of patroller is improved	1	2	3	4	5
	17	Effectiveness of patrols is improved	1	2	3	4	5

A.3.3 System Utilisation Measurement

Provide an opinion on the use and impact of the new technology on the behaviour of the system. This set of questions was not put to the respondents before the introduction of Cmore, as it would have limited contribution. This case study performs a technology push into a system where the participants may not be aware of the current shortcomings or the possible contribution of Cmore. The patrollers and coordinators must tick the box with the statement that they agree the most with on the following:

a) It is Easier to Capture Information. The new technology makes it easier to capture information while patrolling or the coordinator listening to the radio. This includes reporting incidents or suspicious behaviour.

b) A Patroller Knows Better what to Report. With the situation awareness gained through the new technology the patrollers will be more aware of what to expect and what needs to be reported.

c) More Information will be Captured. The electronic means will ensure that more information is captured for the CPF.

d) Information will be better Utilised. The display and interpretation of the available information will ensure improved utilisation thereof.

e) It is Easier to Coordinate Patrols. Having awareness of the high activity areas, exact location of the patrollers and routes already covered, the coordinator will be able to perform better control over the patrollers.

f) Safety of Patroller is Improved. The improved situation awareness will improve the safety of patrollers with the knowledge that they are tracked and awareness of high risk areas.

g) Effectiveness of Patrols is Improved. The patrols will be able to focus on important areas, identify neglected areas and capture more information.

Appendix B BORDER SAFEGUARDING FOCUS GROUP

B.1 Exploratory Focus Group

B.1.1 Planning and Questionnaires

The purpose of this focus group is to gather information for a Command and Control (C2) model that can be used to assess the impact of new technology for Border Safeguarding Operations (BSO).

A preliminary Abstraction Decomposition Hierarchy (ADH) was constructed from literature and personal experience. This was used as a template to derive questions for the focus group discussion as well as to perform the analysis of the transcripts. The questions to guide the discussion in this focus group were:

a) What is the purpose of C2 in border safeguarding? (Also look at the different levels)

b) Which of the main functions executed during C2 in border safeguarding can be supported through technology? (Situation assessment, sense-making, decision making, planning, tasking, control, etc. Is the list complete?)

c) Which of the functions are more important than others?

d) Which variables influence or constraint the success of the C2 system the most? (Information, resources, situation awareness, accuracy, time delays, etc.)

e) Which functions in the C2 system are affect by the identified variables?

f) What are the shortcomings in C2 which can be addressed by technology?

g) Where can a new technology such as Cmore contribute to the effectiveness of the C2 system? (Typical capabilities in Cmore are sensing, information distribution, information management, information display, information analysis, planning tools, order distribution in reference to the variables and functions discussed)

h) How will the technology influence the way people do the work in the system?

i) What will be the effect of the technology on the timeline of events?

j) What will the effect be of extra information captured by Cmore? (Better understanding or information overload)

B.1.2 Participants

The following individuals participated in the Focus Group:

a) Louise Leenen (Facilitator).

b) Rudolph Oosthuizen (Facilitator, recorder and time keeper).

c) Pieter Botha (Software Developer).

d) Priaash Ramadeen (Software Developer).

e) Josephus Kriek (SA Army).

f) Avuya Mxoli (Software Developer).

g) Seanette van Rooyen (Researcher)

h) Cillie Malan (Systems Engineer).

i) Reinier van Heerden (Cyber Security Engineer)

B.1.3 Cognitive Work Analysis Related Outcomes

The outputs were sorted into the headings listed below for capture into the Abstraction Decomposition Hierarchy. The key words or phrases from the recordings are highlighted to support capturing them in the constructs and models.

B.1.3.1 Purpose of C2 in Border Safeguarding

The aim of this category is to define the functional purpose of the C2 system. The first question is supposed to address the mission and its context that is to be supported by the system and the technology. The question should be: Given the context of the mission, what is the role of technology in C2.

a) Not only military, but also police and other departments (JIIM) participate in border safeguarding, each with their own C2 system.

b) C2 support the mission of the border safeguarding operation.

c) The specific purpose of the C2 system and technology requirements needs to be considered in relation to the scenario of the mission.

d) C2 may only address commanding and controlling of own forces, but the technology can enable more than this.

e) The information available must be used to enable action of own forces during border safeguarding.

f) C2 is an orchestration and directing function of all the resources available to perform border safeguarding.

g) The result is that is not pure C2 anymore? It now includes things like coordination and collaboration.

h) There must always be one commander to take responsibility.

i) The doctrine will guide the OODA loop.

j) In border safeguarding C2 is performed by joint operations that consist of police, SANDF, other departments and private security.

k) Different departments have different roles and responsibilities in border safeguarding.

l) Military patrol and secure the border area while the police arrest etc.

m) In border safeguarding the police have a supporting role where the police have arresting function.

n) Although the context differs, the typical C2 cycles still apply.

o) The military is responsible for operations between ports in their normal function. The other departments are responsible for operations in the ports.

p) The type of border is not as big a factor. The same principles should apply everywhere. However the specific environmental constraints can have different effects on them.

q) Joints operations still have one commander but responsibility may be distributed between entities.

B.1.3.2 The C2 Functions during Border Safeguarding

a) Decisions lead to a change in the tasks or mission which may require redistribution of resources.

b) Orders are required to implement decisions.

c) In-time information and situation awareness is very important.

d) Distribution of orders is important aspect to be supported by the new technology.

e) Decision-making with the right information is required in time.

f) Sense-making. The situation is analysed to be understood before a decision can be made.

g) Planning. Dividing and assignment of resources.

h) Intelligence Generation. In time intelligence require some action to be performed on the collected information.

i) Communication (however this is not a function)

j) Collaboration and Coordination is overarching where different forces have to work together (This is on a higher abstraction level of C2). The different forces may consist of own units, Joint ops entities, external groups and people.

k) Collaboration has to enable the establishment of control.

l) The function of sensing should be added as it is the source of all information.

m) Information distribution

n) Information flow to share information and intelligence. Must get the right information the right person in time and at the right time through collaboration.

o) Synchronisation

p) Information representation (SAP) with high level information fusion, filtering.

q) The high level information fusion is important.

r) Intelligence analysis of what is known on a situation or entity. You must be aware of the type and value of information you have available.

s) Situation Assessment

t) Tasking and Control.

u) Situation awareness must be considered all three levels as defined by Endsley, perception, comprehension and projection. All three levels combined refers to perfect SA. Historic data is required to detect patterns and build a context to an incident.

B.1.3.3 New Technology (Cmore) Contribution in the C2 System

a) The technology must enable control of all the information and resources.

b) Technology has to improve the gathering of information.

c) It is not easy to know where to fit Cmore in a C2 system in terms of technology and the functions it support.

d) Cmore was developed as a technology for border safeguarding as a whole. To take it into the military C2 environment is now difficult, especially the modelling thereof.

e) The role of C2 technology in the missions of border safeguarding is to determine red vs neutral vs blue forces.

f) The technology enables the community to participate in the mission and support the C2 (Crowd sourcing intelligence). People may have friends on both sides of the border. Cmore can ensure that the contribution of the community is harnessed to help understand the context of the mission.

g) Sense making require tools and specific displays for support.

h) The commander requires a collaboration of information display. The different languages and units have to be addressed for in the same display. This becomes a problem if more than one type of services uses the same display, especially in a video wall.

i) Cmore enable different entities to work together in a joint mission.

j) Cmore can enable the synchronisation and self-coordination effort. Resources may need to arrive at a point at the same time.

k) Visual representation of the situation and its context is important. It must share a view of someone or an entity. Any mobile device (multiple) on the network can access the information as it is in a website.

l) Use technology to get structured information from unstructured sources in an unstructured environment, situation and related information. In the military commonly trained operators know how to gather and share information in their common context that leads to structured information. Other departments and civilians are part of a collaboration mission and are not on the same level and will provide unstructured and incomplete information.

m) Cmore must support extracting the structured content thereof for use in a structured C2 system (mission). This can be achieved through tags in Cmore that relates to metadata that captures semantic information.

n) Information needs to be filtered and not bother someone busy with work on it. Cmore actually cater for this.

o) Customisation to support a current function or task according to the operator's requirements.

p) Different sensors can be integrated, but some operator must be able to update classifications.

q) The communications infrastructure and its coverage must be considered as well.

r) Intelligence analysis with predictions on outliers, historical behaviour and pattern matching. Even the behaviour of own forces can be monitored to identify suspicious behaviour.

s) Information coverage and cap fillers where required. All entities require network (internet) access. Where possible both commercial and military networks must be used. Cmore can work on any type of internet protocol network.

t) Community and cyber security are other aspects to be addressed in setting up of the system.

u) Cmore can serve as smart operation centre and a portal to secure distributed Intelligence.

v) Predictive capability to help identify anomalies in behaviour extracted from the information and analysis thereof.

w) Smart or digital radios can replace commercial cellular networks.

x) Situation awareness can be enhanced through cause and effect prediction.

y) Accessibility to the available information for more entities and operation participants.

z) The technology can be customised to fit a specific profile to perform a function or task.

B.1.4 System Dynamics Related Outcomes

The outputs were sorted into the headings listed below for capture into the Causal Loop Diagram and Stock and Flow Diagrams.

B.1.4.1 Variables and Constraints in the C2 System

a) Border safeguarding presents a complex and changing environment.

b) The legal aspects and ROEs must be considered.

c) Different participants and resources may have different languages and the technology have to cater for this.

d) Time delays in the various steps of the system, the commander must get information in time. It may be possible to get perfect information, but it will then be too late.

e) The information must be of the right type and format.

f) Information overkill is detrimental. This is a problem with “Big Data”.

g) The value of information to the C2 process is a balance between volume and relevance. It must be sensibly assessed to find patterns and add value to the data.

h) Accuracy of the data/information in terms of sensing and transporting it.

i) Operators must be able to trust the information when they use and process it.

j) Situation Awareness is one of the most important outputs. This influences the effectiveness of the commander in the system.

k) Perfect situation awareness will not ensure success as there are still many other variables and the commander requires support in this.

l) Skills and training of commanders and operators affect success of the total system.

m) Resources are required to execute the plans and orders from the C2 system.

n) Communication and the supporting infrastructure enable collaboration.

o) Shared awareness between the different participants is influenced by information relevance, accuracy, time delays, prediction, degree of sharing and completeness.

p) External factors such as chaos, weather, fire, corruption and politics (psychological and cultural make-up of people) may also be variables that prevents a commander to predict a situation.

q) C2 requires in-time information and in-time intelligence in support of decisions and action.

B.1.4.2 Impact of the New Technology on Human Work

a) You need to know which of the other departments you have to collaborate with.

b) All types and levels of commanders are considered at all location that may use the technology.

c) Need to know what you want to measure to determine the situation awareness of a commander.

d) Be careful of information overload.

e) Even within one organisation different sources of information relative to the same object needs to be catered for.

f) Faster distribution of a wanted person’s image on the cell phones ensures that information can be faster distributed to more people.

g) Enables better intelligence analysis of more information that is available.

h) People may be averse to the new technology but require awareness training to prevent resistance to change. If someone is familiar with working with paper maps, interpretation of information on a screen may not come naturally.

i) This reemphasise the requirement for effective filtering to prevent information overflow for reduction of operator resistance.

j) Effectiveness of operators may be reduced if they are too busy with tool many things or being exposed to too much information.

k) The establishment of trust between operators or between operators and their equipment promotes success.

l) The continuous communication makes you visible in the environment and reduces operational stealth. The continuous sending of information exposes your position which may cause some potential users to avoid it.

m) New procedures or tasks are required for the new technology.

n) Distribution of responsibility does not work well within a military C2 system.

o) The new technology has to fit into existing doctrine or force small changes. Radical changes will kill the technology – this links heavily up with the complex STS issues. This may cause opportunities of the new technology to be missed.

p) The focus should not be on changing doctrine as it is often at a high level of abstraction. The specific tasks and processes to implement doctrine is where most of the changes should take place.

q) Use the technology only to become more effective and not change too much in the overall doctrine. Commanders only have to decide over their own resources and use technology to that more effectively. The tail must not wag the dog.

r) Cmore is a collaborative tool for humans must learn to operate interactive.

s) Collaborative planning may let commanders look bad if a junior can better on the plan.

t) The implementation of Cmore must understand how a Collaboration Tool in a hierarchical structure.

u) The social system and organisation must learn how to implement the new technology to its optimum.

v) The use of the system and the information in it must be applied to the benefit and success of the mission.

w) The relevant support for the technology is required to ensure that it is available when required, otherwise users will lose faith in it.

x) Modern information systems enable faster reaction and increased information dissemination.

B.1.5 Lessons Learnt

The following general lessons were learnt on the execution of an Exploratory Focus Group:

a) During the introduction more time can be spent to identify the problem.

b) Fewer and more concise questions are required.

c) The terminology in C2 is not properly defined. This should be provided during the introduction.

d) The new technology can be experimented with in a command post with reduced personnel.

e) The model and functions are at a higher level than the exact details. The correct level for addressing all the issues must be addressed.

f) The difference between the input and output variables may be addressed like an optimisation problem. The weights to the variables and the transfer function will let you learn about the system.

g) Defining boundaries of the different terms and definitions is difficult in general.

B.2 Confirmatory Focus Group

B.2.1 Planning and Questionnaires

B.2.1.1 Purpose

The purpose of this focus group is to capture feedback on models and simulation outputs for the impact of new technology in a Command and Control (C2) for Border Safeguarding Operations (BSO). The aim is to assess the accuracy and utility of the models and simulation outputs. Interesting discussions and questions about the models and simulation outputs will constitute a successful Confirmatory Focus Group. The outcomes will be used to update the models and simulations in Chapter 5.

B.2.1.2 Participants

The following individuals participated in the Focus Group:

a) Louise Leenen – Facilitator.

b) Rudolph Oosthuizen – Facilitator, recorder and time keeper.

c) Josephus Kriek (SA Army).

d) Cillie Malan (Systems Engineer).
e) Reinier van Heerden (Cyber Security Engineer)
f) Hildegarde Koen (Researcher).
g) Jutta Knoll (Project Manager).

B.2.1.3 Cognitive Work Analysis

The elements in the Work Domain Analysis (WDA) in Figure 33 were derived from literature, documents, literature and the Exploratory Focus Group. The purpose of the C2 system is to enable assets to execute BSO missions. This is achieved through satisfying the values and priorities of the system that includes situation awareness to guide collaboration and synchronisation of assets. The commander needs to control his resources and information through is responsibility and authority. The purpose related functions enable the users of the system to perform their work. The bottom layer provides the physical elements in the system with the second layer the functions they support. The yellow blocks indicate the current capabilities and functions of the technical elements in the system. The blue blocks highlight the additional capabilities and functions provided by Cmore. Most of the yellow blocks are also supported by Cmore. The questions for discussion on the WDA include the following:

a) Are the elements in the WDA representative of the system in terms of completeness, accuracy and relevance?
b) Are all of the links correct in the WDA?
c) Does the WDA contribute to understanding the system and its interactions?

B.2.1.4 Functional System Models

Two functional flow diagrams are provided in Figure 35 and Figure 36 as derived from the ADH in Figure 33. The Purpose Related Functions are combined in Figure 35 and relates to an OODA type model. These are the functions performed by people doing work in the system. The Object Related Functions in Figure 36 indicated the functions performed by the physical elements in the system. Again the configuration of the yellow and blue blocks is used to discriminate between the capabilities of the current and new technologies. The questions for discussion on the functional models of the system with the work related functions in include the following:

a) Are the elements in the functional models representative of the system in terms of completeness, accuracy and relevance?
b) Are all of the links and flow of information correct in the models?
c) Do the functional models contribute to understanding the system and its interactions?

B.2.1.5 System Dynamic Models

The Causal Loop Diagram (CLD) in Figure 38 is constructed from the ADH and functional models. The CLD diagram indicates the causal relationships between entities and variables in the system. This is used to develop the stock and flow diagram (SFD) in Figure 40. The SFD shed light on the effect of the variables of the flow of the main entity (information) through the system as well as of the use of information affect the system. The questions for discussion on the CLD and the SFD of the system include the following:

a) Are the elements in the CLD representative of the system in terms of completeness, accuracy and relevance?

b) Are all of the links and causal relationships correct in the model?

c) Do the CLD contribute to understanding the system and its interactions?

d) Are the elements in the SFD representative of the system in terms of completeness, accuracy and relevance?

e) Are all of the stocks, flows and variables correct in the model?

f) Do the SFD contribute to understanding the system and its interactions?

B.2.1.6 Simulation Outputs

The simulation results of selected stocks and variables of the SFD in Figure 40 are presented in Figure 41, Figure 42 and Figure 43. They demonstrate the effect of information on the system over time. The questions for discussion on the SD simulation outputs of the system include the following:

a) Are the three graphics realistic in the system behaviour the display?

b) Do the three graphs provide insight on the influence of Cmore on the system?

B.2.2 Outcomes

B.2.2.1 Cognitive Work Analysis

The following issues were identified with the elements in the WDA in Figure 33:

a) Link “Decision Support” to “Filter Information”.

B.2.2.2 Functional System Models

The following issues were identified with the functional flow diagrams are provided in Figure 35 and Figure 36:

a) Link “Sensing & Own Position Reporting” to “Build SA” in Figure 35.

b) Take “Identify Lead Agency” out of the “Incident Management Process” to a higher level. In this diagram the “Lead Agency” seems to be isolated inside the military system in Figure 35.

c) Ensure that the model is for the global mission or for an already identified incident.

d) The military personnel prefer to simplify the C2 system to achieve control and use fixed processes of sequenced steps to prevent chaos. The models seem to make C2 seem very complex.

e) The group interprets Figure 36 as a bottom-up model that stop where the system display all the information and includes analysis and filtering.

f) Collaboration is not always visible and is only experienced lower down in the system.

B.2.2.3 System Dynamic Models

The following issues were identified with the elements in the CLD in Figure 38 and SFD in Figure 40:

a) Ensure that the concept of information is rather related to awareness and not level of action in the model.

b) Change following names in Figure 40:

   i) “Own Force Reaction” to “Reaction Force Awareness”.

   ii) Add “Awareness” also to “Planned Patrols”.

   iii) Change “Information Value” to “Decay Tempo”.

c) The type and origin of the data that result in the graphs is not understood. This is an indication that the group does not understand the SD framework.

d) The faster flow of information will not necessarily lead to a higher work rate.

e) The group found it difficult to relate the information flow in the system to the level/capability of reaction.

f) No filtering of the information in the SFD is considered. The “Information” in the system actually relates to the total accumulated information in the system.

g) Filter information that leave the “Information” stock for improved “Own Force Awareness”

h) Time delays to achieve collaboration needs to be considered. Planning and decisions will take time, this is considered in the time delays in the variables. This effect is not captured in the model. Maybe this can be derived from the time delays in the model and resulting graphs.

i) SD is a problem structuring method. It helps to start the problem solving process with formulation of the problem with high level models to identify trends if data is not available. SD support understanding the problem through modelling. Other more mathematic and scientific models are used to further investigate the details of the problem. The aim of the modelling is to try and understand the behaviour of the system to help identifying the problem to be solved.

j) Even with no incident available, information may come from the movement and observations of own forces.

k) After an incident occurs, more information becomes available.

l) The collaboration variable represents the effect of Cmore in the system.

m) The challenge of SD is to calibrate the feedback loops with data. Even though it might be impossible to calibrate or proof the feedback loops, the value is in the process of systemic thinking about the system and the problem it has to solve.

n) The quality of information is not considered in this model, only the total accumulation thereof. The quantity of information must be related to the quality of decisions.

o) An explanation on determining the different rates and constants is required. The places in the model to be used for measurement must be identified. It should be easy to measure the flow of information; however the measurement of timings will be difficult.

p) SD enables simulations on the system without actual data, only with current literature and mental models of the stakeholders.

B.2.2.4 Simulation Outputs

The following issues were identified with the simulation results of selected stocks and variables (Figure 40) as presented in Figure 41, Figure 42 and Figure 43:

a) The reason for the damping in the level of information in Figure 42 and Figure 43 is not clear and should be investigated deeper with additional simulations. This should lead to new understanding of the effect of the flow of information through the system.

b) The source for the frequency of the information level in Figure 42 and Figure 43 is not clear and should be investigated deeper with additional simulations. The roles that the various delays play in the system should contribute to this.

c) Check the naming of the vertical axis, “Own Force Reaction” and change to “Quality/Quantity of information” or “Own Force Awareness”. This should correspond to the changes in the models already discussed.

d) The time taken to plan missions, prepare and move into position is not explicitly visible in the models; however it is implied in the delays between the different steps.

e) The reason for the flattening in the level of information after the initial oscillation in Figure 42 and Figure 43 is not clear and should be investigated deeper with additional simulations. This should lead to new understanding of the effect of the flow of information through the system.

f) The reason for the deep dips in the level of information in Figure 42 and Figure 43 is not clear and should be investigated deeper with additional simulations. This should lead to new understanding of the effect of the flow of information through the system. A possible reason is the requirement to plan action and setting up the collaboration.

g) The reason for the timing and frequency differences between Figure 42 and Figure 43 is not clear and should be investigated deeper with additional simulations.

h) The interesting behaviour in the graphs is the source of interesting discussions on the possible causes.

i) The way information is used in the model and measured for the graphs is not clear. Therefore, it is difficult to understand and accurately interpret the graphs.

j) The underlying assumptions for the graphs are not clear and require better explanation.

k) Three simulations per graph make it difficult to understand. It should be reduced to two lines.

l) Explain what type of information is used in the graphs as there are many types and forms of information in the real system.

m) The effect of quality of decisions also need to be simulated and measured as it may have an influence and explain on the areas where the graph flattens out. One possible measurement is situation awareness; there is a causal relationship between information available and the situation awareness that can be achieved in the system.

n) The unstable behaviour and peaks in the graphs represent unwanted characteristics in the system.

o) The behaviour in the graphs was described using an analogy scenario of a missing child and the information in the operation. This proved to be useful in developing an understanding of the graphs.

p) The impact of no incident and only patrol on the level of information need to be investigated. This needs to be simulated. However, the graphs don’t show the information on a single incident, rather on the accumulation of information from multiple incidents over time (30 days).

q) It seems that after the information on an incident initiates a response, the following information only comes from own movement and action.

r) Add a better explanation on how the information is flowing through the system and how it is measured. This includes the origin of the data that leads to information.

s) The graph without Cmore (collaboration) indicates a smooth but slow build-up of information about the problem situation. This sets a trend and pattern of patrols, incidents and reaction. Eventually the system is settled on an “acceptable level of incidents. If this is acceptable to the system stakeholders, then no new technology is required.

t) The radical behaviour of the system with Cmore relates to the difficulty to correctly apply the large amount of information available in the system. This cause the system to become unstable before it settles on a level of crime. If the lower level is an important requirement, then the system must get mechanisms to cope with the initial oscillations in the system.

B.2.3 Corrective Actions

The following corrective actions were identified to update the models and simulations in Chapter 5:

a) Link “Decision Support” to “Filter Information” in Figure 33.

b) Link “Sensing & Own Position Reporting” to “Build SA” in Figure 35.

c) Take “Identify Lead Agency” out of the “Incident Management Process” to a higher level. In this diagram the “Lead Agency” seems to be isolated inside the military system in Figure 35.

d) Change following names in Figure 40:

    i) “Own Force Reaction” to “Reaction Force Awareness”.

    ii) Add “Awareness” also to “Planned Patrols”.

    iii) Change “Information Value” to “Decay Tempo”.

e) Investigate the reasons for the damping, frequency, flattening and dips in the level of information in Figure 42 and Figure 43 with additional simulations.

f) The description and presentation of the models and graphs need to include a better description and indication of the underlying assumptions.

g) Reduce the simulation lines to two per graph.

h) Investigate the implication of different qualities of information.

i) Simulate the impact of no incident and only patrol on the level of information.

B.2.4 Lessons Learnt

The following general lessons were learnt on the execution of an Exploratory Focus Group:

a) It is difficult for the members of the focus group to come cold into the discussion with the models and graphs that are difficult to interpret. Possible solutions include the following:

    i) Presentations of CWA and SD a day or two before the focus group.

    ii) Distribute the models and graphs beforehand to ensure that the group is not cold in the meeting.

   iii) Better explanations during the focus group.
   iv) Keeping SD the models as simple as possible.
   v) Presentation on C2 and the role of collaboration.

b) The selection of focus group member should consider their knowledge on CWA and SD or their ability to quickly grasp the concepts.

c) Consider using Vensim ® live in the focus group to demonstrate the impact of different variables on the outcomes.

d) The modelling methodology should be shown before each model to show where it fits into the process.

e) Models and graphics did lead to in-depth discussion, which what needs to be done at this stage of the model.

f) Going through the models and simulation outputs more than once helps the participants to improve their understanding.

g) The participants must name the model or graph before discussing it. This will make using the audio recording easier.

h) Many additional effects can be added to the system, but one should focus on the key aspects with direct influence.

i) Bounding of the models and simulations are important, otherwise complexity will make it impossible to achieve anything.

j) Provide a scenario to help understand the models and the resulting graphs.

k) The fact that there were lively discussions about the models and sources of information indicates that the process/methodology is doing its work.

l) If the graphs don’t make sense, the structure of the models may be wrong.

Appendix C ANTI-POACHING OPERATIONS AND COMMUNITY POLICING FORUM FOCUS GROUP

C.1 Introduction

The Exploratory Focus Group on Command and Control (C2) for Border Safeguarding Operations was a rich source of information on the application of a new technology, such a Cmore. This knowledge base applies for other similar implementations of Cmore in C2 systems. For this reason a decision was made to combine the focus groups for the second and third demonstrations of Cmore in different C2 Systems. These two consist of introducing Cmore into Anti-Poaching Operations (APO) and Neighbourhood Watch (NW) patrols in Community Policing Forums (CPF). Furthermore, basically the same pool of people would participate in both focus groups. Most are high profile systems engineers in the environment with limitd time available for long and intensive focus groups.

The focus group focussed on the differences between the two systems and not on the basics of C2 as supported by new technology. The basic contribution was thoroughly addressed during the first demonstration. The focus group addressed the specific environmental constraints of each application of Cmore. The two focus groups were conducted serial to ensure adequate time were spent on each demonstration.

C.2 Anti-Poaching Operations Exploratory Focus Group

C.2.1 Planning and Questionnaires

The purpose of this focus group is to gather information for a Command and Control (C2) model that can be used to assess the impact of new technology for Anti-Poaching Operations (APO) as well as for Neighbourhood Watch (NW) patrols as part of a Community Policing Forum (CPF). There are many similarities between the two C2 implementations of Cmore. Therefore in order to reduce duplication, the two systems will be discussed in series.

Researchers proposed new communication and situation awareness display technology, based on smartphones and web services, to enhance C2 collaboration for border safeguarding operations. The case study will examine the effect of this new technology on a C2 system for APO as well as for NW patrols as part of a CPF.

This is a case of “technology push” where a new technology is available to possibly enhance an existing complex Sociotechnical System where not all the system deficiencies are known. The new technology will add more information to the C2 system that can support situation awareness, sense making, understanding, planning, decisions, and coordination to improve mission success. It ensures that more information is available, often too much to handle. However, existing Intelligence analysis methods and tools may not be adequate any more. Therefore, the advantage of the new technology creates new problems. There is now a need for new and additional analysis (Intelligence) tools to make sense of all the available information.

The impact of these issues needs to be understood when initiating a Systems Engineering based project for C2 system implementation. Therefore, the problem to be addressed in this modelling approach is to understand the contribution of the new technology to situation awareness as well as the factors (variables) influencing its success. This may lead to additional requirements for information analysis tools in the system.

A preliminary Abstraction Decomposition Hierarchy (ADH and Causal Loop Diagram (CLD) was constructed from literature and personal experience. This was used as a template to derive questions for the focus group discussion as well as to perform the analysis of the transcripts. The questions to guide the discussion in this focus group were:

a) What is the purpose of C2 in APO? (Also look at the different levels of strategic, operational and tactical)

b) Which C2 functions executed during APO can be supported with Cmore? (Situation assessment, sense-making, decision making, planning, tasking, control, etc. Is the list complete?)

c) What are the constraints on the success of the C2 system? (Information, resources, situation awareness, accuracy, time delays, etc.)

d) What are the shortcomings in C2 which can be addressed by technology?

e) Where can a new technology such as Cmore contribute to the effectiveness of the C2 system? (Typical capabilities in Cmore are sensing, information distribution, information management, information display, information analysis, planning tools, order distribution in reference to the variables and functions discussed)

f) How will the technology influence the way people do the work in the system?

g) What will be the effect of the technology on the timeline of events?

C.2.2 Participants

The following individuals participated in the Exploratory Focus Group:

a) Louise Leenen (Facilitator).

b) Rudolph Oosthuizen (Facilitator, recorder and time keeper).

c) Pieter Botha (Software Developer).

d) Cobus Venter (Systems Engineer).

e) Charl Petzer (Systems Engineer).

f) Braam Greeff (Systems Engineer).

g) Hildegarde Koen (Researcher).

h) Avuya Mxoli (Researcher).

i) Leon Pretorius (Professor).

C.2.3 Cognitive Work Analysis Related Outcomes

The key words or phrases from the recordings are highlighted to support capturing them in the constructs and models.

C.2.3.1 Purpose of C2 in Anti-Poaching Operations

The aim of this category is to define the functional purpose of the C2 system. The first question is supposed to address the mission and its context that is to be supported by the system and the technology. The question should be: Given the context of the mission, what is the role of technology in C2.

a) Provide the ability to predict possible poaching incidents through pre-emptive information to support planning of reaction.

b) The system must enable collaboration with other entities inside and around the Kruger National Park (KNP)

c) C2 occur at the three levels, they are the strategic, operational and tactical levels.

d) At the strategic level the full scope of poaching problem inside and outside the park (community) need to be addressed. Information is required to support pre-emptive and strategic operations. The C2 system needs to present the information for intelligence analysis. The OODA loop time scale is in weeks and months.

e) At the operational level the deployment and utilisation of the limited available resources is planned. The C2 system needs to support planning of future operations. The OODA loop time scale is in hours and days.

f) At the tactical level the command and control is reactive and reactionary. The C2 system needs to enable the APO resources to react effectively on current events. The OODA loop time scale is in hours and days.

g) Situation awareness is one of the prerequisites of C2.

C.2.3.2 The C2 Functions during Anti-Poaching Operations

a) No new functions of C2 were identified related to APO.

b) Currently, most of the C2 functions are executed without real technological support.

c) The typical C2 functions performed during APO are situation assessment, sense-making, decision making, planning, tasking, control. All of them are used in APO.

d) C2 system must gather the information; interpret the information to determine the future context e.g. age of the spoor detected by the rangers.

e) Prediction is to connect the dots in the information. Connect bits of information may enable the commander to identify the area of a future incident.

C.2.3.3 New Technology (Cmore) Contribution in the C2 System

a) Cmore can support all of the C2 functions, but not all of them completely. Cmore does not do C2; the human role is still required.

b) Maybe ask the question to what degree the system will support C2 and situation awareness as part of the C2 process.

c) Advanced information can support planning of resource deployment to ensure resources are close to the possible contact points.

d) Consider the environmental effects in predicting the possibility of a poaching incident.

e) C2 technology needs to reduce the OODA loop (response time) at the tactical level. Need to shorten the ranger OODA loop for faster and better reaction.

f) The system must enable the rangers to react quicker by analysing the poacher behaviour to suggest actions and identify Rules of Engagement (ROE).

g) The system has to be able to predict the typical situations expected to help planning, including ROE.

h) Ontologies may be useful to interpret the information, connecting the dots.

i) Cmore need to help in prediction of events.

j) Consolidate the information into a useful format and place.

k) Cmore can be used to automate normal office workflow in the Ops Centre. The information is captured once into the system for everybody to use.

l) Errors in the information captured will be reduced through an automated workflow.

m) Cmore has the ability to sanitise, check and verify the information against the other factors and contextual information available.

n) Cmore consolidate, collate and integrate information from a number of sensors into one display for better interpretation and understanding.

o) Superimpose different information, e.g. ecological such as water levels, vegetation or history, onto the same map display to add extra contextual information.

p) Analyse past behaviour and current contextual information to predict the possible location/area for the next incident.

q) The ability to link different pieces of information to develop intelligence is lacking.

r) The map must not be cluttered with unnecessary information. The filtering information is required for this.

s) Information must be managed, controlled and filtered to get the maximum value out of it.

t) Graphical displays will aggregate the information into symbols which can be easily and effectively be integrated by the decision makers to detect patterns.

u) Cmore will automate many of the manual tasks such as recording of information. However, care must be taken to ensure that the system works fine and does not make work difficult to force workarounds.

C.2.4 System Dynamics Related Outcomes

The outputs were sorted into the headings listed below for capture into the Causal Loop Diagram and Stock and Flow Diagrams.

C.2.4.1 Variables and Constraints in the C2 System

a) The rangers aiming to engage the poachers have a much longer OODA loop than the poachers. The rangers must be able to make decisions much faster. Rangers have to call back to higher authority and are tied down by rules.

b) The actions of the rangers and tourists affect situation awareness.

c) Currently very little information is available outside of the Ops Centre.

d) Time delays affect the behaviour and success of the C2 system. On a hot day 15 min is required to keep dog on trial.

e) Coverage will affect the timeline.

f) Timeline effects are not due to distribution of the information, but rather due to the time used to analyse, understand and use the information to take decisions.

g) The time taken to implement the orders is a main factor as in the KNP there is vast distances.

h) The relevance of the information utilisation window is important. Will quick reaction use this information and how can reaction be improved to stay within this window.

i) Response time to poaching incidents must be reduced.

j) Add the actors that will use the new technology into the CLD, which include rangers and tourists.

k) The CLD only show poacher action as only source of information, while ranger and tourist actions as well as environmental information also lead to additional information. Need to understand the impact of information from patrols, rangers and tourists. This needs to be included into the model.

l) The amount of information available influences the C2 system. This is limited for tactical and operational decision making.

m) The amount of intelligence (pre-information) constrain the C2 system

n) At tactical level the speed of delivering information has a huge influence. The information is required immediately for effective decision making.

o) Most of the information in the system is “after the fact”. Information is actually required before the fact. This type of information is very limited and inhibits the ability of rangers to be pro-active.

p) The rate at which the information is ageing really affects the value of the information to react tactically.

q) There is daily, weekly and monthly reports, providing information of different life span and value.

r) The timeline need to be reduced at the operational and tactical level.

s) The amount of information available must not be limited, rather what is used and how it is used and by whom.

t) Many things occur in the tactical environment without intervention of the Ops Centre, making the OODA loop shorter.

u) The different literacy levels of the rangers need to be addressed. This can be addressed with graphical interface with pictures to interact with.

v) At operational level a lot of information is available but it cannot be linked to support planning of operations.

w) One and a half rhinos are poached every day in the KNP

C.2.4.2 Impact of the New Technology on Human Work

a) At the operational level a number of pre-set ROE can be set up for use during operations. This can be planned into an operation.

b) If there are deficiencies in the system, it can be addressed through procedures and workarounds. This may be a source on nonlinearities in the model.

c) Present the information to the users in such a way and format so that less energy is used to understand and make sense of a situation.

d) Need to remove information relay times out of the loop.

e) The information must get to the right person in time to enable collaboration. The will to use the information is not the problem.

f) The information is currently not in a usable and flexible format.

g) Information overload is a problem, but more information is never bad, especially if it is relevant. The important aspect is to determine what the information is and what is done with it.

h) Not everybody in the system need to see all of the information. Corruption need to be reduced through controlling the flow of information

i) Management of information use workflow to ensure that the information is in the correct state with only the relevant information highlighted for immediate action.

j) It may not be best to send everything to everybody, especially in a raw format. Processed information may have a wider relevance throughout the system.

k) Distributing the information may lead to autonomous automatic collaborative behaviour. With the right information to the right person in time may lead to proactive behaviour.

l) With all this information available to more people, they may be able to collaborate without even talking to each other.

m) The Ops Centre has much more information than the rangers in the veldt.

n) More information in the Ops Centre will enable the commander to deploy more resources proactively.

o) Knowledge about the environment and how to conduct operations are situated in the heads of a few people.

p) Cmore can present the information to many people, who have the knowhow, to assess the data (information) simultaneously and to connect the dots.

q) The workflow needs to be simple, reliable and robust.

r) More people can collaborate and work together on the same database to support situation awareness, planning and control. All information is immediately available to more people.

s) The ability to make decisions will be improved with more information available to the rangers busy engaging with poachers.

t) The APO C2 environment is not as hierarchical as in the military C2 environment.

u) The Ops Centre is rather a supportive entity than a commanding entity.

C.3 Community Policing Forum Exploratory Focus Group

C.3.1 Questionnaires

A preliminary ADH, as seen in Figure 4, and CLD, as seen in Figure 3 was constructed from literature and personal experience. This was used as a template to derive questions for the focus group discussion as well as to perform the analysis of the transcripts. The questions to guide the discussion in this focus group were:

a) What is the purpose of C2 in CPF? (Also look at the different levels)

b) Which C2 functions executed during NW patrols in a CPF can be supported with Cmore? (Situation assessment, sense-making, decision making, planning, tasking, control, etc. Is the list complete?)

c) What are the constraints on the success of the C2 system? (Information, resources, situation awareness, accuracy, time delays, etc.)

d) What are the shortcomings in C2 which can be addressed by technology?

e) Where can a new technology such as Cmore contribute to the effectiveness of the C2 system? (Typical capabilities in Cmore are sensing, information distribution, information management, information display, information analysis, planning tools, order distribution in reference to the variables and functions discussed)

f) How will the technology influence the way people do the work in the system?

g) What will be the effect of the technology on the timeline of events?

C.3.2 Cognitive Work Analysis Related Outcomes

The key words or phrases from the recordings are highlighted to support capturing them in the constructs and models.

C.3.2.1 Purpose of C2 in Community Policing Forum

The aim of this category is to define the functional purpose of the C2 system. The first question is supposed to address the mission and its context that is to be supported by the system and the technology. The question should be: Given the context of the mission, what is the role of technology in C2.

a) C2 support is only at the tactical level in CPF environment with very little happening at operational and strategic level.

b) The CPF NW patrollers do not take action on criminals. They got no privileges in terms of engaging criminals or suspicious persons.

c) C2 is less formal than the military environment and a lot more information distribution.

d) It is more coordination than to command and control.

e) CPF is run by civilians under control of a sector in the region of a police station.

f) Police can use the CPF information in a tactical format.

C.3.2.2 The C2 Functions during Community Policing Forum

a) The typical C2 functions performed during CPF is similar to APO and include the following:

b) Situation assessment, sense-making, decision making, planning, tasking, control

c) Information analysis is required to enable collaboration.

d) Formalisation of information capturing, distribution and management is required.

e) The information captured in the CPF must be used to its advantage.

f) Information need to be analysed for timelines, patterns and trends.

g) The CPF members need to plan preventative actions.

h) The NW patrollers are the eyes and ears of the police to gather information.

i) The police need the information from the CPF to plan preventative actions.

C.3.2.3 New Technology (Cmore) Contribution in the C2 System

a) Many CPFs do use new technology for collaboration such as Facebook and push to talk apps

b) CPFs not only use a paper and radio system.

c) Cmore add BFT and aggregation of all the functional elements, capabilities and information onto one platform.

d) Cmore integrate the different sources of information.

e) Police and private security and CPF all need to use Cmore to exchange information.

f) The biggest contribution for Situation Awareness and C2 is geographically based maps with different bits of information on it will help coordinators and patrollers.

g) The CPF committee get the information from the patrollers to identify trends and patterns to take action.

h) Typical action can be to put up cameras, extra patrol, request police patrols or visibility.

i) Distribute information on wanted or suspicious persons.

j) Cmore will ensure that the patrollers have the information to share.

k) The representation of the information can be shared for effective use.

l) More of the minor incidents can be reported to the police without effort and trouble to the resident in the CPF.

m) Cmore provide a more secure form of communication than radios over the air. Important and sensitive messages don’t have to be sent over the air.

n) This will assist in generating public crime stats.

C.3.3 System Dynamics Related Outcomes

C.3.3.1 Variables and Constraints in the C2 System

a) What about the act that control CPF and other legal issues?

b) The ability and to exchange information between the police and the CPF depends on a good relationship with the station commander.

c) The relationship between the station commander and the CPF is not necessarily formal.

d) Not all information is recorded and no intelligence built for the police and CPF.

e) Information over the radio is lost if voice is not recorded and someone does not write it down.

f) Even the private security companies can use the information, but it may not be advantageous to reduce the crime. Here the CPF with Cmore can be competition for the private security company.

g) The effect of separation between the police station and the CPF places a real constraint on the system effectiveness.

h) The legalities of publicising of information need to be considered in using the system.

i) Police and CPF interact with a single point (node) of contact.

j) The private security is also a reactive element. They also don't have a control centre with real C2. They don't develop situation awareness to identify trends for preventative actions.

k) Information exchange needs to be managed with guiding privileges to secure sensitive information.

C.3.3.2 Impact of the New Technology on Human Work

a) Formal structures for collaboration are required between the CPF and the police.

b) The person performing the patrol will not really use any of the information of Cmore while he is patrolling.

c) The patroller does not need to see what is happening now. He does not need the real time awareness.

d) Very little of the assembled information is useful to a patroller.

e) The coordinator need to know where his people are and if they cover all the areas. He actually requires the situation awareness.

f) Driving and operating the smartphone is a risk to safety. The eyes of the patroller need to be outside of the vehicle. Driving while talking or texting might result in a risky act.

g) Difference with ranger is that the ranger needs to act and prevent poaching like a policeman.

h) The NW patroller is only a sensor.

i) CPF members are purely a sensor but require a close interaction with the police for to be effective.

j) The patrollers can share information and representation thereof.

k) The coordinator will know where his people are and which routes are patrolled.

l) Cmore can help improve the safety of patrollers, even if they only feel safer.

m) Ideal is that CPF members operate Cmore inside the police station. This way the information and need for immediate action can be immediately be forwarded to the police.

n) More information will help the residents to avoid crime.

o) Patrollers will feel part of the loop with Cmore

p) The extra information may lead to autonomous behaviour of the patrollers.

q) The availability of information may lead people to exploit the information. It is there, people may just as well use it.

r) The safer and more involved the patrollers feel, more resident will be willing to participate.

C.4 Exploratory Focus Group General Outputs

a) The boundaries of the modelling project need to be clearly stated at the outset of the focus group to contain the discussions and to ensure that the important factors are considered.

b) The level of detail in the discussions must be managed. More detail is required to do complete modelling, but it will only confuse the issue if it goes too deep.

c) CLD is a useful method to derive the measures of effectiveness (MoE) of the system with the systems approach during the initial problem definition phase.

d) Be careful to not take the CLD too wide as it will become complex and too difficult to understand.

e) The higher level detail may even be lost with SD it integrates over time. This is not ABM and the detail is not very important.

f) CPF is a very difficult and complex implementation of the new technology. Due to the limitations on the different role players it is difficult to really model role of the technology. This provides a representative case study for demonstrating the modelling methodology.

g) The impact of information from tourists is not considered in this model. It will still be some time before smartphone applications are available for distribution to the general public.

C.5 Exploratory Focus Group Lessons learnt

a) The amount of new information gained from the focus group was significantly less than the first focus group. The reason is that the ADH with information gained from the first focus group was available to this focus group.

b) The facilitator has to spend more time in the introduction to identify the problem.

c) The model and functions are at a higher level than the exact details. The correct level for addressing all the issues must be addressed.
d) Defining boundaries of the different terms and definitions is difficult in general.

C.6 Anti-Poaching Operations Confirmatory Focus Group

C.6.1 Planning and Questionnaires

C.6.1.1 Purpose

The purpose of this focus group is to capture feedback on models and simulation outputs for the impact of new technology in a Command and Control (C2) model for assessment of the impact of new technology for Anti-Poaching Operations (APO) as well as for Neighbourhood Watch (NW) patrols as part of a Community Policing Forum (CPF). The aim is to assess the accuracy and utility of the models and simulation outputs. There are many similarities between the two C2 implementations of Cmore. Therefore in order to reduce duplication, the two systems will be discussed in series.

C.6.1.2 Participants

a) Louise Leenen – Facilitator.
b) Rudolph Oosthuizen – Facilitator, recorder and time keeper.
c) Brian Naude (Systems Engineer).
d) Cobus Venter (Systems Engineer).
e) Leon Pretorius (Professor).
f) Herman le Roux (Programme Manager).
g) Carel Combrink (Systems Engineer).
h) Priaash Ramadeen (Software Developer).

C.6.1.3 Cognitive Work Analysis

The elements in the Work Domain Analysis (WDA) Abstraction Decomposition Hierarchy (ADH) in Figure 51 were derived from literature, documents, literature and the Exploratory Focus Group. The purpose of the C2 system is to enable assets to execute APO missions. This is achieved through satisfying the values and priorities of the system that includes situation awareness to guide collaboration and synchronisation of assets. The purpose related functions enable the users of the system to perform their work. The bottom layer provides the physical elements in the system with the second layer the functions they support. The yellow blocks indicate the current capabilities and functions of the technical elements in the system. The blue blocks highlight the additional capabilities and functions provided by Cmore. Most of the yellow blocks are also supported by Cmore. The questions for discussion on the WDA include the following:

a) Are the elements in the WDA representative of the system in terms of completeness, accuracy and relevance?
b) Are all of the links correct in the WDA?
c) Does the WDA contribute to understanding the system and its interactions?

C.6.1.4 Functional System Models

Two functional flow diagrams are provided in Figure 52 and Figure 53 as derived from the ADH in Figure 51. The Purpose Related Functions are combined in Figure 52 and relates to an OODA type model. These are the functions performed by people doing work in the system. The Object Related Functions in Figure 53 indicated the functions performed by the physical elements in the system. Again the configuration of the yellow and blue blocks is used to discriminate between the capabilities of the current and new technologies. The questions for discussion on the functional models of the system with the work related functions in include the following:

a) Are the elements in the functional models representative of the system in terms of completeness, accuracy and relevance?
b) Are all of the links and flow of information correct in the models?
c) Do the functional models contribute to understanding the system and its interactions?

C.6.1.5 System Dynamics Models

The Causal Loop Diagram (CLD) in Figure 55 is constructed from the ADH and functional models. The CLD diagram indicates the causal relationships between entities and variables in the system. This is used to develop the Stock and Flow Diagram (SFD) in Figure 56. The SFD shed light on the effect of the variables of the flow of the main entity (information) through the system as well as how the use of information affect the system. The questions for discussion on the CLD and the SFD of the system include the following:

a) Are the elements in the SD models representative of the system in terms of completeness, accuracy and relevance?
b) Are all of the links and causal relationships correct in the model?
c) Do the SD models contribute to understanding the system and its interactions?

C.6.1.6 Simulation Results

The simulation results of selected stocks and variables of the SFD in Figure 56 are presented in Figure 57, Figure 58, Figure 59 and Figure 60. They demonstrate the effect of information on the system over time. The questions for discussion on the SD simulation outputs of the system include the following:

a) Are the three graphics realistic in the system behaviour the display?

b) Do the three graphs provide insight on the influence of Cmore on the system?

C.6.2 Outcomes

C.6.2.1 Cognitive Work Analysis

a) The concept and role of situation awareness stands out clearly here.

b) The elements of situation awareness are not in a logical order to support easy reading and simpler diagram.

c) The tactical C2 as well as coordination and collaboration is required here and need to be supported by the new technology.

d) These models are useful in capturing the mental models

e) No errors were found in the ADH.

C.6.2.2 Functional System Models

a) The interaction between the aircrew and the rangers is not clear. This is done via radio.

b) Add the capability to display and share the situation awareness from the Control Centre. Arrows should indicate the flow of information to and fro the different Situation Awareness displays. It needs a blue block at the right-hand side of the diagram to indicate distribution to the various elements.

c) The contribution of Cmore to situation awareness development and display is not clear.

d) Collaboration in the flow diagram is not visible despite this being a result of the shared situation awareness.

e) The common intent is required for effective tactical C2. This helps you to share the situation awareness.

f) A common intent is required; this will assist in a shared situation awareness if all look at the same information displayed.

g) A calibrated perception is required for a common intent. The common situation awareness picture must be with everybody. This results in the shared situation awareness.

h) Change block to “Common Situation Awareness Picture”. This display is not the same for all the nodes in the system. They may have different objectives or look at different areas. Therefore one generic block could not be sufficient.

i) The blocks provide verbs or functions; therefore display may be the odd one out. It should not be confused to the purpose related functions.

j) Sharing situation awareness means to distribute and display the situation awareness. This requires the Cmore technology to facilitate it.

k) Care is required to ensure that the C2 in APO is not assumed to be strictly related to military C2.

l) The common intent may be established from the bottom instead as from the top as in other C2 systems. The Command Centre intent and decisions need to enable the effectors doing their work. This does not work in a typical top-down hierarchy.

m) The long term and short term intents might originate either from the top or the bottom of the hierarchy. This is an example of an agile environment. This determines for how long the intent will remain valid.

n) This level of intent also relates to the ROE. The ranger arriving at an incident needs to decide what to do and which set of rules to apply.

o) The ability to share information and situation awareness will enable the tactical intent. This is achieved through mission planning.

C.6.2.3 System Dynamic Models

a) Change the variable name “Assets” to resources, effectors or sensors. This tends to become confusing with the general managerial use of the word “asset”, which includes “information”, “buildings”, “vehicles”, etc. This needs to be properly defined.

b) List the assumptions made to construct the CLD. This needs to be systematic.

c) There is data that support the assumption ranger action leads to a reduction in poacher activity.

d) The effect of corruption needs to be considered in the CLD.

e) Add a direct link from Situation Awareness to the Ranger Action. If the rangers know about a regular crossing point, they can plan ahead and leapfrog to engage the poachers there. This can be done with a ghost variable.

f) The model does not cater for only one incident or the choice between the two options or specific types of information.

g) The models need to sort out simple and expanded (built up) as knowledge increases. Not much will be learnt from a complex model. If the model is too complex it cannot be tested.

h) Assume the poachers are bad and the rangers are good.

i) The model represents a set of behaviours of the system. This can be simulated and expanded with the random events aggregated.

j) Moving poacher action variable out of the inflow will improve the understanding.

k) The group can be used to provide inputs on the different assumptions and time constants chosen.

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l) The modeller need to go and look at the different ways the model can work as part of the validation process.

m) The simple behaviour of the model need to be understood first before the more complex issues can be addressed.

n) The environmental effects and time of year also affect the poaching action.

o) The models assume that the poacher modus operandi stays the same, constant, over time, despite the ranger action.

p) Add some more feedback loops to play around with the SD models

q) The variable “Information on Carcasses” may be better interpreted if it is referred to the “Number of Carcasses” instead.

r) The models do support understanding the behaviour of the technology in the complex STS. It may not be perfect but is a useful vehicle to investigate certain aspects.

s) Discriminate between poacher action and the effective killing of animals. This will make the model easier to understand.

C.6.2.4 Simulation Outputs

a) It is not easy for all to understand the way simulation is done.

b) The value of the models can be improved through describing the context.

c) Have another look at the information about the carcasses. This may even be the number of carcasses as a result of poacher action. Even only the fact of knowing there is a carcass can be relevant.

d) The dynamic value of information needs to be considered. The value of 1000 carcasses is less than 100 carcasses; you can do more with this. Therefore, less is more and there is a non-linear relationship.

e) Information may go below zero to become disinformation.

f) Need to have a look at possible nonlinear things or effects in the system. This will make it useful to identify the tipping point behaviour.

g) The influence of Cmore will not be linear in the model as captured in the simulations. The possible non-linear, such as saturation limits, effect needs to be investigated.

h) The Monte-Carlo simulations can be applied here. Collaboration can vary over a range of zero to one, even over a parabolic or S-curve distribution. This might even be for future research.

i) It makes sense that the number of carcasses does not go to zero, this is a useful output.

j) The expectation must not exist that the new technology will eventually stop all poaching. This leads to an understanding of the change that can be expected in a year after implementing the technology.

k) On the information graph do not expect a visible change before a hundred days after implementing the new technology.

l) These comments highlight the value and utility of the modelling methodology and the SD modelling.

m) The fact that the information on Poacher action decrease to zero, does not intuitively feel right. However, in this model with its assumptions is correct.

n) This assumes that the poachers will not change their modus operandi; however, that is not the reality. In real life they will adapt, causing a complex dynamic system. This is something that can be captured in the next iteration of the modelling process.

o) This is a method of validation of the model.

p) This highlights the need for a number of iterations in the SD modelling loops. This was just the first loop to get things going and generated from the modellers own interpretation of the information gathered in the Exploratory Focus Group.

q) A second and third iteration may be required to provide feedback and to improve the models. Here what-ifs and Monte Carlos can be used.

r) The poacher action needs to be increased to be more realistic representations. The increase is also not stable; it increases towards the end of the year.

s) The efficiency of the system needs to be improved. The requirements of rhino horns to the poachers may be a driver for their actions. The requirement of horns in the market will influence the number of carcasses to be generated in the system.

t) The requirement of the technology is to increase the gap between the poacher requirements and the situation (their effectiveness) on the ground. The steady state results must have a bigger gap.

u) The levels of the information are useful in the model. An interpretation is that a lot of information may lead to confusion.

v) The context of a situation leads to better information.

w) The information about the carcases is useful, the more information that is available is useful. This is however dependant on the age of the carcass. Different age carcasses lead to different uses of information.

x) The carcass information is difficult to define and easy to attack. Rather consider Carcass Reports or Carcases Detected. However, the units must still be considered in the model.

y) This stock should be on the information that there is a carcass and does not include all the other related information, such as forensics, as it will make a big influence on the model.

z) The fact that poacher action is not increasing over time results in a decrease of effective poacher action without the new technology. This is not absolutely correct and must be fixed in the model.

aa) There seem to be a discrepancy between the info on carcases and the level of poacher action. However, this is correct as the information on carcasses accumulates (integrates) over time without an outflow in the model. There will not be new information on carcasses, but the information in the archives remains.

bb) The relationship between information and the situation awareness is not linear in real life. Again this refers to a S-curve behaviour as affected by the decision policy. The collaboration may be investigated the same way as a decision policy.

cc) The reasons why the model behaves as it is needs to be explained very carefully to the stakeholders as they may easily misinterpret it and lose faith. The graphs may not be a true reflection of the actual situation.

dd) The steady state and end state conditions must be considered very carefully to ensure they are relevant and valid.

ee) The model may also be used to investigate the effect of response times on the system.

ff) The collaboration is an external influence into the system.

gg) The fact that there is feedback in the current (yellow block) system explains why things lead to a steady state after a very long time.

hh) The initial conditions need to be carefully determined and described.

C.6.3 Corrective Actions

The following corrective actions were identified to update the models and simulations in Chapter 6:

a) Add the function of "Share Situation Awareness" in a blue block on the right-hand side with arrows to "Situation Awareness Display" in the functional diagram in Figure 52.

b) Add the input of "Common Intent" to the functional diagram in Figure 52.

c) Change the variable name "Assets" to resources, effectors or sensors in the CLD of Figure 55.

d) List the assumptions made to construct the CLD.

e) Add a direct link from "Situation Awareness" to the "Ranger Action" variable in Figure 55.

f) The variable "Information on Carcasses" needs to be changed to prevent confusion in Figure 56. Consider "Carcass Reports" or "Carcases Detected".

g) Discriminate between “Poacher Action” and the effective killing of animals. This can be achieved by adding a variable to the inflow of the stack of “Information on Carcasses” in Figure 56.

h) Investigate the effect of nonlinear variables in the SFD for “Collaboration”.

i) Change the vertical axis label of Figure 57 to better reflect the information on the graph.

j) Change the “Poacher Action” variable to reflect an increase and nonlinear periodic effects, as seen in the graph of Figure 60.

C.7 Community Policing Forum Confirmatory Focus Group

C.7.1 Planning and Questionnaires

C.7.1.1 Cognitive Work Analysis

The elements in the WDA in Figure 70 were derived from literature, documents, literature and the Exploratory Focus Group. The purpose of the C2 system is to enable assets to execute CPF missions. This is achieved through satisfying the values and priorities of the system that includes situation awareness to guide collaboration and synchronisation of assets. The purpose related functions enable the users of the system to perform their work. The bottom layer provides the physical elements in the system with the second layer the functions they support. The yellow blocks indicate the current capabilities and functions of the technical elements in the system. The blue blocks highlight the additional capabilities and functions provided by Cmore. Most of the yellow blocks are also supported by Cmore. The questions for discussion on the WDA include the following:

a) Are the elements in the WDA representative of the system in terms of completeness, accuracy and relevance?

b) Are all of the links correct in the WDA?

c) Does the WDA contribute to understanding the system and its interactions?

C.7.1.2 Functional System Models

Two functional flow diagrams are provided in Figure 71 and Figure 72 as derived from the ADH in Figure 70. The Purpose Related Functions are combined in Figure 71 and relates to an OODA type model. These are the functions performed by people doing work in the system. The Object Related Functions in Figure 72 indicated the functions performed by the physical elements in the system. Again the configuration of the yellow and blue blocks is used to discriminate between the capabilities of the current and new technologies. The questions for discussion on the functional models of the system with the work related functions in include the following:

a) Are the elements in the functional models representative of the system in terms of completeness, accuracy and relevance?

b) Are all of the links and flow of information correct in the models?

c) Do the functional models contribute to understanding the system and its interactions?

C.7.1.3 System Dynamics Models

The Causal Loop Diagram (CLD) in Figure 74 is constructed from the ADH and functional models. The CLD diagram indicates the causal relationships between entities and variables in the system. This is used to develop the Stock and Flow Diagram (SFD) in Figure 75. The SFD shed light on the effect of the variables of the flow of the main entity (information) through the system as well as hof the use of information affect the system. The questions for discussion on the CLD and the SFD of the system include the following:

a) Are the elements in the SD models representative of the system in terms of completeness, accuracy and relevance?

b) Are all of the links and causal relationships correct in the model?

c) Do the SD models contribute to understanding the system and its interactions?

C.7.1.4 Simulation Results

The simulation results of selected stocks and variables of the SFD in Figure 75 are presented in Figure 76, Figure 77, Figure 78 and Figure 79. They demonstrate the effect of information on the system over time. The questions for discussion on the SD simulation outputs of the system include the following:

a) Are the three graphics realistic in the system behaviour the display?

b) Do the three graphs provide insight on the influence of Cmore on the system?

C.7.2 Outcomes

C.7.2.1 Cognitive Work Analysis

a) The APO presented a rather well-behaved and structured system where the CPF is an ill behaved system with more random events and human influence.

b) The patrollers are volunteers and tend to be finicky. They will easily disengage and leave the CPF if feeling threatened or disregarded

c) No real inputs were provided here. The inputs from the APO will be considered in this diagram as well.

C.7.2.2 Functional System Models

No additional inputs were provided here. The inputs from the APO will be considered in this diagram as well.

C.7.2.3 System Dynamic Models

a) The criminal action that affect the situation awareness represent the first steps of the OODA loop as new incident information need to be interpreted first.

b) “Patrol Safety” need to affect the “Information”. This needs to be added.

c) Separate the variable of “Criminal Activity” from the “Criminal Action” flow in the SFD.

d) No additional inputs were provided here. The inputs from the APO will be considered in this diagram as well.

C.7.2.4 Simulation Outputs

a) The reason and origin of the assumptions and initial conditions (values) need to be explained along with the models.

b) More data on the problem and system is required from the environment before the time to support the simulations.

c) More information on the delays and other assumptions is required.

d) These models and output graphs focus more on the relative relationships rather than the absolute values.

e) It will be interesting to actually measure the delays in the experiment.

f) If the system is successful, the people in the system will be influenced to make it more successful.

g) What will happen if the system becomes too successful and the NW patrolled become bored and not feeling the need to patrol. This will cause the system to degrade.

h) This will cause oscillating behaviour and is representative of the real world.

i) This results in the coefficients to change over time. This needs to be validated in the model.

j) If the graphs are considered over a longer period of time, this oscillatory behaviour may come out.

k) These simulations need to investigate the natural frequency of the system as a result of the underlying structure of the system.

l) The correlation between coordinator and patroller awareness makes sense, even if the units are different.

m) The collaboration should lead to a higher improvement of the patroller awareness.

n) The patroller awareness is not as high because he has less time available to look at his position on the smartphone.

o) An attempt must be made to measure the reaction time in the experiment as delays determine the dynamic behaviour in the simulation.

p) The assumptions need to be verified in the field experiment.

q) Filters in Vensim can be used to assess the data to determine the values of the parameters, the best parameter fit/set.

r) The criminal action data is available from the CDF of sector policing.

s) If criminal activity goes down, it should affect (through a link) the amount of patrols taking place.

t) No additional inputs were provided here. The inputs from the APO will be considered in this diagram as well.

C.7.3 Corrective Actions

The following corrective actions were identified to update the models and simulations in Chapter **Error! Reference source not found.**:

a) "Patrol Safety" need to affect the "Information" in the CLD.

b) Separate the variable of "Criminal Activity" from the "Criminal Action" flow in the SFD.

c) Rerun the simulations to investigate the effect of coefficients that change over time over a longer period.

d) Apply filters to find the best parameter fit in preparation of the field experiment part of the case study.

C.8 Confirmatory Focus Group General Outputs

a) Not too many blocks must be added to the model as it increases the complexity and loose the objective of the modelling effort. Try and optimise the names in the blocks with the right words instead of adding new blocks.

b) The mental model of the audience has to be considered in the naming of the variables. Naming of the variables is very important.

c) Need to start with a simple model to lead to questions. This leads to enhancements on the model and increase in complexity to investigate certain aspects. These iterations lead to an understanding of the problem.

d) Using the word "all" must be considered as not all of the links in the real system may be present in the model. This refers to "all" the links in the model should be correct.

e) The validation process of the SD simulations need to feature stronger in the model.

f) SD is a powerful tool to model and understand the problems and need to be more prominent in the modelling methodology.

C.9 Confirmatory Focus Group Lessons learnt

a) Discussions never really followed the questions accurately, the questions only initiated and focussed the discussions on the diagrams and output graphs.

b) It is difficult for the FG members to walk in cold into the meeting and not understanding where the models come from and how they were developed. This includes agreeing on the assumptions. The team should be working together with multiple iterations until the models are acceptable. A solution is to send the models and simulation outputs to the participants before the time.

c) Focus groups can be used to get better values for the SD models, this can be used in a number iterations. This needs to be formally planned into the process.

Appendix D SYSTEM DYNAMIC MODELS

D.1 Border Safeguarding Command and Control

The text version of the Stock and Flow Diagram (SFD) from Figure 45 used in Chapter 5 for the simulations is provided below:

Collaboration=

3

~ Dmnl

~ |

Community Participation= DELAY FIXED (

(Criminal Action*Collaboration)/3, 2, 0)

~ information/Day

~ |

Reaction Force Awareness= DELAY FIXED (

(C2 System Information/Reaction Time)*Collaboration , Reaction Time, 0)

~ information/Day

~ |

Reporting=

MAX(0, (Report Suspicious Activity + Incident Reported + Community Participation))

~ information/Day

~ |

Report Suspicious Activity=

(Criminal Action + Planned Patrol Awareness)*Collaboration/3

~ information/Day

~ |

Planned Patrol Awareness=

C2 System Information/Patrol Schedule

~ information/Day

~ |

Criminal Action=

MAX(0, (5 - (Reaction Force Awareness-Planned Patrol Awareness/2)))

~ information/Day

~ |

Patrol Schedule=

1

~ Day

~ |

Information Capture Time=

2

~ Day

~ |

Incident Reported= DELAY FIXED (

(Crime Incident Information/Information Capture Time), Information Capture Time , 0)

~ information/Day

~ |

Reaction Time=

1.5

~ Day

~ |

Decay= DELAY FIXED (

MAX (Information Decay Tempo, 0), 0 , 0)

~ information/Day

~ |

Decay Time=

0.5

~ Day

~ |

```
Information Decay Tempo=
	C2 System Information/Decay Time
	~	information/Day
	~		|
Crime Incident Information= INTEG (
	Criminal Action,
		1)
	~	information
	~		|
C2 System Information= INTEG (
	Reporting-Decay,
		1)
	~	information
	~		|
********************************************************
	.Control
********************************************************~
		Simulation Control Parameters
	|
FINAL TIME  = 30
	~	Day
	~	The final time for the simulation.
	|
INITIAL TIME  = 0
	~	Day
	~	The initial time for the simulation.
	|
SAVEPER  =
```

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```
     TIME STEP
        ~     Day [0,?]
        ~     The frequency with which output is stored.
        |
TIME STEP  = 0.1
        ~     Day [0,?]
        ~     The time step for the simulation.
        |
```

D.2 Anti-Poaching Operations

The text version of the SFD from Figure 63 in Chapter 6 used for the simulations is provided below:

```
Ranger Patrol Awareness= DELAY FIXED (
     (MAX( Collaboration*(Ops Centre Information/(Response Time))-Poacher Action*4, 0)),\
          Response Time/Collaboration, 0)
        ~     information/hour
        ~          |
Patrol Effectiveness=
        200
        ~     Dmnl
        ~          |
Poaching=
        MAX(0, Poacher Action-Ranger Patrol Awareness/Patrol Effectiveness)
        ~     information/hour
        ~          |
Tracks Found= DELAY FIXED (
        Poacher Action/5 + Ranger Patrol Awareness/Patrol Effectiveness , 4 , 0)
        ~     information/hour
        ~          |
```

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```
Shots Heard=
	Poaching/(Patrol Effectiveness)
	~	information/hour
	~		|
Poacher Action=
	(RAMP(0.001, 5, 10000) )/24
	~	information/hour
	~		|
Reporting=
	(Shots Heard + Tracks Found + Carcass Detected)*Collaboration
	~	information/hour
	~		|
Collaboration=
	1
	~	Dmnl
	~		|
Carcass Detected= DELAY FIXED (
	(Animal Carcasses/Detection Delay Time), Detection Delay Time , 0)
	~	information/hour
	~		|
Decay= DELAY FIXED (
	 MAX (Information Value, 0), 0 , 0)
	~	information/hour
	~		|
Decay Time=
	6
	~	hour
	~		|
```

```
Information Value=
    DELAY FIXED( Ops Centre Information/Decay Time, Decay Time , 0 )
    ~   information/hour
    ~       |
Detection Delay Time=
    48
    ~   hour
    ~       |
Animal Carcasses= INTEG (
    Poaching,
        0)
    ~   information
    ~       |
Response Time=
    1
    ~   hour
    ~       |
Ops Centre Information= INTEG (
    Reporting-Decay,
        0)
    ~   information
    ~       |
********************************************************
    .Control
********************************************************~
        Simulation Control Parameters
    |
FINAL TIME  = 5000
```

~ hour

~ The final time for the simulation.

|

INITIAL TIME = 0

~ hour

~ The initial time for the simulation.

|

SAVEPER =

TIME STEP

~ hour [0,?]

~ The frequency with which output is stored.

|

TIME STEP = 0.01

~ hour [0,?]

~ The time step for the simulation.

|

D.3 Community Policing Forum Neighbourhood Watch

The text version of the SFD from Figure 81 in Chapter 7 used for the simulations is provided below:

Criminal Incidents=

MAX(0, Criminal Action-Coordinator Awareness/5)

~ information/hour

~ |

Criminal Action=

1

~ information/hour

~ |

Report Suspicious Activity=

MIN((Criminal Action/3)+(Patrol Safety/3)+(Patroller Awareness/3), 1)

~ information/hour

~ |

Assessment Time=

2

~ hour

~ |

Patrol Safety=

MAX(Coordinator Awareness-Criminal Incidents, 0)

~ information/hour

~ |

Coordinator Awareness= DELAY FIXED (

(CPF Information*Collaboration/3)/(Reaction Time Delay), Reaction Time Delay, 0)

~ information/hour

~ ~ :SUPPLEMENTARY

|

Patroller Awareness=

DELAY FIXED(CPF Information/Assessment Time, Assessment Time, 0)

~ information/hour

~ |

Collaboration=

1

~ Dmnl

~ |

Information Capture Delay=

24

~ hour

```
    ~       |

Incident Reported= DELAY FIXED (

    (Crime Incident Information/Information Capture Delay), Information Capture Delay , \

        0)

    ~   information/hour

    ~       |

Reaction Time Delay=

    1

    ~   hour

    ~       ~   :SUPPLEMENTARY

    |

Reporting=

    MAX( ((Report Suspicious Activity)/2 + (Incident Reported)/2)*Collaboration, 0)

    ~   information/hour

    ~       |

Decay= DELAY FIXED (

     MAX (Information Value, 0), 0 , 0)

    ~   information/hour

    ~       |

Decay Time=

    2

    ~   hour

    ~       |

Information Value=

    DELAY FIXED( CPF Information/Decay Time, Decay Time, 0)

    ~   information/hour

    ~       |
```

```
Crime Incident Information= INTEG (
        Criminal Incidents,
                1)
        ~       information
        ~               |
CPF Information= INTEG (
        Reporting-Decay,
                1)
        ~       information
        ~               |
********************************************************
        .Control
********************************************************~
                Simulation Control Parameters
        |
FINAL TIME  = 100
        ~       Day
        ~       The final time for the simulation.
        |
INITIAL TIME  = 0
        ~       Day
        ~       The initial time for the simulation.
        |
SAVEPER  =
         TIME STEP
        ~       Day [0,?]
        ~       The frequency with which output is stored.
        |
```

TIME STEP = 0.01

~ Day [0,?]

~ The time step for the simulation.

|

D.4 Updated Community Policing Forum Neighbourhood Watch

The text version of the SFD from Figure 89 in Chapter 7 used for the simulations is provided below:

Report Suspicious Activity= DELAY FIXED (

MIN((Criminal Action+Patrol Safety+Patroller Awareness), Criminal Action), Patrol Action Time\

, 0)

~ information/Minute

~ |

Coordinator Awareness= DELAY FIXED (

((CPF Information*Collaboration)/(Coordinate Time))-Criminal Action*2, Coordinate Time\

, 0)

~ information/Minute

~ |

Coordinate Time=

20

~ Minute

~ |

Patrol Effectiveness=

50

~ Dmnl

~ |

Criminal Incidents=

MAX(0, Criminal Action-Coordinator Awareness/Patrol Effectiveness)

~ information/Minute

```
    ~       |

Patroller Awareness=

    Coordinator Awareness

    ~   information/Minute

    ~       |

Patrol Action Time=

    60

    ~   Minute

    ~       |

Patrol Safety=

    MAX(Coordinator Awareness-Criminal Action, 0)

    ~   information/Minute

    ~       |

Criminal Action=

    1

    ~   information/Minute

    ~       |

Collaboration=

    1

    ~   Dmnl

    ~       |

Information Capture Delay=

    120

    ~   Minute

    ~       |

Incident Reported= DELAY FIXED (

    (Crime Incident Information/Information Capture Delay), Information Capture Delay , \

        0)
```

```
	~	information/Minute
	~		|

Reporting=
	MAX( ((Report Suspicious Activity) + (Incident Reported))*Collaboration, 0)
	~	information/Minute
	~		|

Decay= DELAY FIXED (
	 MAX (Information Value, 0), 0 , 0)
	~	information/Minute
	~		|

Decay Time=
	120
	~	Minute
	~		|

Information Value=
	DELAY FIXED( CPF Information/Decay Time, Decay Time, 0)
	~	information/Minute
	~		|

Crime Incident Information= INTEG (
	Criminal Incidents,
		1)
	~	information
	~		|

CPF Information= INTEG (
	Reporting-Decay,
		1)
	~	information
	~		|
```

```
********************************************************
	.Control
********************************************************~
		Simulation Control Parameters
	|
FINAL TIME  = 3000
	~	Minute
	~	The final time for the simulation.
	|
INITIAL TIME  = 0
	~	Minute
	~	The initial time for the simulation.
	|
SAVEPER  = 
	TIME STEP
	~	Minute [0,?]
	~	The frequency with which output is stored.
	|
TIME STEP  = 0.1
	~	Minute [0,?]
	~	The time step for the simulation.
	|
```

Appendix E CASE STUDY DATA

E.1 Coordinator Questionnaires Before

No	**CPF**	**Call Sign**	**Experience**	**SART**										
				Change	Complex	Variables	Alert	Concentrate	Attention	Spare mental	Info quantity	Info Quality	Familiar	Situation Awareness
1	Garscom	T1	3	3	4	3	3	3	2	3	3	3	3	10
2	Garscom	F1	5	4	4	5	5	6	6	3	3	3	3	16
3	Garscom	C1	8	3	3	2	4	4	5	5	3	2	5	20
4	Garscom	F1a	2	4	3	2	6	6	5	5	3	5	5	26
5	Garscom	E3	6	3	2	3	5	5	5	5	2	5	5	24
6	Garscom	E3	7	3	2	3	5	5	5	4	2	4	4	21
7	Garscom	K1	7	1	1	2	4	3	4	6	2	2	5	22
8	MBW	ES	20	2	4	4	7	7	5	6	4	2	7	28
9	MBW	RW	8	2	2	2	4	4	5	6	4	3	5	25
10	MBW	JS	1	2	2	1	6	7	6	5	2	2	5	28
11	MBW	HvH	2	1	1	1	4	4	2	6	2	2	2	19
12	MBW	WL	3	2	2	2	5	5	3	4	5	5	5	26
13	MBW	JJ	2	3	4	6	6	5	4	4	6	5	4	21
14	Garscom	S2	8	4	3	4	6	6	3	6	3	3	6	22

E.2 Coordinator Questionnaires After

No	CPF	Name	Experience	SART										
				Change	Complex	Variables	Alert	Concentrate	Attention	Spare mental	Info quantity	Info Quality	Familiar	Situation Awareness
1	Garscom	T1	3	3	3	2	6	7	5	4	7	7	7	35
2	Garscom	F1	5	4	4	5	7	7	7	6	7	7	7	35
3	Garscom	C1	8	3	3	2	6	6	3	5	7	6	6	31
4	Garscom	F1a	2	4	3	3	6	6	1	4	7	7	6	27
5	Garscom	E3	6	2	2	2	7	6	4	4	6	5	6	32
6	Garscom	E3	7	1	1	2	7	7	4	5	5	6	7	37
7	Garscom	K1	7	1	1	2	7	4	4	6	5	5	5	32
8	MBW	ES	20	3	2	1	6	5	3	4	4	4	7	27
9	MBW	RW	8	2	2	2	4	4	5	6	6	5	6	30
10	MBW	JS	1	2	4	4	5	6	6	5	3	4	4	23
11	MBW	HvH	2	1	1	1	4	4	1	4	3	2	2	17
12	MBW	WL	3	2	2	2	5	5	5	5	6	7	6	33
13	MBW	JJ	1	3	2	3	5	5	3	4	5	4	6	24
14	Garscom	S2	8	4	3	4	6	6	2	6	7	7	7	30

No	**CPF**	**Name**	**Experience**	**Use**						
				Ease of report	What to report	More info	Utilise	Coordinate	Safety	Effectiveness
1	Garscom	T1	3	5	5	5	5	5	5	5
2	Garscom	F1	5	5	5	5	5	5	5	5
3	Garscom	C1	8	5	4	5	5	5	4	5
4	Garscom	F1a	2	5	5	5	5	5	5	5
5	Garscom	E3	6	4	4	4	4	5	4	4
6	Garscom	E3	7	4	4	4	3	3	4	4
7	Garscom	K1	7	4	4	5	4	5	4	4
8	MBW	ES	20	3	4	5	5	3	3	3
9	MBW	RW	8	4	3	4	4	3	2	4
10	MBW	JS	1	4	4	4	4	4	3	5
11	MBW	HvH	2	4	4	5	4	4	3	4
12	MBW	WL	3	4	4	4	3	3	4	4
13	MBW	JJ	1	4	4	4	5	3	4	4
14	Garscom	S2	8	5	4	5	5	5	4	5

E.3 Patroller Questionnaires Before

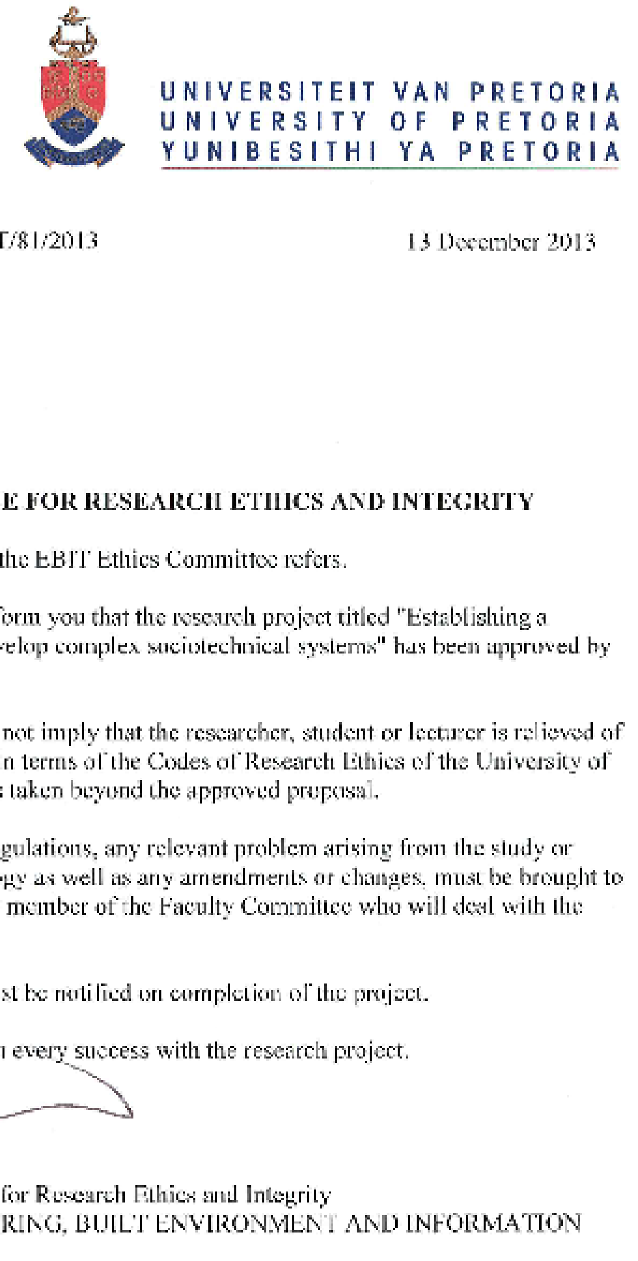
No	CPF	Name	Experience	SART										
				Change	Complex	Variables	Alert	Concentrate	Attention	Spare mental	Info quantity	Info Quality	Familiar	Situation Awareness
1	Garscom	F8	4	3	4	2	2	3	2	2	3	3	2	8
2	Garscom	C4	8	1	1	1	4	5	2	5	2	4	5	24
3	Garscom	C6	4	3	2	2	5	6	5	5	3	4	4	25
4	Garscom	E4	3	3	3	2	5	5	2	5	5	6	5	25
5	Garscom	E6	2	3	3	2	5	5	2	5	3	3	4	19
6	Garscom	E1	10	1	1	1	7	7	2	5	4	6	7	35
7	Garscom	E2	4	1	3	1	6	6	1	6	4	6	4	28
8	Garscom	F6	2	3	2	1	6	5	4	6	3	5	3	26
9	Garscom	F14	2	2	2	2	4	5	3	5	3	3	5	22
10	Garscom	F3	1	2	2	1	6	6	2	5	5	6	4	29
11	Garscom	F2	6	3	4	4	5	5	3	6	5	4	4	21
12	Garscom	T12	2	2	3	3	5	5	3	4	5	6	5	25
13	Garscom	K7	1	2	2	4	5	4	3	5	3	3	3	18
14	Garscom	K6	4	2	1	3	4	4	5	5	4	4	5	25
15	Garscom	K9	2	2	3	2	4	5	3	5	3	2	4	19
16	MBW	JK	2	1	1	2	5	5	3	3	2	5	3	22
17	Ifafi	AO	3	1	3	2	3	2	6	6	1	3	3	18
18	Tuine	IS	2	2	4	4	6	6	4	4	6	3	5	24
19	MBW	RO	3	2	1	2	5	4	4	3	2	2	3	18
20	Cosmos	CM	2	1	1	1	4	4	4	4	1	1	4	19

E.4 Patroller Questionnaires After

No	CPF	Name	Experience	SART										
				Change	Complex	Variables	Alert	Concentrate	Attention	Spare mental	Info quantity	Info Quality	Familiar	Situation Awareness
1	Garscom	F8	4	3	4	2	7	5	3	2	7	7	6	28
2	Garscom	C4	8	2	3	1	4	5	2	5	2	4	5	21
3	Garscom	C6	4	3	3	4	4	5	6	5	5	5	3	23
4	Garscom	E4	3	4	3	2	5	5	4	5	4	4	5	23
5	Garscom	E6	2	3	1	1	5	5	2	5	3	6	5	26
6	Garscom	E1	10	1	1	1	7	7	5	5	5	6	7	39
7	Garscom	E2	4	1	3	1	6	6	1	6	6	7	5	32
8	Garscom	F6	2	2	3	2	6	6	5	6	4	3	4	27
9	Garscom	F14	2	2	2	2	5	4	3	5	4	4	5	24
10	Garscom	F3	1	1	1	1	5	6	4	6	4	4	4	30
11	Garscom	F2	6	3	4	4	4	5	4	4	3	4	5	18
12	Garscom	T12	2	3	2	4	5	5	3	3	4	6	6	23
13	Garscom	K7	1	2	3	2	2	3	3	4	5	4	3	17
14	Garscom	K6	4	2	2	3	4	5	3	5	3	3	5	21
15	Garscom	K9	2	2	3	2	4	5	3	5	6	6	5	27
16	MBW	JK	2	1	1	2	5	5	5	5	5	5	3	29
17	Ifafi	AO	3	1	3	2	5	5	2	6	6	6	6	30
18	Tuine	IS	2	2	4	4	6	6	5	5	7	6	5	30
19	MBW	RO	3	2	1	2	4	5	4	5	5	4	5	27
20	Cosmos	CM	2	1	1	1	4	4	4	4	4	4	4	25

No	CPF	Name	Experience	Use						
				Ease of report	What to report	More info	Utilise	Coordinate	Safety	Effectiveness
1	Garscom	F8	4	5	4	5	5	5	4	5
2	Garscom	C4	8	3	4	3	3	3	4	4
3	Garscom	C6	4	4	4	5	4	3	3	4
4	Garscom	E4	3	4	4	5	4	5	4	4
5	Garscom	E6	2	4	4	4	3	4	4	4
6	Garscom	E1	10	4	4	4	3	3	4	4
7	Garscom	E2	4	4	5	4	5	5	4	4
8	Garscom	F6	2	4	3	3	4	4	3	3
9	Garscom	F14	2	4	4	4	4	4	4	4
10	Garscom	F3	1	3	4	4	5	5	4	5
11	Garscom	F2	6	5	4	4	5	5	5	5
12	Garscom	T12	2	3	4	4	4	5	4	3
13	Garscom	K7	1	4	4	4	4	4	2	5
14	Garscom	K6	4	3	2	4	4	4	3	4
15	Garscom	K9	2	5	4	4	3	4	5	4
16	MBW	JK	2	5	4	4	4	5	2	3
17	Ifafi	AO	3	4	4	4	3	4	4	4
18	Tuine	IS	2	5	4	5	5	5	5	5
19	MBW	RO	3	4	5	4	4	5	5	4
20	Cosmos	CM	2	3	5	5	5	4	3	3

Appendix F ETHICS



UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Reference number: EBIT/81/2013 13 December 2013

Mr R Oosthuizen
PO Box 38558
Garsfontein
0060

Dear Mr Oosthuizen,

FACULTY COMMITTEE FOR RESEARCH ETHICS AND INTEGRITY

Your recent application to the EBIT Ethics Committee refers.

1 I hereby wish to inform you that the research project titled "Establishing a methodology to develop complex sociotechnical systems" has been approved by the Committee.

This approval does not imply that the researcher, student or lecturer is relieved of any accountability in terms of the Codes of Research Ethics of the University of Pretoria, if action is taken beyond the approved proposal.

2 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 any member of the Faculty Committee who will deal with the matter.

3 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