SUSTAINABILITY OF QUALITY IMPROVEMENT PROGRAMMES IN A HEAVY ENGINEERING MANUFACTURING ENVIRONMENT: A SYSTEM DYNAMICS APPROACH

by

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Submitted in partial fulfilment of the requirements for the degree

PHILOSOPHIAE DOCTOR

in the

FACULTY OF ENGINEERING, BUILT ENVIRONMENT AND INFORMATION TECHNOLOGY

UNIVERSITY OF PRETORIA

PRETORIA

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July 2013

“I am able to do all things through the one who strengthens me”

Philippians 4:13 (NIV)

ABSTRACT

SUSTAINABILITY OF QUALITY IMPROVEMENT PROGRAMMES IN A HEAVY ENGINEERING MANUFACTURING ENVIRONMENT - A SYSTEM DYNAMICS APPROACH

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Companies realise that to stay competitive they have to introduce quality improvement programmes. Many companies are challenged today with the sustainability of these quality improvement programmes. Generally the dynamic behaviour of quality improvement programmes is poorly understood with soft issues as factors of the system. System dynamics may solve this problem.

This research is focused on the operational management of operations. The organising framework of this research has been on qualitative research where the research design was a polar type research design and case studies focused on initiatives that were dramatic successes or failures, with the expectation that their comparison would help identify those processes that prevent competence enhancing change.

A dynamic hypothesis has been constructed from archival data, semi-structured interviews and direct observations, gathered during these case studies. A system dynamics model for quality improvement programmes in an automotive environment has been tested and expanded to be applicable for a heavy engineering manufacturing environment. The structure

of the system dynamics model has been expanded to include a sustainability feedback loop which also included a management support model. This model included soft factors such as management support, management pressure and managerial effectiveness.

The complete quality improvement program system dynamics simulation model with sustainability has been tested and validated against real system data, for a heavy engineering manufacturing environment, gathered during the case studies. The model parameters were determined from a calibration algorithm, by using the Vensim® simulation platform, that fitted the real system behaviour the best. A sensitivity analysis has been done on the model parameters determining the information cues for the management decision policies.

From the system dynamics model of the complete quality improvement programme, including the sustainability feedback loop, proposed management decision policies have been studied that could lead to sustainable quality improvement programmes for a heavy engineering manufacturing environment. From these simulation studies several management policies have been proposed.

OPSOMMING

SUSTAINABILITY OF QUALITY IMPROVEMENT PROGRAMMES IN A HEAVY ENGINEERING MANUFACTURING ENVIRONMENT - A SYSTEM DYNAMICS APPROACH

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Maatskappye verstaan dat kwaliteitsprogramme suksesvol geïmplimenteer moet word om as kompeterend beskou te word. Verskeie maatskappye vind dit egter moeilik om kwaliteitsprogramme volhoubaar te implimenteer. Omdat daar leemtes bestaan om die dinamika volledig te verstaan, veral ten opsigte van die nie-tasbare faktore wat moeilik is om te meet, kan "System Dynamics" moontlik gebruik word om hierdie probleem te oorbrug.

Die navorsing soos hierin vervat, is gemik op operasionele bestuur van vervaardigingsoperasies. Hierdie navorsing is gebasseer op kwalitatiewe navorsing. Die navorsingsontwerp het te doen met 'n polêre navorsingsontwerp waar die gevallestudies gefokus het op dramatiese suksesse en falings. Die vergelyking van die data en die prosesse wat bydra tot die sukses van die gevalle, het 'n bydrae gelewer tot die nuwe teorie.

'n Dinamiese hipotese is ontwerp vanuit data wat bepaal is vanaf argiefdata, semi-gestruktureerde onderhoude en direkte observasies. Alle data is versamel tydens die gevallestudies. 'n Stelseldinamiese model vir kwaliteitsprogramme in 'n motorvervaardigingsomgewing, is getoets en geëvalueer om van toepassing te wees in 'n swaar ingenieursvervaardigingsomgewing. Die struktuur van die stelseldinamiese model is uitgebrei om die terugvoerlus van volhoubaarheid in te sluit. Hierdie lus sluit ook die stelseldinamiese model van bestuursondersteuning in, asook bestuursdruk en bestuurseffektiwiteit.

Die volledige stelseldinamiese model van die saamgestelde kwaliteitsprogram, ingesluit die terugvoerlus van volhoubaarheid, is getoets en geëvalueer teen data wat die werklike stelsel voorstel. Hierdie data is versamel gedurende die gevallestudies. Die modelparameters is bepaal met behulp van 'n kalibrasiealgoritme met behulp van Vensim® simulasieplatform, wat die werklike data die beste pas. 'n Sensitiwiteitsanalise is gedoen op die modelparameters om sodoende die inligtingsveranderlikes te bepaal vir die besluitnemingspunte in die stelseldinamiese model.

Vanuit die stelseldinamiese model van die volledige kwaliteitsprogram, ingesluit die terugvoerlus van volhoubaarheid, is voorgestelde bestuurspraktyke bestudeer aan die hand van dinamiese simulasies. Laasgenoemde mag lei tot volhoubaarheid van toepassing op 'n swaaringenieursvervaardigingsomgewing. Vanuit hierdie studie word verskeie betsuurspraktyke aanbeveel wat mag lei tot volhoubare kwalitietsprogramme.

ACKNOWLEDGEMENTS

To my Lord and Saviour for giving me the strength and wisdom in order to have completed this study successfully. To the honour and glory of your Name, without You, none of this would have been possible.

To my loving wife Brenda, for all your support you gave me during the late nights and weekends, especially all the encouragement and small extraordinary reminders that kept me motivated during those long hours.

To my lovely teenage daughter Janda, for all your enquiries and support and for sharing your thoughts with me, it has been truly special.

To Buddy, my loyal four-legged Labrador friend who lay patiently at my feet while I was burning the midnight oil.

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CHAPTER 1

INTRODUCTION, PURPOSE AND EXPECTED CONTRIBUTION OF THIS STUDY

1 Introduction

Organisations are challenged to provide the best return on investment for their shareholders. As Goldratt puts it “The goal of the company is to serve the clients only as a means to the real task, serving the company's shareholders” (Goldratt 1990). This challenge has become increasingly more difficult today through globalisation of the market place. Globalisation introduced competitive forces into the market place, where manufacturing in the western world became under threat from manufacturing from the East. The emphasis being on profit and growth.

In order for companies to stay competitive in this global market, they need to adapt to the changing market needs. The emphasis has shifted more and more towards delighting the customer through delivering a quality product and/or service at a lower price. Focus on quality leads directly to an increase in productivity and other benefits (Besterfield et al 2003). Companies quickly realised to stay competitive they have to introduce quality improvement programmes. Many quality improvement programmes such as quality circles, statistical process control (SPC), total quality management (TQM), six sigma to name a few, are developed in the manufacturing industry with the common goal, to improve the quality of the product or service (Besterfield et al 2003). Oakland (2003) sums it up as follows “Any organisation basically competes on its reputation for quality, reliability, price and delivery, and most people now recognise that quality is the most important of these competitive weapons” (Oakland 2003).

1.1 Background

Manufacturing operations may use quality improvement programmes such as six sigma to improve quality and reduce cost. The DMAIC (Define, Measure, Analyse, Improve and Control) methodology of six sigma is used to reduce variation in a process and shift the mean. When the process is broken or a new product, process or service is introduced, design for six sigma (DFSS) is typically used.

A design for a six sigma project follows the traditional road map with the traditional six sigma tools. One of the steps in the design and analyse phase in the process is to use simulation and design of experiments (DoE) to find the transfer function between the voice of the customer (VOC) and the voice of the process (VOP). The DoE defines the mathematical relationship between the process variables (X) and the process output (Y) and mathematically describes the relationship $Y = f(X)$. This equation could be used to run simulations on the newly designed process to study the variation and probable failure modes (Ginn 2004).

During the simulations the influence of the different factors is simulated, but the influence of the soft factors like stakeholder involvement, policies, training, management support and other related issues is not simulated. Typical causality is studied using one of the six sigma tools, the fish bone diagram, to study cause and effect. This tool does not allow the user to study and understand feedback from other factors in the improvement process system, typically referred to as feedback causality.

Generally the understanding is poor of the dynamic behaviour that relates to the quality improvement programme system with the soft issues as factors of the system. System dynamics may improve this understanding. From a system dynamics point of view, the effect of the soft factors with the interaction of the hard factors can be modelled and therefore studied in more detail. The structures of which quantitative metrics are available are sometimes referred to as hard factors where the term hard is intended to show that numerical data is more real than qualitative data (Sterman 2000:853). This provides a better view of the dynamic behaviour of the complete system in relation to the improvements made by a quality improvement programme such as six sigma.

In a study done by Baines & Harrison (1999), it was found that manufacturing system modelling does represent a missed opportunity for system dynamics modelling, especially in the higher levels of decision making (Baines & Harrison 1999). From the literature it is evident that research on quality improvement programmes in the heavy engineering manufacturing environment is researched to a lesser degree than research on quality improvement programmes in the service, automotive and continuous manufacturing industry (Womack et al 1990), (Lewis 2000), (Abdulmalek et al 2007) and (Hines et al 2004). The heavy engineering manufacturing environment is a typical jobbing shop environment which is a more complex manufacturing environment (Meredith & Shafer 2011). A research gap is identified in the current research on quality improvement programmes in the heavy engineering manufacturing environment.

The purpose with this research is therefore to model the structure of the quality improvement programme system in a heavy engineering manufacturing environment, in order to develop a representative model of the dynamic behaviour with the effect of the hard as well as the soft factors modelled. From this model, the dynamic behaviour of the structure and the effect on the long-term sustainability of the improvements made by the quality improvement programme, can be studied. Revised management policies based on this model may be designed, to ensure long-term sustainability of quality improvement programmes in a heavy engineering manufacturing environment.

Organisations in the manufacturing industry typically suffer from this particular problem, that the benefits from implementing a quality improvement programme such as six sigma, cannot always be sustained after implementation. This research could make a contribution in operations management in developing policies which could lead to long-term sustainability of quality improvement programmes such as six sigma in a heavy engineering manufacturing environment.

1.2 Problem statement

Successful implementation and sustainability of quality improvement programmes, such as six sigma, are very important for the financial gain of any company. It is therefore valid to define the problem statement as follows;

> Why are gains from quality improvement programmes such as six sigma, after successful implementation, not always sustained over a long-term in a heavy engineering manufacturing environment?

1.3 Research objective

The first objective with this research is to study the applicability of system dynamics in the implementation of a quality improvement programme such as six sigma, in a heavy engineering manufacturing environment.

The second objective with this research is to design a system dynamics model of a typical quality improvement programme from a systems thinking perspective. The structure and behaviour of this model will be used to simulate the factors that might have an impact on the successful implementation of a quality improvement programme, such as six sigma, in a heavy engineering manufacturing environment.

The third objective with this research is to use system dynamics to evaluate the long-term sustainability of a quality improvement programme, such as six sigma that has been successfully implemented. The analysis phase of a DMAIC six sigma quality improvement programme uses design of experiments (DoE) to study the influence of the different factors on the variability of the process output (Brassard et al 2002). Simulation could also be used in the design phase of the design for six sigma (DFFS) quality improvement programme to test the variability of a newly designed process (Ginn 2004).

During this research, the objective is to design a system dynamics simulation model to simulate the behaviour of a successfully implemented quality improvement programme and to study the impact of the soft factors on the long-term sustainability of this programme. However, sustainable programmes from the above approaches have been researched to a lesser degree. System dynamics may create new insights into sustainable quality improvement programmes in a heavy engineering manufacturing environment.

The fourth objective with this research is to design new policies for quality improvement programmes in a heavy engineering manufacturing environment which could lead to long-term sustainable quality improvement programmes.

1.3.1 Research questions

The aim with this research is to answer the following research questions applicable to a heavy engineering manufacturing environment;

a) How can the dynamic behaviour of the manufacturing process be explained with system dynamics?

b) How does the implementation of the quality improvement programme influence the dynamic behaviour of the manufacturing process?

c) How do soft factors impact the dynamic behaviour of the quality improvement programme?

d) How can system dynamics be used to model sustainability, after the successful implementation of the quality improvement programme?

e) How can system dynamics be used to design new management policies for the sustainability of quality improvement programmes in a heavy engineering manufacturing environment?

1.4 Dynamic hypothesis

Through the application of system dynamics, the structure and behaviour of a quality improvement programme is modelled, as well as the impact of newly designed management policies, to ensure long-term sustainability of quality improvement programmes in a heavy engineering manufacturing environment.

Time series quality data determined from case studies for a manufacturing process in a heavy engineering manufacturing environment, is analysed over an appropriate period and inspected for dynamic behaviour, from which the reference mode is derived. The reference mode describes the dynamics of the quality system. From this reference mode a dynamic hypothesis may be constructed. According to Sterman (2000), the hypothesis is dynamic because it should provide an explanation of the dynamics characterising the quality improvement programme in terms of the underlying feedback and structure and behaviour of the system. It is a hypothesis because it is always provisional, subject to revision or abandonment as learned from the modelling process and from the real world (Sterman 2000:95).

The dynamic hypothesis is constructed from sub system diagrams, stock and flow diagrams and boundary charts in order to create an endogenous explanation of the phenomena under study, described by the reference mode (Sterman 2000:97). The endogenous explanation endeavour to explain the interaction of the variables represented by the model. From the stock and flow diagram, a simulation model is built with the parameters determined from the case studies. The simulation model is tested and parameters adjusted until the simulation results reproduce the manufacturing process behaviour adequately. Sterman (2000) clearly states the purpose with the model testing is to uncover errors, to understand the models' limitations and to improve it and is therefore inevitably a process of communication and persuasion among modellers and other parties.

Sterman (2000) continues further to argue that instead of seeking a single test of validity, models either pass or fail, good modellers seek multiple points of contact between the model and reality by drawing on a wide range of data and a wide range of tests.

Tests for accepting the dynamic hypothesis are as follows (Sterman 2000:859);

- ✔ **Boundary adequacy**. The main purpose with this test is to determine if the behaviour of the model changes significantly if the boundary assumptions are relaxed and to test if the important concepts are endogenous to the model.

- ✔ **Structure assessment**. The purpose is to check if the structure is consistent with the descriptive knowledge of the system and if the model conforms to basic physical laws such as conservation laws.

- ✓ **Dimensional consistency**. Each equation must be dimensionally consistent without using parameters without real world meaning.

- ✓ **Parameter assessment**. Relevancy of the model parameters with the descriptive and numerical knowledge of the system.

- ✓ **Extreme conditions**. The model behaviour is plausible even when input parameters take on extreme values or the model is subjected to extreme policies and shocks.

- ✓ **Integration error**. Sensitivity of the results towards the choice of time step or numerical integration method.

- ✓ **Behaviour reproduction**. The model behaviour matches the behaviour of the system under study, qualitatively and quantitatively, matches the modes of behaviour, or frequency and phase relationships, observed in the real system.

- ✓ **Behaviour anomaly**. No anomalous behaviours of the model are observed when assumptions of the model are changed or deleted.

- ✓ **Family member**. Can the model generate the behaviour observed in other instances of the system?

- ✓ **Surprise behaviour**. Can the model generate previously unobserved behaviour or successfully anticipate the response of the system to novel conditions?

- ✔ **Sensitivity analysis**. The model is stable towards numerical, behavioural or policy sensitivity, when assumptions about the parameters or boundary are varied over the range of uncertainty.

- ✔ **System improvement**. The modelling process helped to change the system for the better.

Once the system dynamics simulation model, adequately models the observed behaviour of the manufacturing process and quality improvement programme, and passes the model tests, the dynamic hypothesis is accepted.

1.5 Expected contributions

Six sigma improvement projects focus on reducing variability and shifting the mean to meet the customer expectation. However, these improvement programmes traditionally rely on causality from direct interactive factors and do not take into consideration the effect of any factors outside the immediate process under study. The outside factors could create a feedback causality that has a dynamic effect on the output of the process under study.

A contribution from this research is to develop a system dynamics model, from a systems thinking perspective for the implementation of a quality improvement programme in a heavy engineering manufacturing environment. The purpose with this model is to study the dynamic impact of soft factors that could impact on the successful implementation of a quality improvement programme such as, six sigma, in a heavy engineering manufacturing environment.

Another contribution by this research is to develop a theory for sustainability of quality improvement programmes in a heavy engineering manufacturing environment. The theory is supported by system dynamics and systems thinking. Constructing a system dynamics simulation model from the above theory and simulating the dynamic behaviour of a quality improvement programme applicable to the heavy engineering manufacturing environment, is another contribution. Another contribution is where new proposed management decision policies are designed and tested from the system dynamics simulation model, for a sustainable quality improvement programme in a heavy engineering manufacturing environment.

Six sigma is one of the methodologies used worldwide to reduce cost and improve customer satisfaction. This statistical thinking process is not always successful after the improved / newly designed process is handed over to the process owner. The gains from the improved / newly designed process are not always sustained. If the dynamics of this phenomenon is better understood by operations management, then improved management policies could be put into place during the six sigma improvement project, to ensure long-term sustainability.

This research should shed additional light on this dynamic behaviour from which new management policies for six sigma implementation methodologies could be designed, to ensure long-term sustainability. The effect of factors outside the process under study on the variability of the output of the process could also be better understood, for which management policies could be designed. This could have an input into the operations management of the heavy engineering manufacturing industry and enable operations managers to implement more effective quality improvement programmes such as six sigma. Operations managers could be better equipped to have the required insight to implement new management policies in order to ensure long-term sustainability of quality improvement programmes in a heavy engineering manufacturing environment.

1.6 Thesis research road map

This thesis is constructed in nine chapters. Here follows a brief description or road map on how this research was conducted and how this thesis is organised. Refer to Table 1.1 for a description of the research road map, in a tabulated format. The column designated by “sub level”, describes the research activities that pertained to that specific chapter. Fundamentally, the thesis is organised to describe the different building blocks to ultimately arrive at sustainability of quality improvement programmes in a heavy engineering environment, from a system dynamics approach.

CHAPTER	SUB LEVEL
Chapter 1	• The research questions, objective and contribution of the study have been discussed.
Chapter 2	• Literature study on quality improvement programmes and system dynamics have been discussed with references. • A brief discussion on systems thinking, system dynamics and simulation follow.
Chapter 3	• System dynamics and quality improvement programmes from a systems thinking perspective, are explained. • Next are the dynamic aspects of a conceptual quality improvement programme, from a system dynamics simulation model perspective.
Chapter 4	• In this chapter a discussion follows on the two research design strategies, theory testing and theory building, as well as the methodology used in this thesis. • As explained the polar type research design is selected as the preferred research design. • The components of the research design are discussed.
Chapter 5	• In this chapter the two polar type case studies have been described, applicable to a heavy engineering manufacturing environment, where quality improvement programmes have been implemented. • Next is the discussion of the results from theory-testing of a theory, for a system dynamics model of a quality improvement programme from an automotive environment, for validity in a heavy engineering manufacturing environment.

CHAPTER	SUB LEVEL
Chapter 6	• In this chapter the reference mode and dynamic hypothesis, as determined from the case studies, are discussed. • Next is the description of a theory for sustainability from a systems thinking perspective. • The expansion of the theory for sustainability is discussed next, to include soft factors such as management support and management pressure. • The development of a system dynamics simulation model, simulating the dynamic behaviour of the quality improvement programme, is also discussed. • The results obtained from the dynamic simulation of the quality improvement programme model, is finally explained and compared to the dynamic hypothesis.
Chapter 7	• Firstly, there is a description of model testing and validation, based on the model developed in Chapter 6, to gain confidence in the model. • Next are the results from the model calibration of the model parameters that fitted the real time behaviour best. • Next the results from the modelling of management decision policies are discussed. • Finally, there is an analysis and discussion of the newly proposed management decision policies, for sustainable quality improvement programmes in a heavy engineering manufacturing environment.
Chapter 8	• In this chapter the results and future research are discussed. • Next follows a discussion on how the research questions are answered from the research described in this thesis. • The contributions from this study are also discussed.
Chapter 9	• References
Appendix A	• Tables of the coding matrices used during the case studies are displayed
Appendix B	• A collection of the Vensim® equations used during the simulation studies during this thesis.

Table 1.1 Thesis research roadmap

1.7 Summary

The problem statement has been fully described in a setting of a heavy engineering manufacturing environment. Four objectives of this study have been described where the emphasis is on the dynamics of quality improvement programmes in a heavy engineering manufacturing environment and their sustainability.

The dynamic hypothesis has been explained as well as five research questions, aimed to satisfy the problem statement. The expected contributions from this study could add to the body of knowledge on sustainability of quality improvement programmes in a heavy engineering manufacturing environment.

In the next chapter, literature research is done on different quality improvement programmes, system dynamics as well as the applicability of system dynamics in the implementation of quality improvement programmes. Literature research is also done on what sustainability of quality improvement programmes could mean in operations management from a system dynamics and systems thinking perspective.

CHAPTER 2

LITERATURE OVERVIEW OF QUALITY IMPROVEMENT PROGRAMMES, SUSTAINABILITY AND SYSTEM DYNAMICS

2 Introduction

Quality improvement programmes such as continuous improvement, are defined as follows: “a company-wide process of focussed and continuous incremental innovation” (Bessant et al 1994) Continuous improvement can also be defined as a “culture of sustained improvement targeting the elimination of waste in all systems and processes of the organisation.” (Bhuiyan et al 2005). Bhuiyan et al (2005) continues to say that “improvement is achieved through the use of a number of tools and techniques dedicated to searching for sources of problems, waste, and variation, and finding ways to minimize them”. Continuous improvement has its roots in manufacturing where the following methodologies have been developed based on a concept of quality or process improvement, lean manufacturing, six sigma, the balanced score card and lean six sigma (Bhuiyan et al 2005).

System thinking is the ability to see the world as a complex system, where everything is connected to everything else (Sterman 2000:4). Sterman continues to argue that it is challenging to move from system thinking to tools and processes that could help us understand complexity in order to design better decision policies. He postulated that system dynamics is a method that could help us to understand complex systems better and describes system dynamics as follows; “System dynamics is grounded in theory of non-linear dynamics and feedback control developed in mathematics, physics and engineering.”

During this chapter, the literature has been researched for an overview of quality improvement programmes, systems thinking, system dynamics as well as the applicability of system dynamics in the implementation and sustainability of quality improvement programmes.

2.1 Overview of quality improvement programmes

2.1.1 Lean manufacturing

Lean manufacturing, also known as Toyota Production Systems (TPS) focuses on the flow of products by using just-in-time (JIT) production. The essential focus of lean manufacturing is to remove all forms of waste with the net effect of quality and productivity increase by the following three principles, improve the flow of material and information, focus on the pull from the customer and commitment of the organisation towards continuous improvement (Womack et al 1990).

The lean concept is a systematic approach identifying and eliminating elements not adding value to the process with consequences of striving for perfection and a customer driven pull of the process (Anderson et al 2006). Anderson et al (2006) explain the five basic principles of lean manufacturing as follows: (1) Understanding customer value, - what the customer is willing to pay for, (2) Value stream analysis, - analyse the business processes to determine which ones actually add value and if not it should be removed (3) Flow, - focus on continuous flow through the production process rather than large batches, (4) Pull, - customer demand pulls finished products through the system. (5) Perfection, - the elimination of non-value-adding elements (waste) is a process of continuous improvement.

The impact of lean production and the sustainable competitive advantage in the automotive industry are studied, by deriving a new model based on four research propositions in order to study the impact of lean production (Lewis 2000). From this study Lewis (2000) found that, (1) lean does not automatically result in improved financial performance, (2) each firm follows its own lean production trajectory, (3) innovation activity is somewhat narrowed by becoming more lean and (4) becoming lean causes new dynamics and therefore challenges regarding their key staff. He summarised "...that contingency and complexity are the dominant characteristics of any successful implementation process". He further found in his study that a culture shift towards becoming lean in one specific company took four years.

The advantage of adopting lean manufacturing in the continuous process sector, an integrated steel mill, is successfully demonstrated by means of a simulation of the future state value stream map (VSM) (Abdulmalek et al 2007). The outcome of this simulation, and through design of experiments (DoE), proved that total productive maintenance (TPM) and a hybrid push-pull production system have a significant impact on reducing the process lead times with almost 70% and reducing the work in progress (WIP) with almost 90%. The simulation-modelling route is the preferred method in this instance to predict the gains that may be achieved by implementing a lean production system, compared to a costly and time consuming method with only "belief" from management that the process would gain from this initiative.

The primary focus of lean thinking is value creation for the customer; however value creation is seen as equal to cost reduction where in fact a) reduction of internal wasteful activities does reduce cost and increase the overall value proposition for the customer and b) value is also created if additional features or services are offered such as shorter delivery time (Hines et al 2004).

Hines et al (2004) further identified four stages of lean thinking representing the time frame 1980 to 2000+ as follows: (1) cells and assembly lines, (2) shop floor, (3) value stream and (4) value systems. Stage 4 is typical in a learning organisation where contingent factors are considered such as their size, industrial sector, industrial dynamics and technology employed, where a range of tools are typically used such as six sigma, system dynamics and theory of constraints (TOC).

2.1.2 Lean six sigma

One of the criticisms of lean manufacturing is that lean cannot bring a process under statistical control - lean seeks to remove waste while six sigma seeks to reduce variation (Bhuiyan et al 2005). To overcome this weakness a new hybrid methodology is born which is called lean six sigma. Lean six sigma maximises shareholders value by achieving the fastest rate of improvement in customer satisfaction, cost, quality, process speed and invested capital (George 2002). Lean six sigma combines the methodologies of lean and six sigma to increase quality and speed. George (2002) further explains the principle of lean six sigma as follows: "The activities that cause the customers critical-to-quality issues and create the longest time delays in any process, offer the greatest opportunity for improvement in cost, quality, capital and lead time" The main contribution of lean six sigma which neither six sigma nor lean could make is by identifying which process step lean six sigma first should be applied to, in what order and degree and identifying the quickest route to cost, quality and lead time improvement (George 2002).

2.1.3 Six sigma

Six sigma is a business management strategy originally developed by Motorola USA in 1981(Tennant 2001). Six sigma improvement programmes are employed through worldwide corporations citing savings of billions of US dollars resulting from six sigma implementation, and are described as a methodology within the larger frame work of total quality management (TQM) (Klefsjö, Wiklund et al 2001). It is a business strategy which leads to breakthrough in profitability through gains in product/service quality, customer satisfaction and productivity with the main objective to reduce the number of defects (Jiju, Banuelas 2002). Six sigma has mainly been adopted in large business enterprises like GE, Honeywell, (Harry & Schroeder 2000) and FORD to name a few but studies have shown that six sigma has to be modified to be adopted by small and medium-sized enterprises (SME's) (Wessel & Burcher 2004).

Six sigma follows two project methodologies which comprise five phases each, with the following acronyms DMAIC, (Define Measure, Analyse, Improve and Control) and DMADV, (Define, Measure, Analyse, Design and Verify) (De Feo & Barnard 2005). The main difference between these two project improvement methodologies is that DMAIC is mainly applied to reduce variation in a business process where DMADV is used to design a new process, product or service through design for six sigma (DFSS) (Shahin 2008).

The six sigma methodology uses quality management tools throughout the execution of the project. It is an extensive list of statistical tools as well as qualitative tools that is used to reduce variation in a process or design a new process, product or service (Yang & El-Haik 2003). Examples of these tools are SIPOC (Suppliers, Inputs, Process, Outputs, Customers), FMEA (Failure Mode Effect Analysis), ANOVA Gauge R&R, Process Mapping, Pareto Chart, QFD (Quality Functional Deployment), Process Capability, Design of Experiments (DoE) and Simulation, to name a few. The difference in the six sigma methodology to previous quality improvement initiatives, is that six sigma identifies several key roles for its successful implementation. It involves the executive leadership from the CEO to other members of top management, champions who take responsibility for six sigma implementation and employees trained in the tools of six sigma, commonly known as Master - , Black -, and Green Belts (Breyfogle 2003).

A six sigma project is typically identified from key factors in the business process which is critical to the quality (CTQ) of the business process (Brassard et al 2002). After the Define, Measure and Analyse phase, the project typically evolves into either a variance reduction or design for six sigma project with the ultimate goal to improve the process to a six sigma process. Brassard et al (2002) further explain that after successful implementation of the quality improvement project, the new or improved process is handed over to the process owner with the necessary control charts, process management chart and six sigma story board.

2.1.4 Design for six sigma (DFSS)

Most companies operate between 3 sigma to 3.5 sigma (Conlin 1998). Organisations that have adopted the six sigma methodology, realised to take the improvements beyond 5 sigma, the process product or service needs to be re-designed where design for six sigma is typically followed as the preferred methodology (Chowdhury 2001).

However, research shows that the 5 sigma wall is not necessarily the only criterion to select between six sigma and design for six sigma (DFSS), but the decision as to when to embark on a re-design activity can occur at different stages of the project such as project selection and concept selection (Banuelas et al 2004). Research also indicates that the degree of executive involvement is significant for the level of DFSS activities to be implemented (Chung et al 2008). DFSS is also used with success in the new product development environment where models and simulation such as (1) mathematical relationships based on established physical principles, (2) regression equations derived from historical data, (3) design of experiments (DoE) response equations from measured observations and (4) general knowledge of business systems or products are used, as effective DFSS tools (Luce et al 2005).

Goh and Xie (2004) argue, in order for an organisation to go beyond incremental improvements to long-term excellence in a changing and complex world, the organisation needs to adopt two additional S's such as systems perspective and strategic analysis. Systems perspective from a point of view of macro level assessments and reviews and strategic analysis from a point of view such as managing dynamic market demands (Goh and Xie 2004). In this way, DFSS is closely related to systems engineering (El-Haik & Roy 2005).

2.1.5 Total quality management (TQM)

Total quality management (TQM) can also be viewed as an offshoot of continuous improvement (Caffyn 1999). Ambrož (2004) defines total quality management as the core strategy for continuous improvement of product and service quality to achieve customer satisfaction. Besterfield et al (2003) define TQM as both a philosophy and a set of guiding principles that represent the foundation of a continuous improving organisation with the following basic concepts; (1) A committed and involved management to provide long-term top-to-bottom organisational support. A quality council must be established that sets long-term quality goals as well as quality improvement programmes which are in line with the business plan. Managers participate in these programmes to ensure TQM is entrenched in the culture of the business. (2) An unwavering focus on the customer, both internally and externally. The voice of the customer is a key factor in emphasising design quality and defect prevention. (3) Effective involvement and utilisation of the entire work force. The goal is to change the behaviour of employees, down to the lowest level, to continually improve their jobs. (4) Continuous improvement of the business and production process. (5) Treating suppliers as partners with the focus on quality and life-cycle cost rather than price, and (6) To establish performance measures for the process where the quantitative data that measures the continuous quality improvement activity is posted for everyone to see (Besterfield et al 2003).

Klefsjö, Wiklund et al (2001) postulate that total quality management starts from six values namely focus on customer, focus on processes, base decisions on facts, everybody should be committed, to improve continuously and receive top management commitment. For a successful TQM programme these values should be supported systematically and continuously by suitable methodologies and tools. Six sigma and policy deployment are some of these methodologies with factorial design matrices as one of the tools.

In a study on the effect of TQM factors on financial and strategic performance of a company, done on 257 manufacturing firms, the research indicated that firms who implemented TQM, had a significant increase in net income as a per cent of sales while the most important finding was that the operating expense as a per cent of sales had decreased with the implementation of TQM, (this is an indication of a more efficient operation). The last finding is that the implementation years correlate significantly with the increase in sales (Barker et al 2006). Barker et al (2006) also successfully demonstrated that continuous improvement tools are one of the predictors of change in net income and also demonstrated that top management support and product improvement are the predictors of customer satisfaction. This study further illustrated that successful TQM implementation is robust across organisational size and industrial speciality.

Successful implementation of TQM generally depends on the corporate culture as an important factor (Ambrož 2004). Ambrož (2004) further illustrated in this study done on three manufacturing companies in Slovenia, that there is no “ideal type” TQM company culture; however companies that understand the “total” in TQM philosophy, have better results in the global market. Vouzas & Psychogios (2007) identified the following nine key concepts, also referred to as soft issues: (1) Total employee involvement, (2) continuous improvement, (3) continuous training, (4) teamwork, (5) empowerment, (6) top-management commitment and support, (7) democratic management style, (8) customer satisfaction and (9) culture change. The purpose with their research is to study the manager's awareness of the nine soft concepts of TQM. The research, done in the service industry in Greece by interviewing 382 managers, proved that the following three items are statistically significant, (1) continuous improvement and training, (2) total employee empowerment and involvement and (3) quality driven culture. (Vouzas & Psychogios 2007).

2.2 Overview of systems thinking and system dynamics

The previous section provides, an overview of different quality improvement programmes. An overview of systems thinking and system dynamics follows and the applicability of system dynamics in the implementation of quality improvement programmes.

2.2.1 Systems thinking

The newly designed process, product or service may be considered from a systems thinking approach. The interaction of the components in the sub systems determines the outcome of the system as a whole (Stamatis 2003). It is dynamic and complex as a whole. Stematis (2003) further postulates that the system may be described by system dynamics which is an approach to model and study the behaviour of the system over time. It is a methodology and computer simulation technique used to model complex processes and problems. System dynamics originally started in corporate management applications and was later expanded into understanding the behaviour of Urban development and even later to understand the behaviour of the World / Global crisis (Forrester 1989).

Forrester (1994) explains that all decisions are made on models that are mental models that contain assumptions and observations gained from experience. Mental models contain information about structures (connections between elements) and policies and, rules that govern decision making, however mental models do have shortcomings in their inability to draw correct dynamic conclusions from structural and policy information (Forrester 1994). Mental models are defined as follows: “a mental model of a dynamic system is a relative enduring and accessible, but limited, internal conceptual representation of an external system whose structure maintains the perceived structure of that system” (Doyle & Ford 1998). System dynamics may also use computer simulation that overcomes these shortcomings in determining consequences of structural and policy assumptions.

Through systems thinking the six sigma project team may move away from the cause-and-effect thinking (fish bone diagram), and consider the causal interconnections in real systems. These causal interconnections are referred to as causal loop diagrams (Kaufmann & Chieh 2005). Cause and effect statistical techniques such as correlation and design of experiments (DoE) are typically used to identify which process variables (X's) cause variation in the process output (Y). To be valid, most of these statistical techniques require one way cause-effect relationships; however cause-effect is not always one way but could be circular. In these cases, it is the interactions among the circular feedback relationships among the X's, and between some or all of the X's and the Y, that cause variation in Y and therefore referred to as feedback causality. It is in these cases that system dynamics can serve a useful role in six sigma practise (Newton 2003).

2.2.2 System dynamics

Sterman (2000) explains that the modelling process is summarised in five steps (1) problem articulation, (2) formulation of dynamic hypothesis, (3) formulation of simulation model, (4) testing and (5) policy design and evaluation. Duggan (2008) explains that these five steps of the modelling process, map well with the first three stages (defining the problem, diagnosing the problem and remedying the problem) of the six sigma problem solving methodology. Statistical thinking is largely based on the analysis of statistically valid data, and therefore less attention is given to underlying structures that generate these data and long-term dynamic behaviour of the system may not be captured (Duggan 2008). Unfortunately, six sigma seems to lack from investigating the dynamic behaviour of a system's transfer function $Y=f(X)$ (Yuniarto & Elhag 2008).

Supply chain management is another example where quality improvement programmes such as TQM are used to improve the overall performance. Akkermans & Dellaert (2005) propose three approaches to supply chain management namely (1) data-driven approach such as MRP and ERP, (2) process improvement approach such as TQM and just-in-time (JIT) and (3) process control approach such as theory of constraints (TOC). The authors postulate that these three approaches can benefit from system dynamics (SD) due to the fact that system dynamics can model perceived delays, model customer demand as endogenous and from a process control point of view, and model the process as a complex system (Akkermans & Dellaert 2005).

The theory of constraints (TOC) thinking process presents a well-structured systemic approach to understand an organisational structure and its underlying cause-and-effect relationships but system dynamics modelling provides supplemental understanding relative to the knowledge gained through the TOC thinking process, which occurs through the following three dimensions: (1) taking into consideration the effects of the dynamic behaviour within the complex system, (2) providing the opportunity for managers to test various policy alternatives before actual implementation and (3) validating the conclusions drawn from the TOC thinking process (Reid & Koljonen 1999).

Organisational learning is an important aspect of companies subjected to competitive forces in a global market. To be significant, organisational learning must occur at operational level (changing behaviours or methods of doing things to improve the performance of a process) as well as conceptual level (changing one's mental models and the way one thinks about problems and re-framing it in a different context and exploring the implications) (Kim 1990). Kim (1990) postulates that total quality management in an organisation focuses on the operational level of the organisation through analyses of separate parts in the process, using different statistical tools, while systems thinking, utilising system dynamics, focuses to make the mental models of the managers explicit. The author proposes an “Organisational Intervention Model” where these two processes are integrated to enhance operational learning as well as conceptual learning and therefore enhance organisational learning, which is the root from which all competitive advantage stems.

A research study was launched to explore why initially successful improvement programmes often fail with the aim to design a sustainable improvement programme (Jones et al 1996). The research was done on four different types of manufacturing industries ranging from the automotive industry to electronic manufacturing industry in the United States of America. All these companies have successfully rolled out quality improvement programmes and new product development programmes over many years.

The methodology used entails model-based case studies, generalising the idea to a wider setting through an expository model of theory and testing the economic and behaviour foundations of the theories through tools such as statistical analysis. Preliminary results from this study show that even highly successful quality programmes can under certain conditions lead to short-run deterioration in financial results and subsequent loss of commitment to the quality programme. The cause appears to be unanticipated consequences of successful improvement arising from feedback between quality programmes and other functions in the company (Sterman et al 1996).

The authors of this study formed hypotheses such as the following from preliminary results of this research: (1) Improvement rates vary with the complexity of the process. The greater the technical complexity and the more organisational boundaries that must be crossed in the execution of a quality improvement programme, the slower the potential rate of improvement will be. Technical complexity refers to the engineering involved in a process and organisational complexity refers to the number of personnel and organisations involved in the quality improvement programme. (2) Unbalanced improvement can create excess capacity. (3) Feedback to employee morale and commitment to quality programmes is affected. Successful quality improvement programmes increase capacity which creates a fear among employees that they “improve” themselves out of a job. (4) Interactions with accounting metrics are affected. The unit direct cost reduces faster than the indirect cost at the successful implementation of a quality improvement programme. This puts the gross margins under pressure which could lead to management intervening to reduce overheads which could lead to the introduction of lay-offs, for example.

Jones et al (1996) found in their research in one particular company that management is faced by challenges when they launch multiple quality improvement programmes. In further research (Oliva & Rockart 1997) it has been found that the following three basic resources appear to be needed to sustain an improvement programme, (1) employee time, (2) managerial time and (3) skill with programme tools. Skills are increased through experience with the programme's tools, creating a reinforcing process that helps sustain an improvement programme. The authors further found that (a) once the programme champion was removed the employees involved in the programme were unable to see that the improvement efforts will be sustained and (b) competition for resources between simultaneous running improvement programmes can have a negative effect on the overall improvement rate.

Developing products faster has become critical to success in many industries where cycle time reduction is considered as one of the critical success factors (Ford & Sterman 2003). Ford and Sterman (2003) developed a system dynamics model to simulate the interactions in concurrent development and found in their research that schedule pressure degrade schedule performance and overall project quality, mainly due to the increase in organisational and process complexity. However, some companies do perform better than others. In a study by Rahmandad and Sterman (2008), the delay in receiving information feedback caused the managers to systematically overload their organisations and therefore caused capability to erode. They named this phenomenon the adaptation trap (Rahmandad & Repenning 2008). Learning is slowed significantly when decision makers access the length of the delay erroneously (Rahmandad et al 2009).

Many investments opportunities are widely recognised for the positive returns they provide but are still not achieved by many organisations that try. In a study done by Lyneis and

Sterman (2013) they found the presence of tipping dynamics which determines investment outcomes. Even where managers make large initial investments, (if investments are not large enough or long enough to cross tipping threshold), performance begin to gradually erode, wiping out gains. They further found that managers may easily under-invest, even when investments are supported and resources are available. Process improvements then depends not only on managers recognising and acting on opportunities, but also on managers understanding tipping dynamics and sustaining investments beyond levels that might initially appear sufficient (Lyneis & Sterman 2013).

Kim and Nakhai (2008) developed a generic mathematical model to examine the dynamics of quality cost and quality level over time. When the quality improvement program is highly effective the higher-quality lower-cost phenomenon was observed but in less effective quality improvement programs, the higher-quality higher-cost phenomenon was observed. The study showed that most of the firm's savings in failure cost occurred in the early years of the quality improvement program, but to sustain the savings the company must continue with its quality improvement efforts (Kim & Nakhai 2008). Ahmad and Schroeder (2002) suggested in their research for a company to remain competitive, managers should pay close attention to prospective employee's behaviour traits and their fit with the TQM philosophy and not limit their attention to potential employee's technical skills (Ahmad & Schroeder 2002).

A system dynamics model was developed by Repenning and Sterman (2000) that integrated the basic physical structure of process improvement with established theories on human cognition, learning and organisational behaviour to explain the dynamics of process improvement efforts. This study demonstrated that these interactions could lead to self-confirming attributions that could slow down improvement efforts where managers specifically attributed slow improvement to the attitude and disposition of employees (Repenning & Sterman 2000). The study indicated that the slow performance was mainly due to schedule pressure to achieve throughput goals which prevented the experimentation and adaption needed for improvement. The same phenomenon was observed in a study on development processes (Repenning 1999). Research suggests that people generally assume that cause and effect are closely related in time and space, underestimating the delays and fail to account for feedback processes (Repenning & Sterman 2001).

Repenning and Sterman (2002) found that whether a promising improvement programme is successfully implemented, largely remains unknown. They have therefore started with a polar research design in an automotive manufacturing company and electronics manufacturing company where the implementation of manufacturing cycle time was a success but the implementation of a product development process reduction was not a success. In both instances the same general manager was responsible for both programmes and hence created the opportunity to alleviate the variable of senior leadership and management style.

From this research the following two initial findings were made from which a theoretical model of process improvement was developed: (1) Employees from both improvement programmes, manufacturing and development, felt under constant pressure to achieve production objectives and often compelled to cut on time spent on improvement. They experienced a trade-off between doing their "real" work and the improvement work required by the initiative. (2) Managers did not acknowledge the trade-off and instead attributed the failure of the improvement programme as being due to the lack of discipline of the employees involved (Repenning & Sterman 2002).

The above findings are due to interactions among the physical production technology, organisational structures and routines and the mental models and behaviours of workers and managers. The authors developed a process improvement theoretical model from the basis of increasing net process throughput through "work harder" / rework or first-order improvement and “work smarter” or second-order improvement. This process improvement theoretical model, modelled the interaction between first-order and second-order improvements where the reasons for the interaction is due to (1) resources are finite and (2) improvement usually requires a reduction in throughput. This model successfully describes the capability trap where the net process throughput is increased in the short term through “work harder” / rework but in the long-term reduced the time dedicated to process improvement or “work smarter” which in the long run causes process capability to decline.

Morrison (2007) uses the theoretical model of process improvement as proposed by Repenning & Sterman (2002) in a dynamic model simulation to demonstrate the effect of the interaction between the first- and second-order interactions as proposed by Repenning & Sterman (2002). The outcome from the simulation of this dynamic model clearly demonstrates that long after what the manager would observe as process throughput reaching its goal, the workers experience the ongoing deterioration of process capability and are forced to work more and more on first-order production activity (Morrison 2007). The author successfully further demonstrated in this simulation model that the system has a tipping point.

Increasing the desired throughput moderately can result in a sustained improvement but if the desired throughput is increased beyond a critical threshold, the mode of behaviour changes to one that displays a better for worse pattern. The throughput improves at first but at the expense of deteriorating capability that sends the system to a steady state performance level worse than that where it began, even though the resource levels are the same. A manager focusing on throughput and not knowing where the tipping point is, and due to the delayed effects of deteriorating process capability, may only notice the underinvestment in building or maintaining organisational capability once it is too late.

In a recent study (Keating et al 1999), the following internal dynamics have been found true for the sustained improvement in a company: (1) Managers need to address the fundamental trade-off between current and future performance levels. There is fundamental pressure on resources for throughput as well as improvement programmes. To sustain a programme, managers must support the reinforcing nature of improvement by limiting the effect of throughput pressure on effort allocation. (2) Managers need to ensure that the source for commitment to continuous improvement shifts from managerial actions to employee initiative. Managerial push, such as training and financial incentives must translate into employee pull where the employees start to realise the benefit of the programme and start to commit themselves to the programme. Field work from this study suggests that developing employee pull is essential to sustain improvement efforts. Team commitment is critical to activating and sustaining a successful process improvement initiative (Keating & Oliva 1998) (3) as the programme succeeds, management needs to adapt its improvement tools and manage expectations for continued gains. Management should set realistic targets for the improvement programmes taking into consideration the technical and organisational complexity of the system as well as the improvement half-life. Problems that are low in technical and organisational complexity tend to be solved quicker and problems that are more advanced take longer which could lead to de-motivation of the employees and hence slow down the programme. More advanced problems can be broken up into smaller sub processes which are relatively easier to solve.

In a study done on the paradox of successful implementation of total quality management (TQM) at an electronic manufacturer, (but yet financial performance weakened), it became evident that coupling of processes on the shop floor are not strongly linked to other processes where coupling at the upper management levels, such as product development, customer needs assessment and organisation design is strong (Sterman et al 1997). The authors found in this study that quality improvement programmes such as TQM present firms with a trade-off between short-term and long-term effects. In the long-term TQM can increase productivity, raise quality and lower cost, but in the short term these improvements can interact with accounting systems and organisational routines to create excess capacity, financial stress and hence pressure for lay off that undercut commitment to continuous improvement.

A core result of the study is the unbalanced impact of improvement activity on different parts of the organisation. A process with low complexity and rapid improvement rates tends to generate capacity, while processes with high complexity such as new product development, customer needs assessment and reorientation of product mix, have slow improvement rates. If managers underestimate the delay required for a quality improvement programme to be successfully implemented, they are likely to conclude that the programme in question does not work and abandon their efforts to implement it (Repenning 2002).

One of the most powerful aspects of system dynamics is to incorporate the soft factors into models; the kind of factors that seldom show up on financial statements, but which are recognised to be important to understand the organisation (Stepanovich 2004), (Zahn et al 1998).

2.2.3 System dynamics and soft factors

Soft factors are generally more difficult to measure while hard factors are those that are more systems orientated (Lewis et al 2006), (Luna-Reyes and Anderson 2003). The study by Lewis et al (2006) further demonstrated that the most critical factors for a successful TQM programme are soft factors such as top management commitment.

Sterman (2000) recognised, for the problem definition one needs to use the written database as well as the mental data base. He suggests the following methods to help with the characterisation of the structure of the system dynamics model: archival research, data collection, interviews and direct observation. Sterman (2000) further postulates that "Omitting structures or variables known to be important because numerical data are unavailable is actually less scientific and less accurate than using your best judgement to estimate their values" (Sterman 2000:854).

Luna-Reyes and Anderson (2003) report on different methods that could be used by a modeller to gather the qualitative data required during the modelling process where the aim is to query the mental data base and storing the results in the written data base. The modeller interacts with the different actors in the system through interviews and oral history or through direct observation and focus groups. The next step for the researcher or modeller is to analyse the qualitative data, ground the textual information with the assumptions used in the model building process and to build robust documentation of the model. Quotations from the interviews could assist the modeller to build rich stories that give insight into the structure of the system dynamics model (Luna-Reyes and Anderson 2003).

Grounded theory is one example of a method that could be used to build the theoretical structure of the research topic. Through grounded theory, themes or concepts are identified across the written data base, like transcriptions of interviews, where the main aim is to link these concepts to generate meaning full theories through identifying relationships among factors in the system (Luna-Reyes and Anderson 2003). Luna-Reyes and Anderson (2003) continue to say that these concepts could become stocks and flows for a system dynamics model. These concepts could be dynamic behaviours, variables or policy related topics where each concept is grounded in a set of quotations or examples across the data base.

Care must be taken with assumptions about scales for soft factors (McLucas 2003). McLucas (2003) adds that an important aspect with soft factors is to "see" the effect in the dynamic hypothesis rather than 100% correctness. One useful way of treating soft factors is to normalise the data to be dimensionless and having values between 0 and 1 (McLucas

2003), (Akkermans 1995). The influencing variable is therefore also normalised and can be quantified through tools such as interviews. McLucas (2003) further recommends evaluating the sensitivity of the results to ascertain uncertainty.

2.3 Sustainability and continuous improvement

Successful total quality management programmes are underpinned by continuous improvement over time and therefore sustainability becomes an indispensable factor (Curry & Kadash 2002). Sustainability is broadly defined as “sustainability implies that new working methods and performance levels persist for a period appropriate to the setting” (Buchanan et al 2005). The authors further postulate that sustainability may concern the stability of work methods, or the consistent achievement of performance goals independent of the methods used, and may also apply to the maintenance of the consistent trajectory of performance improvement and concluded that sustainability may thus acquire different meanings in different contexts and at different times. Sustainability is also defined as “the ability of an organisation to adapt to change in the business environment to capture contemporary best practise methods and to achieve and maintain superior competitive performance”. This concept implies for an organisation to maintain competitiveness (Zairi & Liburd 2001)

Buchanan et al (2005) identified the following eleven factors affecting sustainability in their research, substantial (fit with organisation), individual (commitment or expectations), managerial (style and behaviours), financial (contribution), leadership (vision and goals), organisational (policies and systems), cultural (shared beliefs and priorities), political (stakeholder influence), processual (implementation methods), contextual (external conditions) and temporal (timing and flow of events).

A study conducted on a model for assessing the sustainability of shop floor based process improvement programmes, consists of two elements to identify the level of sustainability achieved by process improvement programmes. The first element identifies five different levels of sustainability at each cell and the second level identifies to which degree the tools and techniques have been used in each cell (Bateman & David 2002). The authors conclude that most process improvement activities do not either fail outright or succeed in every aspect, but rather have differing degrees of success.

In another research on sustainability of process improvement involving shop floor personnel, a number of factors that enable success or inhibit progress in terms of performance and sustainable improvement has been identified (Bateman & Rich 2003). Although "lack of resources" came out tops in the inhibitors for sustainable process improvement programmes, "others" came out as high for inhibitors and enablers of sustainable process improvement programmes. Bateman and Rich (2003) therefore concluded that it is difficult to provide generic advice that companies can use to cover all of their sustainability issues and that sustaining process improvement programmes, has a high degree of complexity.

In a study on TQM sustainable performance, the author proposes a TQM maturity and sustainable performance model (TQM-MSPM) that suggests the creation of an organisational system that encourages co-operation, learning and innovation to facilitate the implementation of process management practises (Zairi 2002). This in turn leads to continuous improvement of processes, products and services and employee fulfilment. One element of the model is sustainable performance of which measurement is an important aspect.

The business balance score card approach is an integral part of this model for measurement. Another element of this model is the culture of continuous improvement. In the context of this model, it means better and better quality with less and less variation, which results from process management practices that bring forth incremental improvements and innovations.

2.4 Summary

The literature overview in this section gave insight into different quality improvement programmes that could be used to improve the operational performance. From the literature review it was clear that system dynamics could be used in quality improvement programmes to model their successful implementation and sustainability.

It also became clear from the literature review that soft factors over and above hard factors could also have an impact on the successful implementation and sustainability of quality improvement programmes. Although soft factors are complex and difficult to measure they should not be omitted from the system dynamics model.

The literature review also gave insight into a system dynamics model developed in an automotive environment that demonstrated the competing nature of quality improvement programmes with normal production output. It further described a tipping point that further illustrated the competing nature of quality improvement programmes and operational requirements.

The literature overview gave new insights into the applicability of systems thinking and system dynamics into the development of a conceptual theory demonstrating the dynamics of quality improvement programmes. Sustainability and the factors influencing sustainable quality improvement programmes, were also highlighted during the literature overview. What has been learnt from the literature overview in this section have been used in the next chapters to create greater focus on sustainable quality improvement programmes in a heavy engineering manufacturing environment from a system dynamics approach.

In the next chapter the conceptual theory developed by Repenning and Sterman (2000) for an automotive manufacturing environment, has been fundamentally reconstructed. The system dynamics simulation model, as proposed by Morrison (2007), has been adapted to fundamentally recreate, with the Vensim® simulation platform, the tipping point as indicated from the literature overview.

CHAPTER 3

CONCEPTUAL THEORY - SYSTEM DYNAMICS AND QUALITY IMPROVEMENT PROGRAMMES

3 Introduction

Research into quality improvement programmes (Jones et al 1996, Sterman et al 1996, Repenning and Sterman 2002, Keating et al 1999, Sterman et al 1997) indicated that to maintain the sustainable benefit after quality improvement programmes have been successfully implemented, remains a challenge to managers of organisations. Repenning and Sterman (2002) created a theoretical dynamic model for quality improvement programmes in an automotive environment, based on system dynamics (SD), which has been developed in order to study the interaction of allocating of resources time between process improvements and to meet the production demands.

This theoretical model is developed from the following three aspects (Repenning & Sterman 2002): (1) Prescriptive writings of the creators of improvement techniques for example Crosby, Ishikawa, Deming and Juran. TQM is important in this respect because it provides information on technical tools such as statistical process control (SPC), as well as behaviour and organisational fundamentals. (2) Existing research already done on quality improvement programmes such as TQM and (3) existing research that considers feedback confirming the complexity of the dynamics from implementing improvement programmes.

A polar type research design, i.e. where initiatives were identified that were a major success or failure with the expectation that their comparison would help identify those processes that would influence business behaviour, was used to identify two substantial improvement initiatives namely (1) manufacturing cycle time reduction and (2) product development process. These two initiatives, by comparison, were in contrast to each other. The manufacturing cycle time reduction programme was a huge success while the product development process programme failed to achieve most of its objectives. The same executive led both these initiatives which also gave the opportunity to control the variable of senior leadership and management style.

Data was collected through interviews as well as follow-up via telephone, e-mail and follow-up conversations. The people interviewed were representative samples of the people directly involved in the initiatives as well as people who were influenced by these initiatives. Through traditional field work, two case studies were used during their research for the two respective improvement initiatives. These case studies were analysed again by the research team and compared to field notes, field data and interview transcripts. The interviewees were also given the opportunity to read through the respective case studies and checked for completeness. An opportunity arose for additional information which was verified through field data and additional interviews.

A theoretical model for the quality improvement programme from a systems thinking perspective was proposed from these two case studies through causal loop diagramming and stock and flow diagrams. The causal links were compared to existing studies to ascertain whether they are supported in the literature. These causal links formed the basis for the dynamic behaviour of the system. These methods helped to ensure that the model was grounded in the field data and consistent with principles of operations and quality management, organisational theory and the experimental literature on human decision making.

The above theoretical model, as proposed by Repenning and Sterman (2002), was fundamentally reconstructed from systems thinking principles. The reconstruction and systems thinking process are discussed in the next section.

3.1 System dynamics model of a quality improvement programme

The theoretical model of the quality improvement programme, refer to Figure 3.1, is developed around the net process throughput of the system which defines the inputs which are successfully converted into outputs. The net process throughput is a function of the following three variables, gross process throughput, defect introduction and defect correction and is defined by equation (3.1).

$$\begin{matrix} Net\ Process \\ Throughput \end{matrix} = \begin{matrix} Gross\ Process \\ Throughput \end{matrix} - \begin{matrix} Defect \\ introduction \end{matrix} + \begin{matrix} Defect \\ correction \end{matrix} \qquad (3.1)$$

The gross process throughput is the total quantity of new work accomplished and the defect introduction is the flow of work that is not done correctly. The defect correction is the rate at which previous work not done correctly receives additional attention to become usable.

The throughput gap is the difference between the DESIRED THROUGHPUT, which is the exogenous demand in terms of the modelling purposes, and the net process throughput. The DESIRED THROUGHPUT is an exogenous goal of the system and is determined by the manufacturing manager in a typical manufacturing facility. The throughput gap is defined in equation (3.2) as follows,

$$Throughput\ Gap = DESIRED\ THROUGHPUT - Net\ Process\ Throughput \qquad (3.2)$$

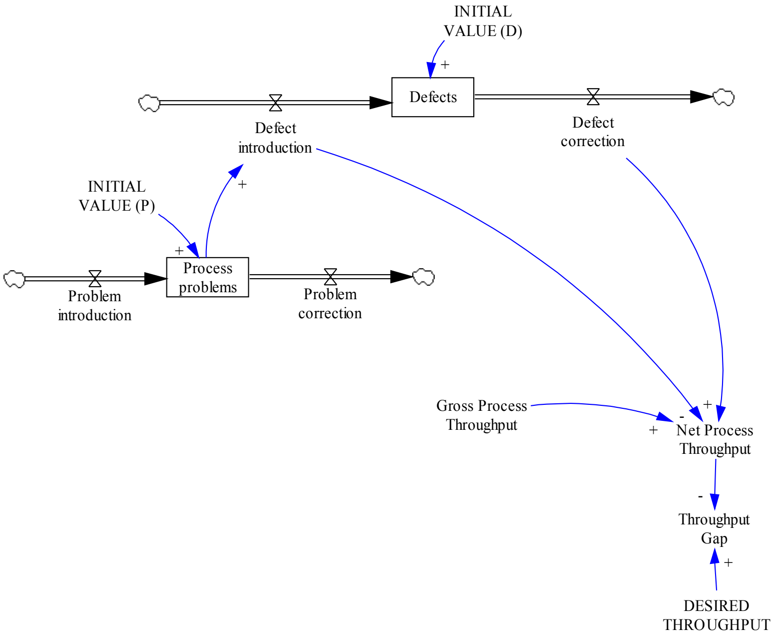

Figure 3.1 Stock and flow diagram of process throughput. Reconstructed from Repenning and Sterman (2002)

In Figure 3.1 the defects are modelled as a stock of defects which is defined as the accumulation of the rate at which defects are introduced less the rate at which defects are corrected. Refer to equation (3.3).

$$Defects(t)=\int_{t_0}^{t}(Defect\ introduction(t)-Defect\ correction(t))\,dt+Defects(t_0) \qquad (3.3)$$

Where $Defects(t_0)$ is defined as the INTITIAL VALUE (D) of the defects at time t_0.

The rate of defect introduction is determined by the stock of process problems. The process problems of the system are described by the physical problems of the machines and will continue to produce defects until the machine is stopped and the defect-causing elements are eliminated.

The process problems are modelled as an accumulation of problems, or a stock of problems, and determined by the difference between problem introduction and problem correction with the initial number of process problems defined by, INITIAL VALUE (P) at time t_0. Process improvement initiatives focus on the reduction of defects and therefore ultimately reducing the stock of process problems and hence reducing the defect introduction rate and therefore improving net process throughput. The stock of process problems is defined by equation (3.4). The focus of the process improvement initiative should therefore be reduction in process problems and not reduction in defects.

$$\begin{matrix} Process \\ problems(t) \end{matrix} = \int_{t_0}^{t} \left(\begin{matrix} Problem \\ introduction(t) \end{matrix} - \begin{matrix} Problem \\ correction(t) \end{matrix} \right) dt + \begin{matrix} Process \\ problems(t_0) \end{matrix} \tag{3.4}$$

Where *Process problems (t_0)* is defined by INITIAL VALUE (P) of the Process problems at t_0.

The DESIRED THROUGHPUT is an exogenous model variable for the system and is determined by the manufacturing manager as a function of the business requirements. This introduces a feedback loop to eliminate the throughput gap by increasing the net process throughput. This feedback loop is achieved by two means: (1) first-order improvement and (2) second-order improvement. The model of this feedback loop is depicted in Figure 3.2.

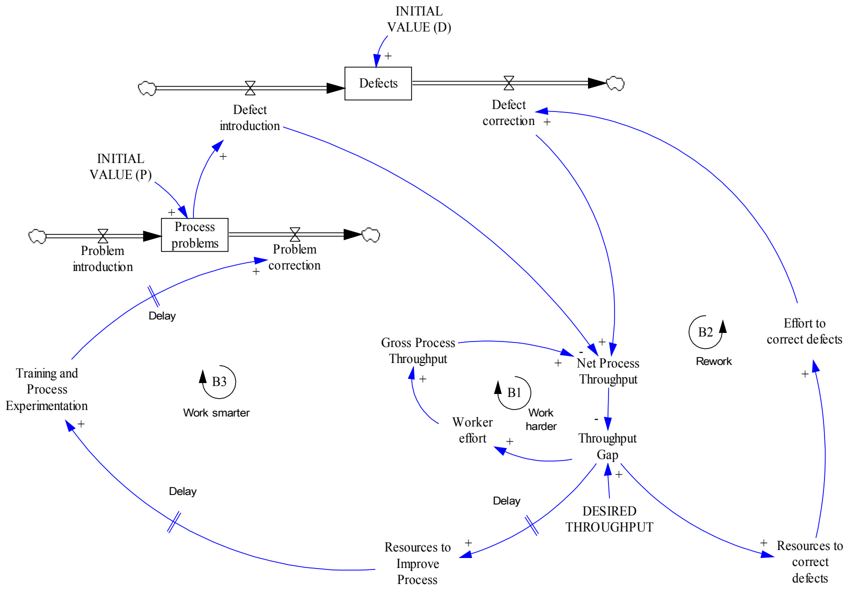

Figure 3.2: Stock and flow diagram with balancing feedback loops. Reconstructed from Repenning and Sterman (2002)

With first-order improvement activities, the net process throughput is increased by increasing the efforts or worker effort of the workers and hence increasing their utilisation or let them work harder as depicted by the balancing loop (B1) in Figure 3.2. An alternative loop is the balancing loop (B2) where managers allocate workers to correct defects through rework. Managers might also reduce the throughput gap by introducing more capacity by hiring more labour or buy more machines, but capacity expansion is excluded from this model.

The first-order improvement balancing loops are identified as follows: Balancing loop (B1), Net process throughput, throughput gap, worker effort and gross process throughput. Worker effort increases which in turn increases the gross process throughput and therefore increases the net process throughput which reduces the throughput gap. This relates to balancing loop (B2), net process throughput, throughput gap, resources to correct defects, effort to correct defects and defect correction. The more resources allocated to correct defects, the more the effort to correct defects increases and therefore the defect correction increases which in turn increases the net process throughput and hence reduces the throughput gap. The first-order improvement process can be a costly process due to typically allocating extra labour hours by working extra hours.

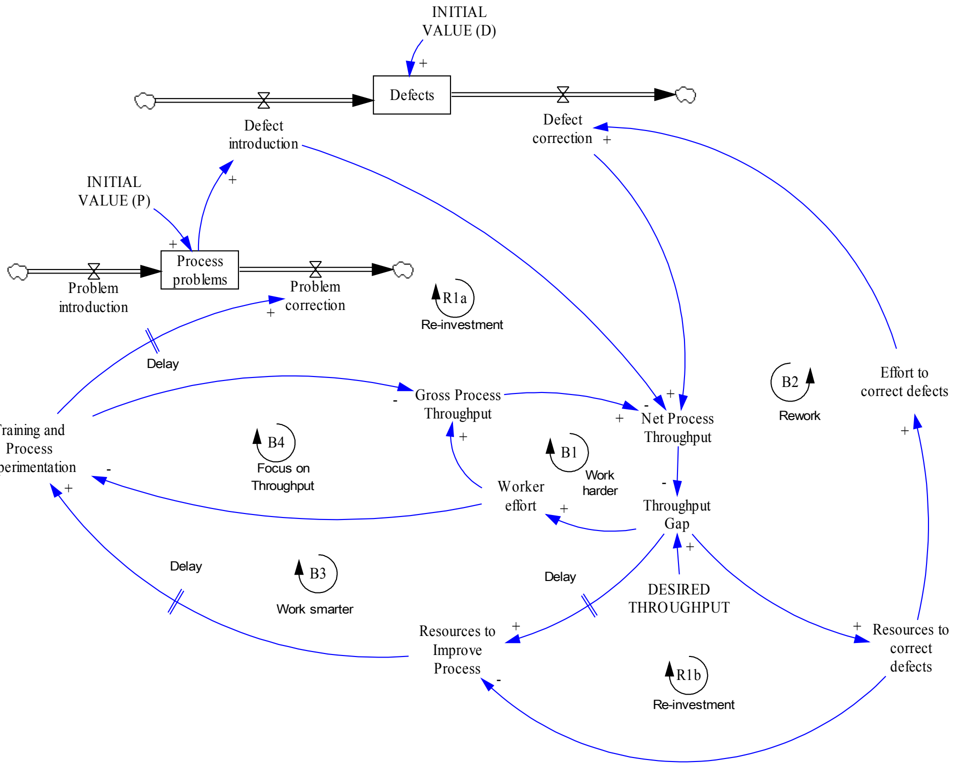

Figure 3.3: Stock and flow diagram with reinforcing feedback loops. Reconstructed from Repenning and Sterman (2002)

The second-order improvement process (work smarter loop B3) is a more effective improvement process where the focus is on problem correction rather than defect correction. If the rate of problem correction is increased, the process problems are reduced and therefore cause a reduction in defect introduction which in turn increases the net process throughput and hence reduces the throughput gap. In order for this process to be successful, the management not only needs to train the workforce in quality improvement programmes and methods but also to allow the workers adequate time off from their normal duties in order for them to practise these improvement initiatives.

The efforts from the first-order improvement initiatives are relatively quickly realised but the efforts from the second-order improvement initiatives are only realised after a substantial delay. These delays are mainly due to training in these improvement methods, experiments and building up the required resources. The length of the delay depends on the technical- and organisational complexity of the process. The balancing loop (B3) or work smarter loop, as depicted in Figure 3.2 is identified by: net process throughput, throughput gap, resources to improve process, training and process experimentation, problem correction, process problems and defect introduction.

Allocating resources to improvement initiatives can be accommodated by management providing there is slack in the production schedule. However, if the manufacturing process is strapped for capacity, the workers will short circuit the work smarter loop in order to boost gross process throughput. This phenomenon was clearly revealed in the field studies done by Repenning and Sterman (2002) and therefore the balancing loop (B4), focus on throughput, is derived as follows; net process throughput, throughput gap, worker effort, training and process experimentation and gross process throughput. Refer to Figure 3.3.

This process delivers temporary gains in net process throughput but due to less effort in problem correction, process problems continue to increase which leads to an increase in defect introduction and hence a reduction in net process throughput. This creates more pressure on workers to focus on throughput and therefore forming the self-reinforcing reinvestment loops, (R1a) and (R1b). These loops are different to the previous loops due to the fact that they amplify changes in throughput. Refer to Figure 3.3.

If the throughput gap is large for example, the workers focus all their efforts on throughput and hence training and process experimentation gets less attention. This causes the process problems to accumulate and therefore defect introduction increases which causes an even bigger reduction in throughput gap. This reinvestment loop is defined by loop (R1a) as follows; net process throughput, throughput gap, worker effort, training and process experimentation, problem correction, process problems and defect introduction.

Similarly, a large throughput gap shifts the focus towards defect correction and away from process improvement. Process problems accumulate at a faster rate, leading to still more process problems and hence more defects being introduced. This causes the net process throughput to reduce even more with a greater throughput gap. This loop is defined as the reinvestment loop (R1b) and is identified as follows; Net process throughput, throughput gap, resources to correct defects, resources to improve process, training and process experimentation, problem correction, process problems and defect introduction.

In the above situations the reinvestment loops, (R1a) and (R1b), operate as vicious cycles that accelerate the deterioration of the process and increasing the throughput gap in spite of the increased efforts to work even harder. On the other hand, the reinvestment loops, (R1a) and (R1b), can operate as virtuous cycles, successful improvement reduces defect introduction and increases net process throughput, which allows workers to meet their throughput goals and freeing additional resources for learning and improvement. If these loops work in a virtuous cycle, the performance will continue to improve, but if these loops work in a vicious cycle, the organisation could be trapped in a vicious cycle of declining capability.

During the field studies done by Repenning and Sterman (2002), this phenomenon was clearly evident. The workers facing a shortfall in their production goals or big throughput gap, focused on working harder (loop B1), doing more rework (loop B2) and more focus on throughput (loop B4) with the net effect of reduced focus on learning and improvement. This reduces the throughput gap in the short term, at the expense of improvement in the long run. However, due to the feedback delay, the negative impact on the capability of the process is not immediately realised until the process falls into the trap of the vicious cycle.

A typical quality improvement programme focuses on the training and process experimentation loop (B3); however, there is a delay between the introduction of such a programme and the benefits seen in the reduction of the throughput gap. The immediate effect is therefore an increase in the throughput gap, due to the allocation of resources to the training and process experimentation loop. However, through the virtuous cycle of the process, the net process throughput will increase, closing the throughput gap. Due to the fact that process problems are invisible in time and space to the agents in the process except for the defects they create, the virtuous cycle is not visible to the management and workers. The study done by Repenning and Sterman (2002) suggested that management will most likely opt for the fundamental improvement loop such as (B1), (B2) and (B4) where the gains are immediately visible, rather than the training and process experimentation improvement loop (B3).

3.2 Modelling of the interaction between first- and second-order improvement loops

The decision process for management is therefore more complex than they realise due to the interaction of the first-order and second-order improvement loops. This interaction is simulated in a system dynamics simulation model as reconstructed and refined in this research from Morrison (2007) , which models the interaction of the first- and second-order improvement loops as depicted by Repenning and Sterman (2002). Refer to Figure 3.4 for the system dynamics simulation model. The challenge workers and management face is the pressure to produce output and to do process improvement.

The work harder loop (B1) is identified by, net process throughput, throughput gap, resource gap, desired allocation to production, indicated allocation to production, adjusting allocation, allocation to production and gross process throughput. The Reinvestment loop (R) is identified as follows, net process throughput, throughput gap, resource gap, desired allocation to production, indicated allocation to production, adjusting allocation, allocation to production and gross process throughput.

The success of the organisational performance is measured by the net process throughput as described in equation 3.5 as follows,

$$\mathit{Net\ process\ throughput} = \mathit{Gross\ process\ throughput} - \mathit{Defect\ introduction} \tag{3.5}$$

The gross process throughput is a function of the allocation to production and the productivity of production time and is defined in equation 3.6 as follows,

$$\begin{matrix}\mathit{Gross\ process} \\ \mathit{throughput}\end{matrix} = \begin{matrix}\mathit{Allocation} \\ \mathit{to\ production}\end{matrix} * \begin{matrix}\mathit{Productivity\ of} \\ \mathit{production\ time}\end{matrix} \tag{3.6}$$

Where productivity of production time is a measure of the productivity in units per hour.

Allocation to production is the stock of production hours per week that is allocated to produce the net process throughput. Refer to equation 3.7.

$$\begin{matrix}\mathit{Allocation} \\ \mathit{to\ production}(t)\end{matrix} = \int_{t_0}^{t} \left(\begin{matrix}\mathit{Adjusting} \\ \mathit{allocation}\end{matrix} (t) \right) dt + \begin{matrix}\mathit{Allocation} \\ \mathit{to\ production}(t_0)\end{matrix} \tag{3.7}$$

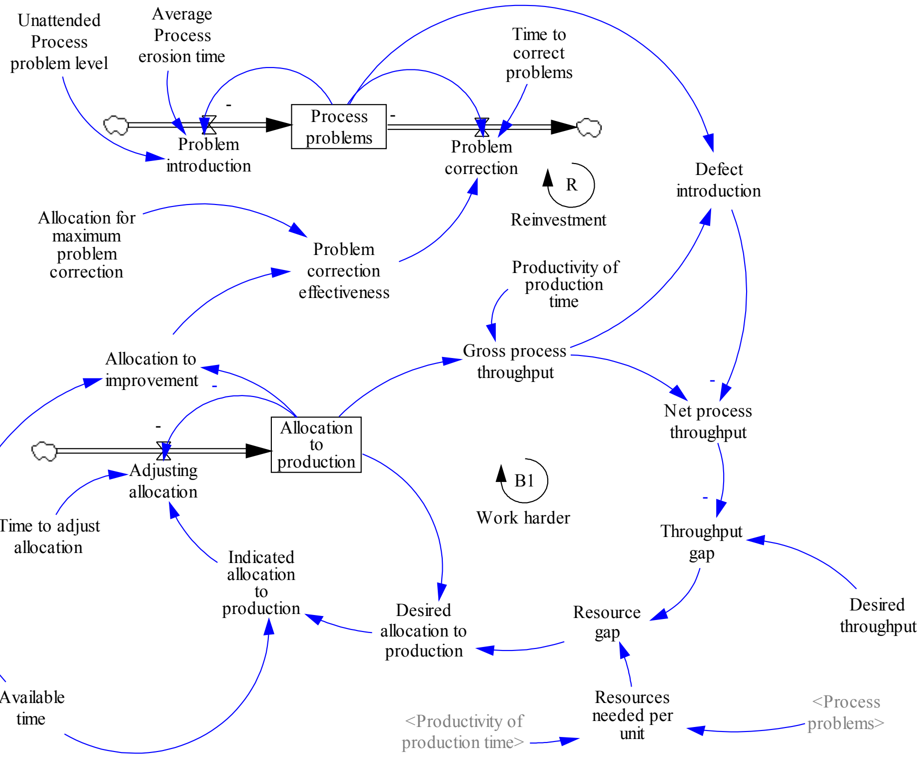

Figure 3.4 System dynamics simulation model of the interaction between first- and second-order improvement loops. Reconstructed and refined from Morrison (2007)

Where Allocation to production (t_0) is defined as the initial value allocated to production at time t_0 in hours per week.

Adjusting allocation is the rate of the fraction of the gap between, indicated allocation to production, and allocation to production, and is defined by equation 3.8 as follows,

$$\begin{matrix}\text{Adjusting} \\ \text{allocation}\end{matrix} = \frac{\left(\begin{matrix}\text{Indicated allocation} \\ \text{to production}\end{matrix} - \begin{matrix}\text{Allocation to} \\ \text{production}\end{matrix}\right)}{\text{Time to adjust allocation}} \tag{3.8}$$

Where Time to adjust allocation is a model constant in weeks.

In this model the assumption is made that all the workers' available time is either allocated to production, first-order improvement or process improvement which is second-order improvement. In the work harder loop the workers respond to the throughput gap which is relative to the desired throughput and net process throughput. The throughput gap is defined in equation 3.9 as follows,

$$\text{Throughput gap} = \text{Desired throughput} - \text{Net process throughput} \tag{3.9}$$

Where Desired throughput is an exogenous goal for this process in units per week.

This model further assumes that the allocation decision is made with full knowledge of the throughput rate, defect introduction rate, productivity of production time and the current allocation to production. The reason for this assumption is to eliminate any flaws in perception, information processing or allocation decision making as possible causes for the observed behaviour of the model (Morrison 2007).

The indicated allocation to production, is a function of the available time, desired allocation to production and the resource gap, where the resource gap is determined by the throughput gap and the resources needed per unit. Refer to equation 3.11. The indicated allocation to production is constrained to be non negative and not to exceed the available time. Refer to equation 3.10. The resources needed depend on the productivity of production time and the fraction of process problems that generate defects. Refer to equation 3.12

$$\begin{matrix} Indicated\ allocation \\ to\ production \end{matrix} = MAX\left(0, MIN\left(Available\,time, \begin{matrix} Desired\ allocation \\ to\ production \end{matrix}\right)\right) \tag{3.10}$$

$$Resources\ gap = \frac{Throughput\ gap}{Resorces\,needed\ per\,unit} \tag{3.11}$$

$$Resources\,needed\ per\,unit = \frac{Pdy\,of\ production\,time}{(1 - Process\,problems)} \tag{3.12}$$

Defect introduction, equation 3.13, arises as some of the gross throughput achieved is done incorrectly. The fraction of the gross throughput that is done incorrectly is a function of the process capability as identified by process problems where the process problems are identified as a stock which increases with problem introduction and decreases with problem correction. The process problems are defined as a dimensionless index ranging from 0 to 1 and are therefore an indicator of the fraction of the gross process throughput that is done incorrectly. Refer to equation 3.14.

$$Defect\,introduction = Gross\ process\ throughput * Process\ problems \tag{3.13}$$

$$\begin{matrix} Process \\ problems \end{matrix} = \int_{t_0}^{t}\left(\begin{matrix} Problem \\ introduction(t) \end{matrix} - \begin{matrix} Problem \\ correction(t) \end{matrix}\right)dt + \begin{matrix} Process \\ problems \end{matrix}(t_0) \tag{3.14}$$

Where Process problems (t_0) is defined as the initial value of the process problems at (t_0).

The problem introduction is the average rate of increase of the stock of process problems. Process problems are simulated with the analogy of the second law of thermodynamics. The similarity between the second law of thermodynamics and process problems, is that the state of the system changes. According to the second law of thermodynamics, heat will flow naturally from a high temperature to a low temperature and hence the entropy increase (Sears et al 1982), (Van Wylen & Sonntag 1985). In a manufacturing process, when the process is left unattended, the process would decay over time due to the increase in process problems. The process will not be restored unless effort is put into the process.

When the process is left unattended without any process improvement activity, the process deteriorates at a rate of average process erosion time, to a high level of process problems, as given by unattended process problem level. The problem introduction is therefore defined in equation 3.15 as follows,

$$\begin{matrix}\textit{Problem}\\ \textit{introduction}\end{matrix} = \frac{\left(\begin{matrix}\textit{Unattended process}\\ \textit{problem level}\end{matrix} - \textit{Process problems}\right)}{\textit{Average process erosion time}} \tag{3.15}$$

Problem correction occurs when workers spend time to improve the process through improvement activities such as investigating problems, conducting experiments and making process changes. The improvement rate is relatively high when the process is in a state of low process capability and when the process is in a state of high process capability, the improvement rate is relatively slower. The problem correction (Equation 3.17) is therefore also a function of the problem correction effectiveness which is defined as a ratio between allocation to improvement and allocation for maximum problem correction. The allocation to improvement depends on how much time is available and how much time is allocated to production. Refer to Equation 3.16

$$\textit{Allocation to improvement} = \textit{Available time} - \textit{Allocation to production} \tag{3.16}$$

$$\begin{matrix}\textit{Problem}\\ \textit{correction}\end{matrix} = \textit{Problem correction effectiveness} * \frac{\textit{Process problems}}{\textit{Time to correct problems}} \tag{3.17}$$

Where problem correction effectiveness is defined by Equation 3.18

$$\textit{Problem correction effectiveness} = \frac{\textit{Allocation to improvement}}{\textit{Allocation for maximum problem correction}} \tag{3.18}$$

Morrison (2007) developed this system dynamics model on the assumption that production always takes priority in the decision between allocating time to improvement and allocating time to production. Allocation to improvement is the amount of time left over after the allocation to production has been made.

3.3 Discussion of the simulation results from the interaction of the first - and second-order improvement loops

The system dynamics model described in Figure 3.4 is simulated by means of Vensim® computer simulation language and is compared to the results obtained by Morrison (2007). Refer to Appendix B.1 for a listing of the equations created when the system dynamics model depicted in Figure 3.4 has been programmed in Vensim®. In order to simulate the model, base line values of the model parameters are described in Table 3.1.

Model parameter	Value	Units
Unattended Process problem level	0.9	dimensionless
Average Process erosion time	36	weeks
Time to correct problems	16	weeks
Productivity of production time	1	unit/hour
Allocation for maximum problem correction	4000	hours/week
Available time	4000	hours/week
Time to adjust allocation	1	weeks
Initial Process problems	0.4	dimensionless

Table 3.1 Baseline parameter values for the simulation of the system dynamics model. Values obtained from Morrison (2007)

The initial value of process problems is a dimensionless index ranging between 0 and 1 where 0 depicts zero process problems. The unattended process problem level is an indication of how much the process could erode, as depicted by the average process erosion time, without any process improvement activities.

The desired throughput is an exogenous goal and is determined by the process owner. The simulation in Vensim® is started in the equilibrium condition where the allocation to production is zero and the desired throughput is zero. The first test is to establish basic behaviour patterns of the system by setting the desired throughput equal to a pulse input at week 10. The pulse function is defined in equation 3.19 where the pulse function returns the value 1.0 from the time interval *start* at an interval width of *width* and 0.0 at all other times.

$$Pulse=(start\,,\,width) \tag{3.19}$$

Where start defines the start time of the pulse that lasts for an interval width

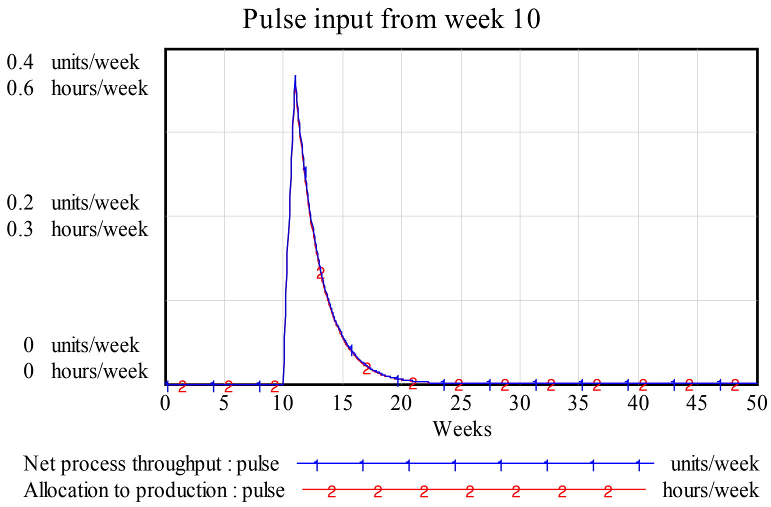

Figure 3.5 Behaviour of the system with a pulse input at week 10

The input pulse causes an increase in the throughput gap that causes an increase in the allocation to production. This increases the gross process throughput that in turn increases the net process throughput. The desired throughput only changes temporarily in accordance to the pulse input and then returns to zero. The net process throughput smoothly returns to its initial value while the allocation to production returns to its initial equilibrium level of zero. Refer to Figure 3.5.

The next simulation is to test the basic behaviour of the system when the desired throughput is set equal to a step increase of 1 100 units per week. The step function is defined as follows in equation 3.20. The step function returns the value zero until the simulation time equals *step time*, from which then onwards, the step function returns the value equal to *height*.

$$Step = (height\ ,\ step\ time) \tag{3.20}$$

Where height defines the value of the step function at step time.

The throughput gap increases in order to close the gap between the desired throughput and the net process throughput. The net process throughput increases and smoothly approaches the desired throughput of 1 100 units per week where it stabilises. Although the system reaches its goal of 1 100 units per week, the allocation to production continues to rise long after the net process throughput has reached its goal. Due to the continued allocation to production, the process problems also continue to rise and stabilise at a level slightly higher than the initial level of 0.4. Refer to Figure 3.6.

The simulation indicates that where the first-order improvement is effective, the net process throughput meets the desired throughput, but at the expense of the process capability. This is clearly visible in the increase of the process problems long after the net process throughput equals the desired throughput. These results are in line with those predicted by Morrison (2007). Refer to Figure 3.6.

The allocation to production has to increase to compensate for the increase in process problems. This phenomenon is in line with the re-investment working as a vicious cycle (R1) as predicted by Repenning and Sterman (2002) in their theory. The dysfunctional attributions, that management blames the workers for being lazy, are central to the story in Renning and Sterman (2002) and are easy to imagine based on the results of this simulation.

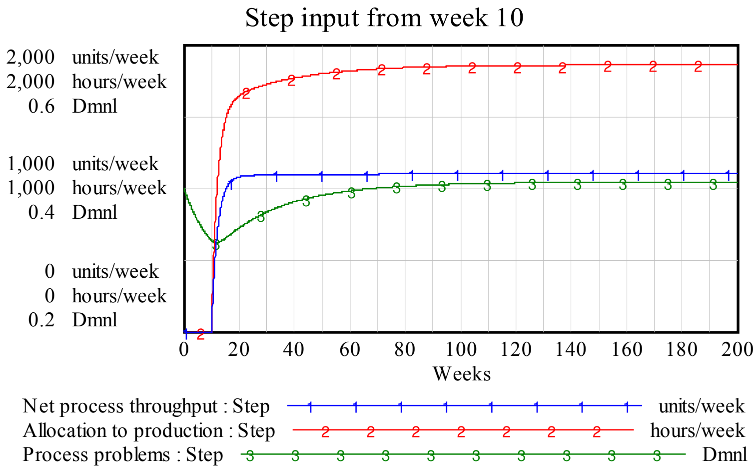

Figure 3.6 Behaviour of the system with a step input of 1 100 units per week at week 10

The process owner or manager has control over the process goals when they set the production targets by typically adjusting the desired throughput. In the next simulation the behaviour of the system is inspected by adjusting the desired throughput to 1400 units per week from week 10, at the same baseline parameters as depicted in Table 3.1. The desired throughput is simulated with a step input of 1400 units per week from week 10. Refer to Figure 3.7 for a graphic presentation of the results.

The net process throughput increases sharply after week 10, while approaching the value of the desired throughput of 1400 units per week. After approximately 110 weeks, the net process throughput equilibrium is no longer maintained at the value of the desired throughput, but starts to decline.

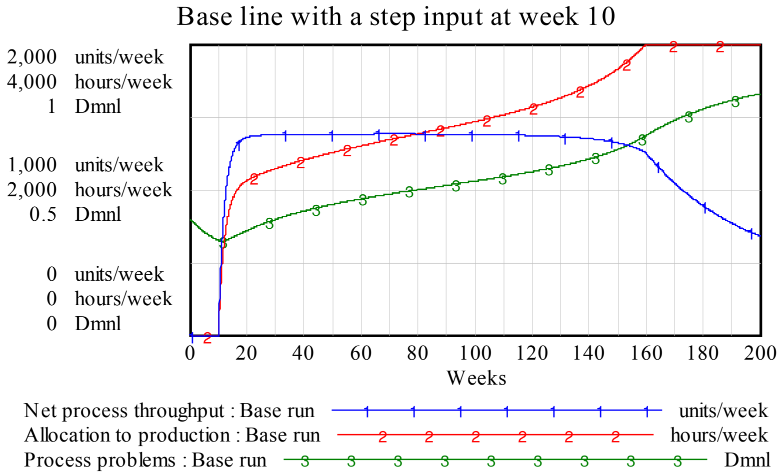

Figure 3.7 System behaviour displaying a tipping point with a step input of 1400 units per week at week 10

While the net process throughput increases after week 10 and approaches the desired throughput, the process problems continue to rise after week 10 even though the net process throughput approached the desired throughput at 1400 units per week. The allocation to production also continues to rise until it reaches the maximum of the available time of 4000 hours per week at approximately week 160. Eventually the net process throughput starts to steadily decline and at approximately week 155 starts to decline steeply and eventually ends at approximately 650 units per week which is lower than the desired throughput of 1400 units per week. This demonstrates the behaviour of better before worse, as also described by Repenning and Sterman (2002).

Morrison (2007) further states that allocation to production, to meet the desired throughput, is achieved at the expense of allocation to problem correction. With less problem correction the stock of process problems rises and therefore defect introduction rises. The reinvestment loop as depicted in Figure 3.4 starts to work as a vicious cycle, and the system is locked in a downward spiral. The vicious cycle starts when the allocation to production is allocated entirely to production until it equals the available time, while the process problems tends to reach their natural limit. Therefore the system reaches a steady state of low levels of capability and performance, despite the full allocation to production (Morrison 2007).

Between Figure 3.6 and Figure 3.7 the data clearly demonstrates that the system has a tipping point. If the desired throughput is increased beyond a critical threshold, the system displays the behaviour of a better before worse pattern (Morrison 2007), (Repenning & Sterman 2002). Morrison (2007) further postulates that tipping points are unstable equilibrium points. The system either reaches steady state behaviour in the one direction or a different steady state behaviour in the opposite direction.

Increase in allocation to production increases the net process throughput but an increase in allocation to production in the long run deteriorates the net process throughput. Due to the parameters controlling the tipping point not known to the process owner or production management, the decision to increase the desired throughput, may push the system over the critical threshold and hence into a deterioration cycle. These parameters could be the following: unattended process problem level, average process erosion time, time to correct problems, available time and allocation for maximum problem correction, where available time is directly observable (Morrison 2007). Morrison (2007) further states that in practice managers are highly unlikely to know the parameters necessary to choose their desired throughput targets to achieve optimal production conditions.

3.4 Summary

The competing nature of labour hours required for production and labour hours required for process improvement is clearly demonstrated by the theory developed by Repenning and Sterman (2002) for a typical manufacturing facility, during the dynamic simulations. The interaction of the first-order and second-order improvement loops are described which also explains the vicious and virtuous cycles that a system could be locked into.

The simulation results from a system dynamics simulation model redeveloped and adapted in this research from Morrison (2007), clearly demonstrates the tipping point in the system, when the desired production is increased beyond a critical threshold. The model parameters determining this threshold are typically unknown to the production manager and could lead to a system that could be locked into a downward spiral. The simulation results also demonstrated that managers typically would opt for the rework loop to close the throughput gap, where the results of their efforts are more visible.

The conceptual model of a quality improvement programme, fundamentally reconstructed from Repenning and Sterman (2002), has become the base line structure for the later development of a theory for a sustainable quality improvement programme in a heavy engineering manufacturing environment. From the research in this and the previous chapter, the theory for sustainability of quality improvement programmes from a systems thinking perspective, is developed in the later chapters of this thesis and expanded to a system dynamics simulation model to simulate the behaviour of a quality programme in a real system.

In the next chapter, the research design and methodology is discussed which was used to (a) test the theory from Repenning and Sterman (2002) in a heavy engineering manufacturing environment and (b) develop the theory for sustainable quality improvement programmes in a heavy engineering manufacturing environment.

CHAPTER 4

RESEARCH DESIGN AND METHODOLOGY

4 Introduction

This research has been focused on the operational management of operations, specifically in the heavy engineering manufacturing industry. The first strategy for this research has been theory testing using case studies which are qualitative in nature (Meredith 1998), (Johnston et al 1999), (Hillebrand 2001). It provided an in-depth description of the theory developed by Repenning and Sterman (2000), testing the applicability in a heavy engineering manufacturing environment. The second strategy for this research has been theory building using additional data gathered during case studies which are also qualitative in nature. The data gathering methods have been semi-structured interviews, documentary resources and computer simulation studies (Mouton 2001).

Literature research has been done, as presented in Chapter 2, to gain more insight into quality improvement programmes such as six sigma, Total Quality Management (TQM), lean six sigma and others. The purpose of the literature research was to study previous work done on applications of system dynamics in quality improvement programmes. The literature research has also given insight into the application of quality improvement programmes and system dynamics in an operations management environment.

Repenning and Sterman (2000) developed a theory on quality improvement programmes, developed from case studies in the automotive industry and grounded in literature. This theory has been tested during this research for applicability in a heavy engineering manufacturing environment as well as expanded and modelled with mathematical modelling utilising a computer simulation language such as Vensim®. This model may provide causal accounts of the operations problem and may allow one to make predictive claims regarding the sustainability of quality improvement programmes. The accuracy of the model depends on the assumptions specifying the model as well as the quality of the data against which the model has been fitted (Mouton 2001). From the literature, models have also been an essential part of development of theories (Haig 2010).

As demonstrated in later chapters in this research, the modelling process is an iterative process which starts at the problem articulation, dynamic hypothesis, formulation, testing and policy formulation and evaluation (Sterman 2000). The theory from Repenning and Sterman (2000) has been expanded through theory building, specifically aimed at qualitatively describing a new theory, grounded in the literature and case study data, for sustainability of quality improvement programmes in a heavy engineering manufacturing environment. The newly formulated theory has also been mathematically modelled utilizing a computer language such as Vensim®.

4.1 Research design

The organising framework for this research is essentially descriptive. Information has been collected with the intention of describing a specific group with no intention to go beyond the group, and in essence an applied research or problem-based research, addressing an existing problem (Hancock & Algozzine 2006). Another organising framework for this study is qualitative research where the purpose of this research was to “get under the skin” of the organisation to find out what really happened and to carry out research into the processes leading to results (Gillham 2000).

With the qualitative research design, the goal has been to understand the situation under investigation primarily from the participant's perspective through individual interviews and reviewing of existing documents. This type of qualitative research has been represented by case studies which have an intensive analysis and description of a system bounded by time and space (Hancock & Algozzine 2006). Information and insight gained from these case studies could influence policy, procedures and future research (Merriam 2001).

The research design used by Repenning and Sterman (2002) is a polar type research design where the case studies focused on initiatives that were dramatic successes or failures in an automotive environment, with the expectation that their comparison would help identify those processes that prevent competence enhancing change (Eisenhardt 1989). This research identified two initiatives, (a) manufacturing cycle time reduction and (b) product development process. The first initiative, (a) has been a big success while the second initiative (b) has been a failure. In both these initiatives in the automotive environment, the same executive led both these initiatives and therefore senior leadership and management style has been a controlled variable.

The literature pointed out that case or field research is often preferred over more traditional rationalist methods of optimisation, simulation and statistical modelling, for building new operations management theories (Meredith 1998). Case methods can also be used for testing theories or testing particular issues or aspects of an existing theory (Meredith 1998), (Eisenhardt 1989). One set of factors or parameters define the population of interest and is kept constant in the population under study, where in case studies, these factors are controlled through the selection of the situation or site to be studied (Meredith 1998). Meredith (1998) further argues that the rigour of the research is demonstrated by applying the resultant case study theory to a somewhat different set of conditions. Increasing generalisability is done by testing the original theory on alternative populations. Meredith (1998) further states that a large set of cases can aid in generalisation but so can a depth of understanding of a single case.

Case studies may be used for theory testing, where this confirmatory case method consists of three elements (Johnston et al 1999). The first element states that the research must begin with a hypothesis developed by theory. The research hypothesis guides all the decisions in the development of the research design. The second element states that the research design should be logical and systematic. One should define the unit of analysis, select the appropriate cases to study and decide on what data to collect and how to collect it. The third element states that the findings should be independently evaluated, focusing also on external validity by choosing multiple case studies and internal validity through triangulation of the evidence. The authors further suggest that the findings are subjected to the scrutiny of those individuals upon which the case study is based. However, the authors caution on the generalisability of the results.

Hillebrand et al (2001) disagree with Johnston et al (1999) about generalisability of the results and argues that case studies can be used to test theories through theoretical generalisation. Theoretical generalisation is defined as declaring the results of a case research valid for a larger population on the basis of both structural and logical argumentation. The emphasis is on demonstrating causal relationships through logical argumentation (Hillebrand et al 2001). In principle, logical proof that A results from B is superior to a statistical correlation between A and B. Hillebrand et al (2001) further argue that when a researcher is able to formulate logical argumentation in support of causal relationships, it may be concluded that these causal relationships also hold for cases that are structurally similar, which means all situations that are equal to the investigated situations with respect to the critical variables investigated.

4.2 Methodology

The sources of the data for the case study were semi-structured interviewing (individual) and use of documentary sources and other existing data (Mouton 2001). Intrinsic case studies of the current employed quality improvement process of the real life problem in a heavy engineering manufacturing environment, was done where the boundaries were set by the criteria determined by the research problem (Hancock & Algozzine 2006). From previous studies the following three types of data to develop the structure and decision rules in models are proposed, (a) numerical, (b) written and (c) mental data (Forrester 1980). This type of data is determined by interviews, document review, observations and other methods.

4.3 Selecting the cases

According to Eisenhardt (1989) two activities occur at this stage, (a) the population of interest is specified and (b) the sample cases must be determined based on their theoretical usefulness.

In the first instance, the theory also discussed in depth in Chapter 3 by Repenning and Sterman (2000), is derived from cases in the automotive industry. The purpose with this research was (a) to test the theory from Repenning and Sterman (2000) in a heavy engineering manufacturing environment and (b) to expand the theory from Repenning and Sterman (2000) in order to develop a theory for sustainability of quality improvement programmes in a heavy engineering manufacturing environment. The case studies were done in a South African company which manufactures underground mining equipment. It is a medium-sized company with 1600 employees with an annual turnover of R4 billion. The company consists of two different manufacturing facilities in Johannesburg, South Africa where mining equipment is manufactured and exported to global markets. Quality improvement programmes such as lean manufacturing and six sigma (DMAIC) have been implemented in both these manufacturing facilities.

In the second instance for the purpose of this research, two case studies have been conducted. The one case study has been conducted in the business unit (machine shop) of the one manufacturing facility, while the second case study has been conducted in the other business units of the second manufacturing facility. The implementation of the business-wide quality improvement programmes have been a dramatic success in the one manufacturing facility while the implementation has been a failure in the other manufacturing facility. The two manufacturing facilities are overseen by the same executive but have different business unit managers for the different business units. The business units under study form an integral part of the complete manufacturing facility which is big enough to be a fair representation of the operations management principles for the complete business. It is also different enough, due to the size of the company and being on different locations, to be a good representation of the different business units organisational behaviour.

The research done by Repenning and Sterman (2000), is based on a polar type design where the two case studies have been done on a successful quality improvement programme and a second quality improvement programme which was less successful. However, in both these instances the executive overseeing the implementation has been the same person. For the purpose of this research, polar type case study design was also used (Eisenhardt 1989). In the case studies proposed in this research, two cases have been identified where the implementation of the quality improvement programme has been less successful than the implementation of the quality improvement programme in the other instance.

The data, within the boundaries of the problem, was used to build a mathematical model based on the theory developed by Repenning and Sterman (2000). The mathematical model has been analysed through computer simulation on a computer program such as Vensim®. The purpose with the computer simulation was to prove the dynamic hypothesis of the expanded model representing the research problem in the real world (Mouton 2001). The model was used to generate data that was comparable with actual data determined from the case studies. Once the model was validated, it has been used to study policy formulation and evaluation contributing to sustainability of quality improvement programmes in a heavy engineering manufacturing environment.

4.4 Planning of the case study

The case study method is the preferred method to answer the "how" research questions where the investigator has little or no control over the behaviour of the events with the focus on contemporary events (Yin 2009).

A relevant literature review has been done in order to develop more insightful questions about the research topic and to find any existing theories on the sustainability of quality improvement programmes that could be adapted for an application in a heavy engineering manufacturing environment. The literature review is fully described in Chapter 2, literature overview of quality improvement programmes, sustainability and system dynamics. The articulation and dynamic hypothesis of the real world problem, based on the reconstructed and expanded theory developed by Repenning and Sterman (2000), was tested in this research on case studies from a heavy engineering manufacturing environment. Yin (2009) technically defined the case study as benefiting from prior development of theoretical propositions to guide data collection and analysis. Yin (2009) further explained that case studies are used to describe the real life context in which it occurs and illustrate certain topics.

A concern with the case study is that it provides little basis for scientific generalisation (Yin 2009). However, Yin (2009) continues to argue that case studies are generalisable to theoretical propositions where the goal of doing a case study is to expand and generalise theories or analytical generalisation. Johnston et al (1999) further argue that case studies can also be used to test theories. Hillebrand (2001) supports this argument that case studies can be used to test theories and continues to argue that case studies in theory testing can be generalised through theoretical generalisation by demonstrating the existence of causal relationships along with the results. Lucas (2003) supports this view due to the fact that when a theoretical principle is supported in diverse replications, confidence is assumed in the theory.

4.4.1 Components of the research design

The following components for research design are important for the design of the case studies, (1) the research questions, (2) the propositions, (3) the unit of analysis, (4) the logic linking the data to the research questions and (5) the criteria for interpreting the findings (Yin 2009).

4.4.1.1 Case study questions

The research questions for this research are defined in paragraph 1.3.1 which addresses the fundamental question "How" of which the case study is the most appropriate method to be used. These research questions are aligned with the research objective in order to answer the fundamental questions on long-term sustainability and applicability of systems dynamics in quality improvement programmes in a heavy engineering manufacturing environment. Refer to Table 4.1 and Table 4.2 for a description of the detailed field research questions and instruments adapted from Rule and John (2011) for this particular research.

4.4.1.2 Case study propositions

Traditional quality improvement programmes such as TQM, six sigma, lean manufacturing, lean six sigma and operational excellence, use cause-and-effect thinking but do not consider causal interconnection or causal loop diagrams as in systems thinking (Kaufmann & Chieh 2005). The manufacturing process consists of sub systems and the interaction of the components of the sub systems determine the outcome of the system as a whole (Stamatis 2003). The dynamic behaviour of the manufacturing process with the implementation of a quality programme is therefore to be studied in this research with the possibility of using system dynamics. To test theory with case studies, Johnston et al (1999) argue that any case study starts with theory and the development of research hypotheses.

Repenning and Sterman (2002) developed a theory based on system dynamics, to describe the interaction of allocating resource's time between process improvements and meeting production demands. This model is based on a polar type research design in an automotive manufacturing environment. One of the aims with this research is also to test this theory in a heavy engineering manufacturing environment. The research hypothesis is a dynamic hypothesis as described by Sterman (2000).

Key research questions	**Data sources**	**Data collection method**	**Data collection instrument**	**Level 2 field questions (Yin 2009)**
How can the dynamic behaviour of the manufacturing process be explained through system dynamics?	- Employees of the company - Historical data on production output - Historical reports on order in take	Interviews Document analysis	Interview schedules Voice recorder Prepared questionnaire Note book	- Why is there dynamic behaviour? - Factors with an effect? - Type of dynamic behaviour? - Effect of up steam and downstream processes? - Types of upstream and downstream processes? - Types of feedback loops? - Which elements define levels and rates?
How does the implementation of the quality improvement programme impact on the dynamic behaviour of the manufacturing process?	- Production and quality personnel - Historical data on quality reports - Historical data on quality improvement programmes	Interviews Document analysis Focus groups	Interview schedules Voice recorder Prepared questionnaire Note book White board	- What type of quality programmes have been introduced? - The effect of the quality improvement programme on the dynamics of the manufacturing process? - How was the quality improvement programme implemented? - Which resources were used for the implementation? - How long did the implementation take?
How do the soft issues impact on the dynamic behaviour of the quality improvement process?	- Management at different levels - Employees of the company - Company policies	Interviews Document analysis Observations	Interview schedules Voice recorder Company intranet Note book	- What was the reaction of the workforce upon implementation? - How was the quality programme rolled out to the work force? - Which channels of communication were used? - Did the workforce perceive any job losses? - What did management do to motivate the workforce? - Does the management demonstrate commitment? - What is the perception towards successful implementation? - How much learning has there been? - Has resources been competing for time?
How can system dynamics be used to model sustainability, after the successful implementation of the newly designed process?	- Management at different levels - Executives of manufacturing, finance and human resources - Production and quality personnel	Interviews Document analysis	Interview schedules Voice recorder Note book	- What does the organisation perceive sustainability to be? - What measurements are in place to monitor progress over time? - What methods and tools have been put into place after implementation? - Have these tools been used consistently over time? - What is the leadership's vision and goals regarding continuous improvement?

Table 4.1: Field research questions and instruments adapted from Rule and John (2011) for theory testing for this research

Key research question	**Data sources**	**Data collection method**	**Data collection instrument**	**Level 2 field questions (Yin 2009)**
How do the managers meet the requirements of the organisation?	- Managers of the organisation - Historical data on the quality improvement programmes	Direct observations Interviews Document analysis	Interview schedules Voice recorder Prepared questionnaire Note book	- What are the requirements of the quality improvement programme? - How are the requirements managed? - How motivated are the workers? - How successful is the training and development which was done as part of the quality improvement programme roll out? - How effective is the newly created organisational environment after the implementation of the quality improvement programme?
How do managers manage their time?	- Managers of the organisation	Direct observations Interviews	Interview schedules Voice recorder Questionnaire Note book	- How does the manager plan his day? - How does the manager's actual day turn out versus the plan? - What behaviour s do the unplanned activities create with the manager? - How much time does the manager plan to spend on the quality improvement programme each day or week?
How does the managerial effectiveness change with management pressure?	- Managers of the organisation's - Historical data on the quality improvement programmes	Direct observations Interviews	Interview schedules Voice recorder Questionnaire Note book	- How do managers manage a measurement deviation from the target of the process? - How does the manager's time allocation to the quality improvement programme change over time? - What unplanned activities prevent the manager to achieve his planned allocated time to the quality improvement programme? - How much do the organisational requirements change over time?

Table 4.2: Field research questions and instruments adapted from Rule and John (2011) for theory building of sustainability of quality improvement programmes – from a management support perspective

Sustainability of quality improvement programmes is a key issue identified in the industry and is therefore an indispensable factor (Curry & Kadash 2002). Recent research ((Buchanan et al 2005), (Bateman & David 2002), (Bateman & Rich 2003), (Zairi 2002)) proposed several different methodologies and practices to ensure sustainability of different types of quality improvement programmes. The theory developed by Repenning and Sterman (2002) tested in a heavy engineering manufacturing environment, has been expanded to model sustainability of a quality improvement programme in the heavy engineering manufacturing environment as demonstrated later in Chapter 6.

4.4.1.3 Unit of analysis

The unit of analysis or “case” for this research is defined by studying the dynamic behaviour of the manufacturing process in a heavy engineering manufacturing environment where quality improvement programmes have been implemented. From the literature overview it was clear that system dynamics could be used successfully in describing the structure and behaviour of a manufacturing process in the automotive environment (Repenning and Sterman 2002). A purpose with this research is also to test the applicability of system dynamics in a heavy engineering manufacturing environment.

The unit of analysis is therefore the structure and dynamic behaviour of a manufacturing process in a heavy engineering manufacturing environment with the implementation of a quality improvement programme in two instances. Firstly the first case study was done at the one manufacturing facility, where a six sigma (DMAIC) quality improvement programme has been introduced, in order to reduce the number of defects created by the machining processes. Secondly a second case study was done at a different plant of the same manufacturing company where a lean manufacturing programme has been introduced in the second manufacturing facility.

The unit of analysis has been carefully chosen in the different plants of the same manufacturing company where the implementation of a quality programme in the one plant has been a success but less successful in the other plant while the same executive was responsible for the implementation in both instances. See also (Eisenhardt 1989). The choice of these two case studies has contributed to the research into the sustainability of quality improvement programmes in a heavy engineering manufacturing facility.

4.4.1.4 Selecting the cases

Sustainability of quality improvement programmes is a phenomenon that challenges the industry (Jones et al 1996, Sterman et al 1996, Repenning and Sterman 2002, Keating et al 1999, Sterman et al 1997). The purpose with this case study was to test an existing theory developed by Repenning and Sterman (2000) specifically in a heavy engineering manufacturing environment and to expand the theory to include sustainability.

The dynamic behaviour of the manufacturing process, specifically the machine shop in the one manufacturing facility, was one of the case studies with the purpose to determine the parameters that describe the structure and behaviour of the manufacturing process. The theory developed by Repenning and Sterman (2002), has been tested with this case study for its applicability in the heavy engineering manufacturing environment. In the literature it is stated that “When a theoretical principle is supported in diverse replications, we gain confidence in the theory, and each successive test increases external validity” (Lucas 2003).

Morisson (2007) developed a system dynamics simulation model for the theory developed by Repenning and Sterman (2002) which simulated the interaction of the first – and second-order improvement loops. This simulation model has been fundamentally reconstructed and expanded for a heavy engineering manufacturing environment, with the model parameters determined from these case studies. Once this simulation model adequately simulated the manufacturing process, it has been developed further to predict sustainability by designing and testing policies that could sustain quality improvement programmes in a heavy engineering manufacturing environment, as explained later in detail in Chapter 7.

The dynamics associated with the implementation of a quality improvement programme in the manufacturing process, embedded in the holistic case of a heavy engineering manufacturing environment, was chosen as the unit of analysis. A six sigma process (DMAIC) has been successfully implemented in the machine shop during April 2010, in order to reduce the number defects produced in this department. Data for the last 3.5 years for defects measured by the quality process, has been available to construct the dynamic hypothesis of this particular quality improvement programme. This data also clearly illustrated the "before and after" picture from the impact of the six sigma quality improvement programme as well as the sustainability of the improvement programme 12 months after the initiation. Newly introduced policies and procedures were also available for investigating.

Another case study has been done in the other manufacturing facility, where lean manufacturing has been implemented. This manufacturing facility is overseen by the same executive but overseen by a different business unit manager. This programme has been rolled out with mixed results, being less successful. The second case study has been chosen specifically in line with a polar type design as described by Eisenhardt (1989) and also followed by Repenning and Sterman (2000).

The existing theory from Repenning and Sterman (2000) has been expanded to include sustainability of quality improvement programmes in a heavy engineering manufacturing environment, from data gathered during these case studies, which is discussed in detail in Chapter 6. The expanded theory included the required policies as well as other information for the decision rules, as discussed later in Chapter 7, to ensure long-term sustainability of quality improvement programmes in a heavy engineering manufacturing environment.

4.4.1.5 Field procedures, data collection plan and instruments

The unit of analysis has been the structure and dynamic behaviour of the manufacturing facility after the implementation of a quality improvement programme. The total layout of the manufacturing facility has been studied to be fully understood as well as the manufacturing process, mapping the flow of the product, interventions from management, quality and operators. The fit of the machine shop in relation to the bigger picture of the holistic case (heavy engineering manufacturing environment) was referenced to the organisational structure.

The case studies were completed in a real-life context, therefore the “dynamics” of the manufacturing facility such as, timing of the study relevant to month end, shifts that have been worked, leave schedules for the key agents in the study and production demand, have been taken into consideration.

The data collection plan included reviewing of current available data such as measurements for the defective units per unit produced (DPU), policies and procedures of the current improved process, information on visual measurements, minutes of meetings held regarding the improvement programme and vision and goals / strategy from the company's top management regarding quality improvement programmes. Confidentiality of the data was discussed upfront with the company's management in order to have a clear understanding in which data can be made available for public knowledge.

The data collection instruments that have been used were interview schedules which have been approved by the executive management. These interview schedules have been compiled in such a way to accommodate month-end schedules, leave schedules and production requirements. A voice recorder has been used in all the interviews to ensure that all the relevant information has been captured and to ensure that the interviewer concentrated on the interview to ask further relevant questions if required. The interviewer worked from a prepared questionnaire as a guideline but has not been limited to these questions only. The questions have been semi-structured interview questions. It has been a qualitative study with the purpose to test and build theory and therefore the questions varied with every interview, depending on how the interview progressed. The company intranet has also been used to down load company policies and procedures.

4.5 Summary

The research design and methodology have been described where the qualitative research design was preferred. A polar type case study design has been described as the preferred design, where the dramatic success or failure for the implementation of a quality improvement programme has been used for the selection of the cases. The unit of analysis has been described as the dynamics of a manufacturing facility where a quality improvement programme has been implemented.

The selection of the cases have also been explained in terms of the population of interest and sample cases based on their theoretical usefulness. The components of the research design have been discussed in detail which included the field research questions and instruments used during the case studies, applicable to both theory testing and theory building.

In the next chapter, the case studies and results are discussed in detail and which pertained to the theory testing of the theory developed by Repenning and Sterman (2002) in a heavy engineering manufacturing environment. In Chapter 6, which follows directly after the next chapter, the case study data and results for theory building, for a sustainability theory of quality improvement programmes in a heavy engineering manufacturing environment, are discussed in detail.

CHAPTER 5

THEORY TESTING THROUGH A QUALITATIVE RESEARCH DESIGN

5 Introduction

Organisations are challenged to provide the best return on investment for their shareholders. As Goldratt puts it: “The goal of the company is to serve the clients only as a means to the real task, serving the company's shareholders” (Goldratt 1990). This challenge has become increasingly more difficult today through globalisation of the market place. In order for companies to stay competitive in this global market, they should adapt to the changing market needs.

Companies quickly realised that to remain competitive they should introduce quality improvement programmes. Many quality improvement programmes such as quality circles, statistical process control (SPC), total quality management (TQM) and six sigma were developed in the manufacturing industry with the common goal to improve the quality of the product or service (Besterfield et al 2003). Oakland sums it up as follows “Any organisation basically competes on its reputation for quality, reliability, price and delivery, and most people now recognize that quality is the most important of these competitive weapons” (Oakland 2003).

The purpose with this chapter is therefore to test the theory developed by Repenning and Sterman (2002) for an automotive manufacturing environment, redeveloped and also briefly evaluated in Chapter 3, in a heavy engineering manufacturing environment. Typical causality is studied using one of the six sigma tools, a fish bone diagram, to study cause and effect. This tool does not allow the user to study and understand feedback from other factors in the improvement programme system, typically referred to as feedback causality. Generally the understanding is poor of the dynamic behaviour of the improvement programme system with the soft issues as factors of the system. System dynamics may improve this understanding.

The analysis phase of a six sigma improvement project uses design of experiments to study the influence of the different factors on the variability of the process output, while simulation is used in the design phase of the design for six sigma improvement project to predict the variability of the newly designed process (Ginn 2004). Quality improvement programmes in a heavy engineering manufacturing environment are not researched to the same degree as quality improvement programmes in an automotive manufacturing environment. Continuous improvement has its roots in manufacturing where the following methodologies have been developed, (based on a basic concept of quality or process improvement), lean manufacturing, six sigma, the balanced score card and lean six sigma (Bhuiyan et al 2005).

During this research, system dynamics has been used to study the dynamic behaviour of a quality improvement programme in a heavy engineering manufacturing environment as explained in more detail in Chapter 6 and 7 of this thesis. System dynamics originally started in corporate management applications and was later expanded into understanding the behaviour of urban development and even later to understand the behaviour of the World / Global crisis (Forrester 1989). Through systems thinking the six sigma project team may move away from the cause-and-effect thinking (fish bone diagram), and consider the causal interconnections in real systems. These causal interconnections are referred to as causal loop diagrams (Kaufmann & Chieh 2005). It is in these cases that system dynamics can serve a useful role in six sigma practise (Newton 2003).

In this research, the heavy engineering manufacturing environment is described as a jobbing shop in contrast to an automotive manufacturing environment which is described as continuous flow manufacturing. Most of the research on quality improvement programmes is done in an automotive manufacturing environment and related industries. A job shop is a typical shop where each output or each small batch of outputs, are processed differently (Meredith & Shafer 2011). Therefore the flow through the facility tends to be intermittent where large variation in system flow times typically occur. Typically each output takes a different route through the organisation, requires different operations with different inputs and hence takes a different amount of time to complete.

A research study by Sterman et al (1996) was launched to explore why initially successful improvement programmes often fail with the aim to design a sustainable improvement programme. This research was done on four different types of manufacturing industries ranging from the automotive industry to the electronic manufacturing industry in the United States of America (Sterman et al 1996), but a heavy engineering manufacturing environment was not part of this research study. Preliminary results from this study showed that even highly successful quality programmes can under certain conditions lead to short-run deterioration in financial results, and subsequent loss of commitment to the quality programme. The cause appears to be unanticipated consequences of successful improvement arising from feedback between quality programmes and other functions in the company.

Repenning and Sterman (2002) developed a theoretical dynamic model, based on system dynamics (SD), which has been developed in order to study the interaction of allocating of resources time between process improvement, and to meet production demands. This theoretical system dynamics model was designed from case studies through causal loop diagramming and stock and flow diagrams. The causal links were compared to existing studies to ascertain whether they are supported in the literature. These causal links formed the basis for the dynamic behaviour of the system. It is this theoretical system dynamics model, developed by Repenning and Sterman (2002), redeveloped and evaluated in Chapter 3, that is used in this study to test its validity in a heavy engineering manufacturing environment through a qualitative research design.

The research is focused on operational management of operations, specifically in the heavy engineering manufacturing environment. One of the strategies for this research is theory testing, as described in detail in Chapter 4, using case studies (Meredith 1998), (Johnston et al 1999), where the emphasis is on demonstrating causal relationships through logical argumentation (Hillebrand et al 2001). It provides an in-depth description of the theory developed by Repenning and Sterman (2002), testing the validity to a heavy engineering manufacturing environment. The data gathering methods are semi-structured interviewing, documentary resources and focus groups (Mouton 2001). All the interviews and focus group meetings have been digitally recorded and typed up. The case studies have been read by key members of the quality improvement team to ensure correctness and external validity.

Literature research was done to get more insight into quality improvement programmes such as six sigma, Total Quality Management (TQM) and others. See also Chapter 2 for more detail. The purpose of the literature research was to find previous work done on applications of system dynamics in quality improvement programmes. The literature research also gave insight into the application of quality improvement programmes and system dynamics in an operations management environment.

Another organising framework for this study was qualitative research where the purpose of this research has been to “get under the skin” of the organisation to find out what really happens and to carry out research into the processes leading to results (Gillham 2000). With the qualitative research design, the goal was to understand the situation under investigation primarily from the participant’s perspective through individual interviews and review of existing documents. The research questions addressed the fundamental question “How” of which the case study is the most appropriate method to be used. These research questions have been aligned with the research objective in order to answer the fundamental questions on validity of systems dynamics in quality improvement programmes in a heavy engineering manufacturing environment. Refer to Table 4.1 for a list of level II field questions, data sources and instruments. The unit of analysis or case for this research was defined by studying the dynamic behaviour of the manufacturing process in a heavy engineering manufacturing environment where quality improvement programmes have been implemented.

During the analysing phase the data has been coded to move methodologically to a slightly higher conceptual level. Items that seemed to be essentially similar have been assigned the same code. The codes used in the process have been derived from the theory developed by Repenning and Sterman (2002) and developed here in association with the different settings in the two case studies. The higher conceptual level was the enabler to sort the items into similar groups which gave more insight into them. This sorting method has been summarised into a matrix format. Refer to Appendix A for the matrix of the coding data.

The sources of the data for the case study are semi-structured interviewing (individual) and use of documentary sources and other existing data. The case study database was constructed from this data as well as from notes and direct observation. Information and insight gained from case studies could influence policy, procedures and future research (Merriam 2001). The research design used in this study has been a polar type research design where the case study focused on initiatives that were dramatic successes or failures, with the expectation that their comparison would help identify those processes that prevent competence enhancing change (Eisenhardt 1989).

In the case studies presented in this research, two cases have been identified where the implementation of the one quality improvement programme has been less successful than the implementation of the other quality improvement programme. However, in both instances the same executive has been leading the implementation of the two different quality improvement programmes.

The first case study, done in the machine shop in the one manufacturing facility, is explanatory of one of the more successful implementations of a quality improvement programme. The second case study, done in the manufacturing and assembly plant of the second manufacturing facility, is explanatory on one of the less successful implementations of a quality improvement programme as recalled by the operational excellence manager,

> “The wave *[implementation]* in the machine shop has been more successful than in the manufacturing and final assembly”.

The Operational excellence and 6S continuous improvement status report, *[operational excellence implementation measurement report],* contained in the case study database[1], confirmed this statement.

Also refer to Table A.1and Table A.2 in Appendix A for the coding matrix used during the case studies to conduct the theory testing for validity in a heavy engineering manufacturing environment. The case studies have been read by key members of the quality improvement team to ensure correctness and external validity. Data gathered during the interviews has also been triangulated with evidence gathered during plant visits and archival data.

5.1 Case study Background

Quality improvement programmes in a heavy engineering manufacturing environment are not researched to the same degree as quality improvement programmes in an automotive manufacturing environment. In the heavy engineering manufacturing environment, production is typically depicted by low volume high value. The manufacturing director recalled,

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[1] The case study database is available upon request from the author

> "In terms of our kind of business, you are looking at low volume, high specialisation, high differentiation ..."

The heavy engineering manufacturing environment used in this study is a global heavy engineering manufacturing company, with manufacturing facilities around the world. It is a 3.284 billion dollar Fortune 1000 company (2010), currently listed on the New York stock exchange. The company serves the mining sector globally and manufactures underground as well as surface mining equipment for coal, iron ore and related minerals extraction.

The company has rolled out globally an operational excellence quality improvement programme as well as six sigma quality improvement programmes. Refer to Appendix D for a schematic diagram of the time line for the operational excellence programme. The roll out process is encapsulated as part of their Global Business System. Their Global Business System is based on Operational Excellence with specific focus on people, continuous improvement, process focus and plan and measure.

This research was done in the South African subsidiary situated in Gauteng, South Africa. The operation in South Africa has two major manufacturing facilities on the east rand in Johannesburg, servicing the surface as well as the underground mining industry in Africa as well as globally, exporting selected underground mining equipment to the rest of the world. The South African subsidiary is quite large with over R 2.6 billion sales per annum.

5.2 Compiling case studies for theory testing

The research focused on two case studies. The field research was performed in two divisions of the South Africa-based heavy engineering manufacturing company. The global quality improvement programme has rolled out in these facilities as part of the second implementation of the global roll out of their Global Business System. The South Africa-based company is quite large with over 2.6 billion Rand sales per annum. These two divisions are on different locations and are big enough to have their own unique organisational behaviour. Both these programmes have been rolled out under the supervision of the same executive. The implementation of a quality improvement programme, embedded in the holistic case of the heavy engineering manufacturing environment, was chosen as the unit of analysis.

During the analysing phase the data has been coded to move methodologically to a slightly higher conceptual level. Items that seemed to be essentially similar have been assigned the same code. The higher conceptual level was the enabler to sort the items into similar groups which gave more insight into them. Refer to Table A.1 and Table A.2 in Appendix A for more detail on the coding matrix.

Case study one was done in the machine shop. The roll out of the operational excellence programme started in September 2008 with class room training and identifying the goals and objectives for the quality improvement team. The team focused on productivity increase, cycle time reduction and improved space utilisation. The supply chain has also rolled out initiatives to improve the flow through the machine shop through the reduction of picking cycle time for raw material and improved layout of the raw material yard. All these initiatives were based on lean methods which form part of the foundation of their Global Business System. Reduction of the seven types of waste was also part of the lean methods where defects have been one of the seven types of waste. The manufacturing director recalled,

> “There are various elements to operational excellence … TIMWOOD, where D is for defects. Thus we have utilised six sigma to deal with the defects part of it”.

A six sigma process (DMAIC) has therefore been successfully implemented in the machine shop during April 2010, in order to reduce the number defects produced in this department. Data for the last 3.5 years measuring the defects from the machining process is available on their business management system to construct the dynamic hypothesis of this particular manufacturing process. This data also clearly illustrated the "before and after" picture from the impact of the six sigma quality improvement process. Newly introduced policies and procedures were also available for investigating.

Case study two was done in the assembly and manufacturing plant of the second manufacturing facility, where lean manufacturing as part of the operational excellence has been implemented as part of the roll out of their Global Business System. This manufacturing facility is also overseen by the same executive but with a different operations manager. This programme has been rolled out less successfully with mixed results as reported by the Opex manager *[operational excellence manager]*. The second case study has been chosen specifically in line with a polar type design as described by Eisenhardt (1989) and also followed by Repenning and Sterman (2002) for an automotive manufacturing environment.

The global roll out started in 2007 when the president and COO of the company announced the initiative as part the organisation's new Global Business System. The message "taking *[the company]* to the next level, is to become operational excellent". The programme encapsulated manufacturing excellence, service excellence and supply chain excellence with engineering excellence being in the centre of it all. The initial phases of the quality improvement programme have primarily focused on the manufacturing excellence part.

The president and COO further introduced the goals and objectives of the programme as follows,

> “..The six main goals of the programme are safety, velocity (reduce cycle time), productivity, quality (flawless execution in everything we do), capacity and customer satisfaction. The focus of the programme is on lean manufacturing and will be rolled out with dedicated resources..., technical training and skills development.., model plant transformations and JOE *[kaizen]* events ...”

The quality improvement programme's focus was to remove waste from the business processes through the reduction of the 7 wastes (TIMWOOD) which are defined as Transportation, Inventory, Motion, Waiting, Overproduction, Over processing and Defects (Besterfield et al 2003). Dedicated personnel was identified from each of the businesses around the world to be trained as the core team members and then to roll out the quality improvement programme globally to each and every manufacturing facility around the world.

5.2.1 Case study 1 – machine shop

Another model plant roll out was done in the machine shop of the other manufacturing facility, which formed part of the roll out of operational excellence. The quality improvement programme was started in September 2008 with specific focus to improve the manufacturing cycle time in the machine shop. The programme focused on the following areas for improvement, production, production support and supply chain. The goals and objectives for the machine shop quality improvement programme were to increase capacity utilisation by 17.5% by reducing manufacturing cycle time and improving productivity. The second objective was to improve supply chain performance by efficient raw material delivery to the shop floor.

The production demand on the machine shop was not clearly visible to all the stakeholders in the component manufacture value stream. The productivity was found to be only 66% mainly due to unbalanced loading and set-up times. Kaizen events were held to introduce 6S and to determine the optimum plant layout. The outcome from the Kaizen was machines that were moved, WIP (work-in-progress) racks installed and WIP stock consolidated into racks. Enough space was freed up to accommodate two more machines.

A contributing factor to the low productivity of 66% was found to be a lack of communication. Visual production management boards were installed at the working cells as well as a departmental board. The technical manager recalled,

> "We use the departmental performance management board to discuss our problems and to look forward for our production demand. We also have cell performance boards where there are regular meetings at the board to discuss production related problems and what we have to do for the day."

The visual communication improved the production planning in the machine shop which created a balanced production. Through the visual performance management board, the business unit manager could see where the bottlenecks were in his process and therefore pro-actively sub contract to create capacity. He recalled,

> "When it comes to production requirements and the load exceeds the capacity, I need to look at outsourcing to balance my load".

From a production support point of view, the improvement project investigated the condition of the raw material as supplied. The improvement project reduced the machining cycle time by introducing pre-machined castings and forgings, introducing set up reduction and developing a single supplier for the heat treatment process. One of the operators recalled,

> "...the morale of our team has been taken to the next level and it is visible with the improvement in our production throughput..."

In-line inspection was introduced into the machining process with the goal to detect a defect early in the manufacturing process. The challenge has been to create ownership for quality at operator level and move the emphasis from quality-to-inspect to operators taking responsibility for quality. Operators were trained on measurement methods through internal as well as external trainers. The business unit manager commented about the success of the training as follows,

> "People started taking ownership of the work they perform...the ownership is with the operator to do it correctly the first time."

The management team realised that the focus of operational excellence also included defects as part of reducing the seven wastes. The general perception about operational excellence was that it is about improving housekeeping through 6S. The business unit manager recalled,

> "Opex *[operational excellence]* has been only about 6S and not about reducing defects".

The manufacturing executive also recalled,

> "So far the programme has mainly been focussing on 6S and some process flow changes that improved the cycle time, but not much on the defects part. So we have utilised six sigma to deal with the defects part of it".

The machine shop has been haighly disciplined in using the management information system and hence recorded all the defects in the management information system utilising the quality notification process. Very good records therefore existed for the cost of quality for the machine shop. Through this system the production team used to "... try and track the defect at the origin of the defect" as recalled by the business unit manager. A six sigma project was launched in late 2009 under the leadership of the quality manager. A cross-functional team was put together and put through six sigma training. Pareto analysis and Ishikawa diagrams were some of the tools used by the team to identify the root cause of the defects. The quality manager recalled,

> "We follow the complete methodology of six sigma that is plan, do, check and act". The improvement project focused on the bevel gear manufacturing where the root cause turns out to be the turning operation".

Visual measurements tracking the defects per unit were created as well as a six sigma quality performance board. These measurements have been done on a monthly basis and shared with the production team. The technical manager recalled,

> "Every morning we have a board meeting where we discuss quality".

These measurements have been discussed at the departmental visual performance board on a monthly basis. All machine operators were put through a training programme on Metrology. The variability due to the gauge being used, decreased significantly. Other improvements include updated operating method sheets for the operators and inspection and verification of the geometry of the CNC lathes.

The implementation of the programme was very successful with a significant reduction in the defects over time reducing from 2.59% to 0.76%. The quality manager commented saying,

> "The programme was very successful...even now we are sustaining the improvement"

The quality inspector recalled,

> "We noticed all the defects reduced at that machine...I found he *[the operator]* was following the new operating method sheet".

The machine shop still continues with continuous improvement of their related processes even after the implementation of the global quality improvement programme is complete. The technical manager commented as follows,

> "...not taking ownership in quality... we are trying to move that mind-set that quality belongs to the operator... I am trying to put a system in place where the activity goes to the actual operator performing that specific task. That is currently my biggest aim."

The business unit manager commented on the question if the implementation has been successful,

> "Absolutely yes" and recalled "People started taking ownership of the work they perform "

5.2.2 Case study 2 – manufacturing and assembly plant

The quality improvement programme in this area of the business was rolled out in October 2007 as the next implementation of operational excellence in the manufacturing and assembly plant in the second manufacturing facility. The specific goals and objectives for the implementation in the manufacture and assembly of the underground mining equipment have been to increase the capacity by one underground mining machine per month, to reduce the assembly hours per underground mining machine by 10% and to improve the supply chain performance for better parts availability and delivery to the manufacturing and assembly lines. The focus was to improve the overall cycle time of the value stream of the underground mining machines.

During the executive report back on the status of the implementation in February 2008, the team reported that the cycle time in fabrication reduced by 13%. However, the improvement could not be sustained. During the interview the business unit manager said,

> "...you can do it once off, but never prove they could sustain it...I do not believe they have done what operational excellence *[the quality improvement programme]* could have achieved at that stage."

Other improvement initiatives in the supply chain also showed improvement in the overall supply chain process. However, parts availability for the assembly line did not increase significantly. The business unit manager commented,

> "...the programme that was implemented was supposed to address some of those issues...the supply chain issues do not get solved overnight...I do not think we will have everything in time to build the machine in time."

The implementation of the global quality improvement programme as part of operational excellence in supply chain started in February 2009. The goals for the supply chain initiative were driven from a global perspective and not aligned with the local objective to focus the improvement of the manufacturing and assembly of the underground mining machines. One of the managers responsible for the roll out of the quality improvement programme commented as follows,

> "There had been limited success, but the goal to reduce the cycle time of the mining machines was never achieved ...the goals for the supply chain were determined by the global supply chain and not by the local improvement team...even today the shortage on parts is still an issue"

The start of the value stream for the manufacture and assembly of the rebuild underground mining machines started at the tear down area. The goal for the tear down kaizen was to reduce the cycle time to 10 days. The improvement programme was rolled out with success to an extent. The cycle time did reduce and also a reduction in travel time of 200 metres was realised. Apart from the travel time, the improvement in cycle time reduction could not be sustained. A visual measurement system was implemented, but failed after a while. This section had to work extra hours to make sure that the flow of the value stream was not interrupted. The business unit manager commented as follows,

> “Previously when people were achieving 10 days, they were working excessive overtime”

The fabrications department is responsible to manufacture all the main components for the underground mining machines, which get assembled onto the machine in the assembly department. The goal for the quality improvement programme was to improve the cycle time with 25%. During the implementation of the quality improvement programme, the plant layout was changed to improve the flow and reduce travelling time. 6S initiatives were also rolled out. Limited success has been achieved with the cycle time reduction as reported out by the operational excellence team in February 2008. Apart from the improved plant layout, none of the other improvement activities have been sustained. The business unit manager recalled,

> “The complete process was not improved; only that one step in the process”

The team leader commented as follows,

> “I had to speak to *[business unit manager]* and tell him, we need the parts to make the target dates...I will start to prepare for the frame, but then I do not have the parts...”

The final assembly is where all the parts get together to be assembled into the underground mining machines. As part of the quality improvement programme roll out, a model plant was also created in the final assembly. 6S has been introduced with success and is still sustained today through frequent audits and reports to the global organisation. The implementation of lean initiatives to reduce time travel and supply of common parts has been introduced through changing of the plant layout. However, the supply of parts to the assembly process was still a problem. The one business unit manager commented,

> "The only real improvement we can see is the house-keeping of the shop..."

The programme has been rolled out initially to improve the cycle time of the underground mining machines value stream. During the initial implementation the value steam approach has been followed but as time passed the improvement initiative has been mainly focusing on 6S. Comment from participants in the process follows,

> "Tools have not really been used over time other than 6S"

The roll out of the quality improvement programme was less successful than the roll out in the machine shop. A regular monthly audit done by the operational excellence manager on areas where the quality improvement programme has been implemented, confirm this with the following comment,

> "The implementation in the machine shop is more successful ...improvements that have been introduced are still being used and the queries from the supply from the machine shop are less"

5.3 Discussion of the results determined from the case studies

In this section the results obtained from the case studies, as described in section 5.1 and 5.2 of this chapter, are discussed and explained relative to the theory developed by Repenning and Sterman (2002) for quality improvement programmes in an automotive environment. One of the aims of this research has been to test the validity of the theory developed by Reppening and Sterman (2002), in a heavy engineering manufacturing environment.

From a systems thinking perspective, the results from these case studies have to be read in conjunction with Figure 3.3, Stock and flow diagram with reinforcing feedback loops. Reconstructed from Repenning and Sterman (2002). The results for case study 1 for the machine shop and case study 2 for the manufacturing and assembly plant are now discussed in section 5.3.1 and 5.3.2 respectively.

5.3.1 Case study 1 – machine shop

The quality improvement programme introduced in the machine shop primarily focussed on cycle time reduction on machine parts through the machine shop, the efficient supply of parts to the work centres and improving productivity. Another focus area was the reduction of quality defects.

Although the quality improvement programme required resources for the improvement, the production team balanced the work load in order to free up resources for the improvement programme. The technical manager commented as follows,

> “We would take one operator out of the section and balance between production requirements and quality improvement programme requirements. We value the quality improvement programmes very highly...”

Machines that require process experimentation are made available to ensure the machines are producing at the correct level of accuracy. The business unit manager commented as follows,

> "I cannot just carry on producing and therefore have to stop the machine...The operator is moved to the quality inspector to help there for a couple of days."

Resources have been made available for both these focus areas. Overall the implementation of the quality improvement programme in the machine shop has been the most successful. The operations excellence manager commented as follows on the success of the implementation,

> "Out of the three programmes *[including supply chain excellence]*, the machine shop has been the most successful."

All operators received training on Metrology and selected operators were included in the six sigma project where they also received training on six sigma tools. The business unit manager commented as follows,

> "...I will rather see if I can fix the problem and take the operator and train him further if that is what it is required. I have invested a lot of time and money in that skill"

Machining centres were also made available for maintenance to conduct machine capability studies. Alternative production planning was put in place in order to overcome the short fall in resources. The business unit manager commented on the question on how to do quality improvement as well as meet the production demand,

> "When it comes to production requirements and the load exceeds the available capacity, I need to look at outsourcing to balance my load."

The frame work followed by the machine shop as depicted in Figure 3.3 is the work smarter loop (B3). Resources are allocated to improve the process through training and process experimentation. Process problems are reduced through six sigma tools such as Ishikawa diagrams for root cause analysis, SPC charts and control charts. The quality manager recalled,

> "We used the Ishikawa diagram, MSA analysis and Pareto chart."

Due to these six sigma tools the root cause for the machining errors were identified and hence the process problems were addressed with therefore a reduction in defect introduction rate as indicated by the work smarter loop (B3) in Figure 3.3. The stock of defects (machining errors) started reducing with long-term gains in defects reduction.

5.3.2 Case study 2 – manufacturing and assembly plant

All the improvement activities were focused on the implementation of the quality improvement programme, which is to reduce the cycle time of the underground mining machines in manufacture and assembly. However, the focus of the supply chain improvement activities were driven by the objectives from the global supply chain organisation. The supply chain excellence goals were communicated in the implementation report out in September 2009 as follows,

> "On time and on specification ...increase in material productivity...and increase in material velocity"

The operations excellence manager recalled,

> "...the supply chain initiative was not very successful...There have been certain successes, but none of these improvements made an improvement on the *[underground mining machines]* reduction in cycle time. The problem was that the goals were prescribed by the global supply chain function and not the team".

The improvement team was directed to allocate resources to correct the defects (Refer to Figure 3.3 for the output rate of defect correction), where the defects in this instance have been the poor performance of the fulfilment of the orders from the suppliers and excess inventory. The allocation of resources to the rework loop (B2) reduced the effort of the team to work on the improvement project depicted by the work smarter loop (B3) - to investigate the supply chain process applicable to the underground mining machine's value stream. This activity would have led to a decrease in problem correction as depicted in Figure 3.3. The supply chain personnel therefore had to increase their effort, work harder loop (B1), to close the gap in the parts supply and hence have the correct parts delivered to the value stream. During the direct observations it became clear that the material requirement planners had to make special interventions and hence increased efforts to expedite parts in an effort to fulfil the order requirements.

The quality improvement programme in fabrications also suffered from the spin off from the above frame work. Special effort has been taken by the team to have parts ready during the training and process experimentation in the fabrications shop to reduce the cycle time. Special intervention was needed but could not be sustained. The business unit manager recalled,

> "They *[improvement team]* claimed that they could achieve certain results...you can do a once off, but they never proof they could sustain it".

The workers in the fabrication shop had to increase their worker effort, depicted by the work harder loop (B1), to achieve the goals as per the improvement project. The team leader recalled,

> "...I achieved it but I had to work without breaks."

There is also a lot of pressure on production, (depicted by focus on throughput loop (B4)), which has a negative effect on the improvement programme (depicted by training and process experimentation which is part of work smarter loop (B3)) in the section. The team leader made the following comment about rolling 6 S out to the rest of the section,

> "... we tried the first week and the second week and then they stopped..."

Allocating resources to training and process experimentation has a negative impact on gross process through-put (Repenning & Sterman 2002).

Increase in defect introduction (poor on time delivery) generated by the supply chain introduced more defects (on time delivery) in the fabrication section which in turn introduced more on time delivery problems (defects) into the underground mining machine value stream. The business unit manager recalled,

> "...if all the information and parts are not available to the people that are supposed to give me the finished product, I sit with the rework."

The production team has to close the throughput gap and therefore resources are allocated to correct defects which will increase the effort to correct defects, following rework loop (B2). The improvement in the net process throughput was realised over a much shorter period. The production team saw the benefit and claimed success in their management decision.

The improvement was short term due to the fact that the process problem, late delivery due to supply chain process problems, were not solved and hence defect introduction (or late delivery of parts) would continue. To counter the shortfall in the delivery lead time, the assembly team increased their worker effort through over time, as depicted by the work harder loop (B1). To reduce the poor on time delivery performance of the machines, resources should be allocated to improve the process, as depicted by the work smarter loop (B3). The operational excellence manager recalled,

> "It is a value stream issue; our planning for the machines and parts does not meet up."

The flow of parts to the final assembly were not fully synchronised within the value stream. The business unit manager recalled,

> "The main frame delivery will extend with one month...the problem is now that the parts are sitting all over because we have already picked it."

Also another worker recalled,

> "We just do not get to the point when we get the item on time according to the quality we need ..."

Process problems in the supply chain created defects downstream that created further rework and defects. The following comment came from the one employee in the value stream,

> "...if all the information and parts are not available ...I sit with the rework. We got very little control over my productivity, or my cost ..."

This organising frame-work is typical as described by the rework loop (B2) in Figure 3.3.

A kaizen was initiated by the operational excellence manager to create a value stream map of the assembly process but half way through the session, the production manager called back the workers to complete urgent orders for month end. The operational excellence manager recalled,

> "I started a session with the team from the final assembly to draw up a value steam map, but we had to stop half way into the session. The team had been pulled back to their work stations due to machines that had to be built urgently..."

Resources from the assembly team have been co-opted to help with the improvement initiative, but the programme was interrupted half way due to machines that had to be assembled urgently, as depicted by the focus on throughput loop (B4). The value stream mapping effort or (training and process experimentation) suffered and hence process problems continued to cause defect introduction.

5.3.3 Discussion of the results for the re-investment cycle

Ever increasing worker effort was apparent in the manufacturing and assembly plant through the workers working harder, but in spite of the increased effort of the workers, the defect (on time delivery) did not improve. More resources were allocated to correct the poor on time delivery performance with only short-term results. However, the production managers were happy with their decisions due to the immediate improvement they saw in expediting the parts.

Due to the nature of the re-investment loops (R1a and R1b in Figure 3.3), the cycle was trapped in a vicious cycle. The more resources were allocated to correct the defects, working harder expediting parts for example, the less time was available to allocate resources to improve the process. The root cause of the supply chain problems was not solved and hence the rate of defect introduction increased. The cycle repeated itself as a vicious cycle.

However, the decline in the machining errors in the machine shop, since the introduction of the quality improvement programme, was due to the frame work of the virtuous cycle. Resources were made available through the quality improvement programme continuation after the successful implementation of the quality improvement programme by operational excellence. The technical manager recalled,

> “There was a massive improvement and it was proven by the stats *[data]* pulled out from SAP. I would like to see it rolled out to the other machines as well...”

Process problems were declining due to improvement activities that drove the root cause analysis process of the machining errors which in turn reduced the number of defects. More resources became available to be allocated to more training and process experimentation, (as depicted by the work smarter loop (B3)), for yet another quality improvement programme to be reducing defects. The cycle repeated itself as a virtuous cycle.

5.4 Summary

Case studies, for two different manufacturing facilities where quality improvement programmes have been implemented, were described. The one case study was done on the successful implementation of a quality improvement programme while the second case study was done on a less successful implementation with mixed results. The theory developed by Repenning and Sterman (2002) and fundamentally reconstructed, was demonstrated through these polar type case study design, to be valid in a heavy engineering manufacturing environment, through logical argumentation.

Following the discussion of the results from these case studies, it was clearly demonstrated that the theory has been theoretically generalised for a larger population as previously proposed in the literature (Hillebrand et al 2001). The validity has been proven by demonstrating causal relationships through structural and logical argumentation as proposed by Hillebrand et al (2001).

The different balancing loops in the system dynamics model proposed by Repenning and Sterman (2002) and fundamentally reconstructed in Figure 3.3, were clearly demonstrated through semi-structured interviews and direct observation. The re-investment loops were also demonstrated where evidence of virtuous and vicious loops are found from data gathered during the semi-structured interviews and direct observations.

One of the aims for this research was to test the theory, developed by Repenning and Sterman (2002) for an automotive environment, to be valid in a heavy engineering manufacturing environment. This is one of the contributions of this research. The conceptual model of a quality improvement programme, fundamentally reconstructed from Repenning and Sterman (2002), and proven to be valid for a heavy engineering manufacturing environment, has become the base line structure for the later development of a theory for a sustainable quality improvement programme in a heavy engineering manufacturing environment.

In the next chapter, the theory developed by Repenning and Sterman (2002) and fundamentally reconstructed in Figure 3.3 and valid for a heavy engineering manufacturing environment, has been redeveloped and expanded to include sustainability from a systems thinking perspective, of quality improvement programmes in a heavy engineering manufacturing environment. During the next chapter this theory for sustainability has also been further developed to a system dynamics simulation model to simulate the dynamic behaviour of this quality improvement programme. The simulation has been done by means of Vensim®, a computer simulation program designed to simulate system dynamics models.

CHAPTER 6

SUSTAINABILITY -THEORY BUILDING THROUGH A QUALITATIVE RESEARCH DESIGN

6 Introduction

In Chapter 5, the theory developed for quality improvement programmes in an automotive environment by Repenning and Sterman (2002), has been proven to be valid for a heavy engineering manufacturing environment. The theory developed by Repenning and Sterman (2002) has been fundamentally reconstructed to be used as a baseline structure for the development of a sustainability theory for quality improvement programmes in a heavy engineering manufacturing environment. The purpose of Chapter 6 is to (a) develop a theory of sustainability for quality improvement programmes in a heavy engineering manufacturing environment from a system thinking perspective and (b) to develop this theory further to create a system dynamics simulation model to simulate the dynamic behaviour of a quality improvement programme in a heavy engineering manufacturing environment.

In section 6.1 of this chapter, the reference mode has been drawn from time series data gathered from the polar type case study design pertaining to the dynamics for the implementation of a quality improvement programme. The dynamic hypothesis, based on this reference mode, has also been discussed from which the theory from a systems thinking perspective for sustainability of quality improvement programmes, has been developed. The same research design, as already discussed in detail in Chapter 4, has been used during the theory building described in this chapter. Refer to Table 4.2 for the field research questions and instruments used during the polar type case study design as well as Table A.3 and Table A.4 in Appendix A for the coding matrix. During the analysing phase the data has been coded so that items that seemed similar have been assigned the same code.

In section 6.2 of this chapter, the system dynamics simulation model for a quality improvement programme from a simulation perspective, is discussed in detail. In this section, the dynamic impact of soft factors such as management support and management pressure are also discussed. An analogy has been drawn between a capacitated delay structure and management support. The system dynamics structure for the rework loop, applicable to a heavy engineering manufacturing environment, has also been developed and discussed in detail.

In section 6.3 of this chapter the results of the dynamic simulation have been discussed and analysed in detail. The results which have been discussed and analysed are, (a) the results demonstrating the dynamic behaviour of the quality improvement programme, demonstrating the tipping point in the system as previously discussed in Chapter 3 of this thesis and (b) the simulation results demonstrating the dynamic impact of the sustainability loop. The exponential decay, clearly visible in the results, satisfied the dynamic hypothesis developed in section 6.1 of this chapter.

The development of the theory for sustainability of quality improvement programmes, has been grounded in the literature. Buchanan et al (2005) defines sustainability as follows; " sustainability implies that new working methods and performance levels persist for a period appropriate to the setting" The authors further postulate that sustainability is about the stability of work methods, where work methods in this study referred to the work methods associated with the operational excellence and six sigma quality improvement programmes. They further postulate that sustainability could also be the consistent achievement of performance goals and may also apply to the maintenance of the consistent trajectory of performance improvement which inherently implies consistent measurement of the improved process.

Buchanan et al (2005) identified eleven factors affecting sustainability in their research, which were already discussed in Chapter 2. The factors highlighted in this research were managerial (style and behaviours), leadership (vision and goals) and processual (implementation methods). The management and leadership aspect is indicative of management support of the quality improvement programme while the implementation methods refer to the tools used to implement the quality improvement programme and the long-term use thereof. Bateman and Rich (2003) found a lack of resources to be an inhibitor for sustainable process improvement programmes which was also the centre of the study of Repenning and Sterman's (2000) systems dynamic model of a quality improvement programme in an automotive environment.

Zairi (2002) proposed a model that led to continuous improvement of processes, products and services and employee fulfilment. One element of the model is sustainable performance of which measurement is an important aspect. Another element of the model is process management practices that bring forth incremental improvements, which inherently means a culture of continuous improvement. Committed and involved management to provide organisational support and performance measures for the improved process were two of the important factors identified for sustainable quality improvement programmes (Besterfield et al 2003).

Measurement of the improved processes as well as effective usage of the quality improvement programme tools (consistently over time), with management support, were identified in this research as key possible elements for sustainability of the quality improvement programme (operational excellence and six sigma) implemented in a heavy engineering manufacturing environment as part the company's global business system. During this research, these two key elements have been further expanded in theory building grounded in literature.

6.1 Theory building for sustainability of quality improvement programmes

6.1.1 Conceptual theory for management feedback

Management decision making is a process of converting information into action and therefore management success depends primarily on what information is chosen and how the conversion is executed (Morecroft & Sterman 1994). This is a framework in its simplest form of an information-feedback system. Information is the input to the decision-making point that controls action which in turn yields new information. The decision is based on the state of the system. Refer to Figure 6.1 for a schematic diagram of the decision and information feedback loop adapted from Morecroft and Sterman (1994).

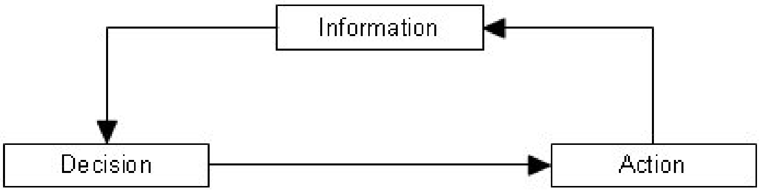

Figure 6.1: Decisions and information feedback loop. (Morecroft & Sterman 1994)

Decisions are determined by decision-making rules which are policies and protocols specifying how the decision maker processes available information which governs the rates of flow in systems. Decisions are therefore the result of applying decision rules to the available information cues, where these cues are generated by measuring and reporting processes, in the physical and functional structure of the system (Sterman 2000:515). Refer to Figure 6.2.

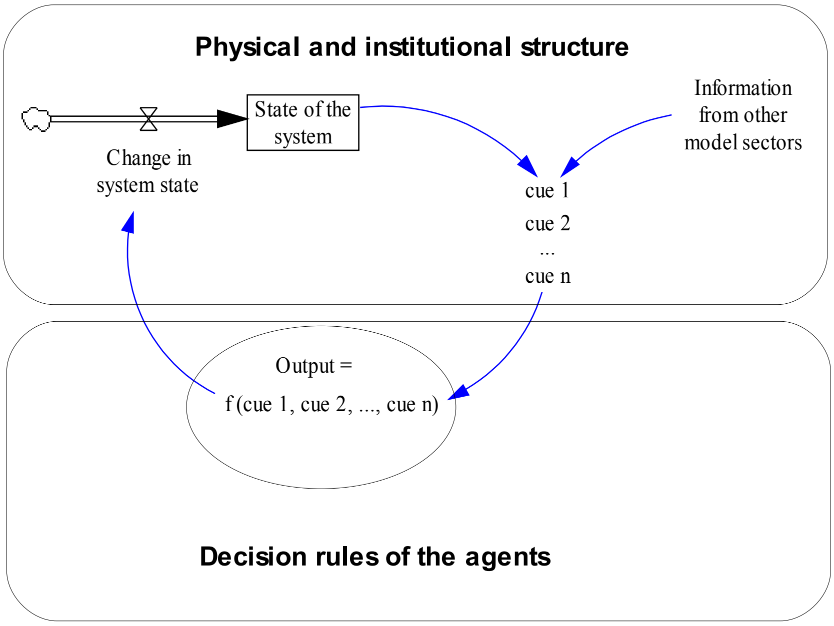

Figure 6.2: Decision rules adapted from Sterman (2000)

Measuring processes are one of the key elements of successful implementation and sustainable quality improvement programmes by controlling in process performance using measures such as defect reduction and control charts (Brassard et al 2002). Measurements are a fundamental part of the continuous process improvement cycle, which is based on the Deming cycle of plan, do, check and act. Refer to Figure 6.3. During phase 5 – Study the results, have the objective of monitoring and evaluating the change by tracking and studying the effectiveness of the improvement efforts through data collection and progress review. The ongoing measurement and evaluation efforts may lead to continuous improvement (Besterfield et al 2003).

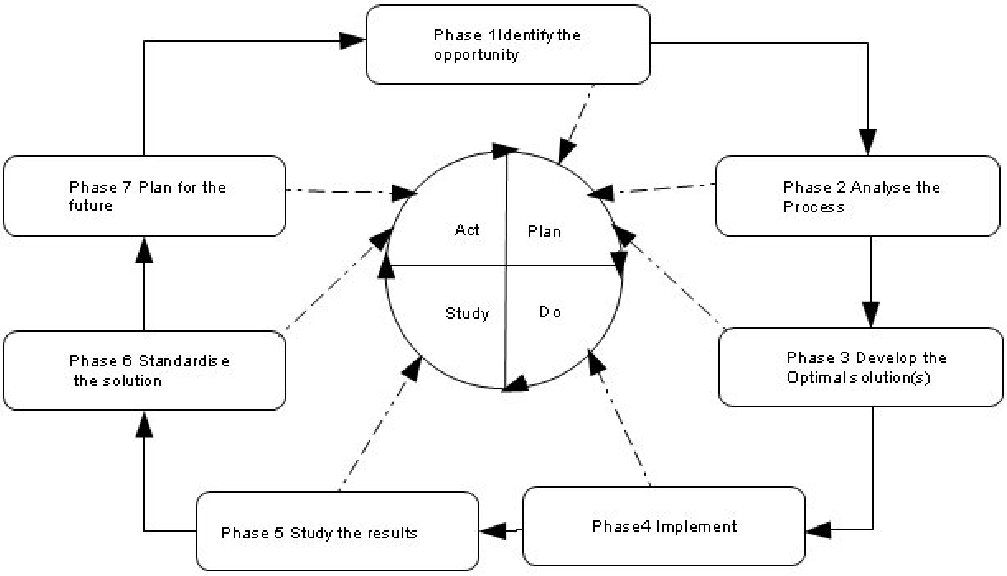

Figure 6.3: Continuous improvement cycle adapted from Besterfield et al (2003)

The measurement process creates a feedback loop in the system, between data gathered from the output from the actions taken during the quality improvement programme, from the decision making process, to eventually changing the state of the system.

These measurements are discussed by the different teams and management during the departmental meetings and cell board meetings as depicted typically by operational excellence and lean six sigma quality improvement programmes (Brassard et al 2002:221). During these discussions the measurements are compared to the original goals and objectives determined at the implementation of the quality improvement programme.

When the actual measurements deviate from the goals and objectives for the relevant processes, the team and management discuss corrective actions aimed at the root causes that could close the gap between the actual measurements and the original goals and objectives.

Different measurements are used during the implementation of typical quality improvement programmes such as six sigma, lean six sigma and lean (Brassard et al:204). Run charts are one such measurement which enables the team to study the data for trends and patterns. Process sigma is another measurement method which measures process performance from the customer's perspective by demonstrating the variation relative to the customer or target specification. The process sigma value is based on the defects per million opportunities (DPMO) where a high process sigma value depicts a high process performance with less variation and a low process sigma value depicts a low process performance with more variation (Meredith & Shafer 2011:147).

6.1.2 Reference mode of the dynamics for the implementation of a quality improvement programme

The reference mode, associated with the dynamics for the implementation of a quality improvement programme in this research, is displayed in Figure 6.4. The reference mode describes the dynamic behaviour of the impact of the implementation of a quality improvement programme in the machine shop. The data for the reference mode has been gathered from archived data and semi-structured interviews during the polar type case study design. Refer to Chapter 4 for more detail. The data in Figure 6.4 is a graphical representation of the number of defects per unit produced in the machine shop where the units are representative of the components manufactured. The components manufactured varied typically from gear box housings, gear blanks to pins and bushes. This is typically what one would expect from a jobbing shop manufacturing environment.

The reference mode is measured in defects per unit and the time horizon is sufficient to demonstrate the dynamics associated with the quality improvement programme, before the implementation as well as after the implementation of a quality improvement programme such as six sigma. A six sigma quality improvement programme was successfully implemented and rolled out from May 2010 in the machine shop. The behaviour of the defects per unit approaches exponential decay from May 2010 up to December 2010.

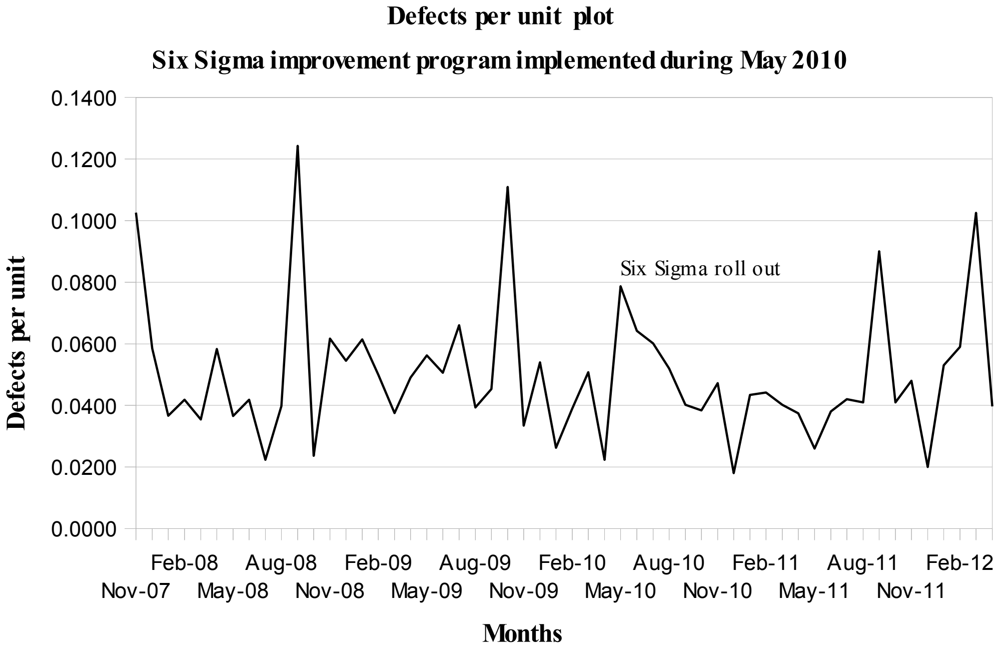

Figure 6.4: Reference mode of the defects per unit measured for the machine shop

The data displays a low signal-to-noise ratio from November 2007 to April 2010 and represents the period before the six sigma quality improvement program was rolled out. A statistical significant correlation analysis of the data suggests that a statistical significant correlation exists between the desired throughput and the defective units. Refer to Appendix

C for a detailed quantitative analysis. Generally higher demand corresponds with more defective units. The next phase in the time series data is represented by the time period since the implementation of the six sigma quality improvement program from May 2010 to December 2010. The data displays an exponential decaying behaviour where the statistical significant correlation analysis suggests that there is no correlation between desired throughput and defective units per month. Refer to Appendix C for a detailed quantitative analysis. This is what one would generally expect for a sustainable quality improvement program where the rate of improvement is maintained (Buchanan et al 2005).

The final phase of the time series data represents the time period from January 2011 to April 2012. From the data gathered during the case study for the machine shop, this time period represents the time period since the gear strategy has been rolled out as well as the build up to the program. Refer to Appendix D for a schematic time line as well as paragraph 5.3 . The statistical significant correlation analysis indicates that there is no correlation between the desired throughput and defective units per month which is indicative of the implementation of the quality improvement program. Refer to Appendix C. The low signal-to-noise ratio is an indication of the gear strategy implementation where the data gathered during the case study for the machine shop suggests that the complexity of the machine shop scheduling increased creating more schedule pressure (Ford & Sterman 2003).

The purpose with this time series data is to investigate the impact the implementation of a quality improvement programme has on the dynamic behaviour of the machine shop during the implementation process. In the next sub-section the dynamic hypothesis is derived from the data analysis done in this sub-section.

6.1.3 Dynamic hypothesis

A dynamic hypothesis is a theory which characterises the behaviour of the system under study. The hypothesis is dynamic because it provides an explanation of the dynamics characterising the behaviour in terms of the underlying feedback and stock and flow structure of the system. It is a hypothesis because it is always provisional, subject to revision or abandonment as more learnings are acquired from the modelling process and the real world (Sterman 2000:95). The dynamic hypothesis therefore guides the modelling efforts by focusing on certain structures.

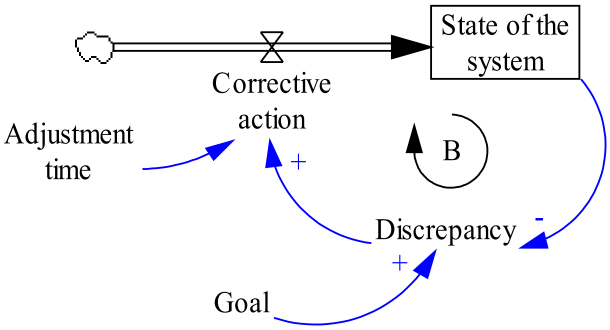

Figure 6.5: A typical balancing feedback loop structure with goal seeking behaviour

The display of the time series plot for the reference mode in Figure 6.4 is typically the recorded behaviour of the manufacturing system after the implementation of the six sigma quality improvement programme in the machine shop. The data clearly demonstrated a decaying behaviour over time, from May 2010 to December 2010, which is typical for a balancing feedback loop depicted by goal seeking behaviour where negative feedback loops act to bring the system in line with a goal or desired state (Sterman 2000:111). A typical structure and behaviour of a system dynamics model for a balancing feedback loop is depicted in Figure 6.5 and Figure 6.6 respectively where the results for the behaviour are displayed in Figure 6.6. The state of the system is depicted by the stock of the system and the input rate (corrective action) changes the stock at an average adjustment time (Sterman 2000).

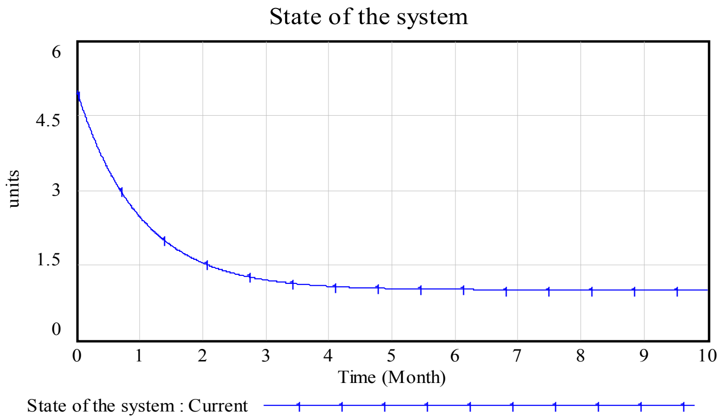

Figure 6.6: Dynamic behaviour of a typical balancing feedback loop with goal seeking behaviour, based on the structure in Figure 6.5

The state of the system is compared to the goal, where the goal in this instance is one. If there is a discrepancy between the desired state or goal and the actual state, corrective action is initiated to bring the state of the system back in line with the goal. The corrective action is the rate at which the system changes at an average equal to the adjustment time.

The rate at which the system approaches its goal reduces as the discrepancy gets less. This behaviour is depicted as a goal seeking behaviour which is typical for an exponential decaying behaviour (Sterman 2000) p 112. Refer to Figure 6.6. This decline as depicted in Figure 6.4 from May 2010, since the six sigma implementation in April 2010 to December 2010, is typical for an exponential decay. If an exponential regression is done on the data during this period, the relationship in equation 6.1 arises.

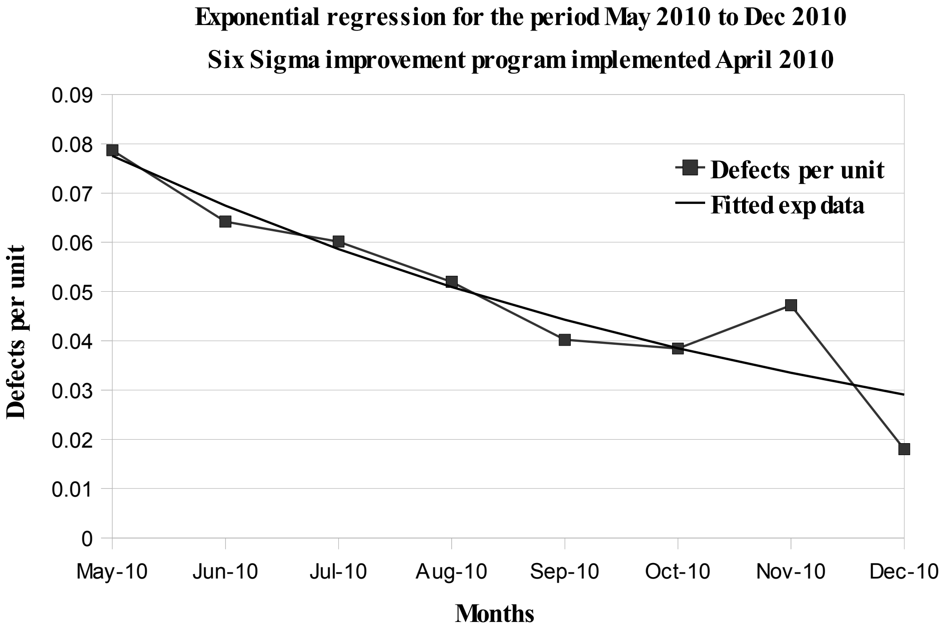

Figure 6.7: Exponential regression of defects per unit data from May 2010 to December 2010

Equation 6.1 describes the relationship between defects per unit and time in months with a R^2 value of 0.97. The R^2 is an indication of how well the regression equation fits the data. The more accurate the equation fits to the data, the closer is the R^2 is to 1. Refer to Figure 6.7.

$$y = 0.0892 * e^{-0.14\,t}$$
$$where \quad t = Time\ in\ months \tag{6.1}$$

Equation 6.1 describes the equation for an exponential decay of the manufacturing process studied in this research, which equates to a half-life of approximately 7.1 months which means that every 7.1 months the value for the y variable could halve. In an empirical study done on different processes in order to arrive at a model to assist with setting of quality goals, the half life for manufacturing scrap is reported at seven months where the half life for defects per unit is reported at 7.6 months (Schneiderman 1988).

If the equation is extrapolated to Dec 2011, the data approximately follows the regression line up to December 2010. From December 2010 the data breaks away from the regression line and shifts upwards due to the implementation of the gear strategy. Refer to paragraph 5.2.1 for an explanation of the gear strategy. The exponential regression equation is therefore only appropriate for the time period from May 2010 to October 2010 with a R^2 of 0.97. Refer to Figure 6.8 depicting the extrapolated data up to December 2011 as well as paragraph 6.1.2 for an explanation of the data behaviour. The purpose with the exponential regression is to help with the behaviour analysis of the data for the construct of the dynamic hypothesis.

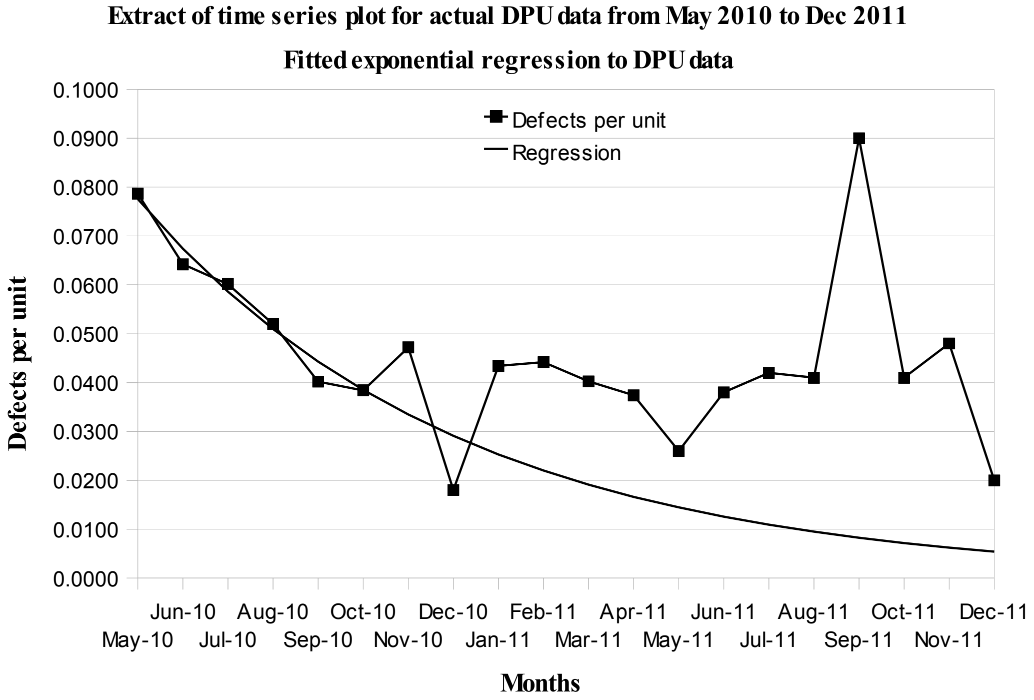

Figure 6.8: Extrapolated exponential regression data up to December 2011 against the plot of the exponential decay as depicted in equation 6.1

The negative feedback loop or balancing loop behaviour of the data, since the implementation of the six sigma quality improvement programme, could be an acceptable dynamic hypothesis for the structure and behaviour of a measuring process, which could be integral to the implementation of a quality improvement programme (Besterfield et al 2003), (Brassard et al 2002).

The output from the measurement process is endogenous to the structure of the quality improvement programme. The measurement of the defects could be used in the measurement process by management as guidance to find the discrepancy between the actual defective units of the system and the goal or target of defective units for the system. The discrepancy could lead to corrective actions by management to bring the process back to the original goal or target. The discrepancy could be due to defects such as the process not delivering on time, defective materials or parts or the process sigma value not being on target.

6.1.4 Introduction to operations management and organisational behaviour

Operations management is defined as the management of the direct resources necessary to create the products and services supplied or provided by a business (Adendorf & De Wit 1999:2). The direct resources include human resources, facilities, processes, transporting or supplying goods and providing services where the facilities include the plant or factory and equipment involved in the transformation process. Refer to Figure 6.9 for a schematic diagram of the transformation process. The feedback is typically happening on a continuous basis to ensure the success of the transformation process.

Different transformation processes exist to deliver low cost, high quality, enhanced functionality and speed, in an efficient and effective manner. Some examples are flow shop, job shop and cellular production (Meredith & Shafer 2011:55). A flow shop is a typical shop where the organisation produces high volumes at a small variety of outputs at low cost. This type of operation lends itself to standardisation which provides for a known, fixed throughput time, giving managers easier control over the system and more reliable delivery dates. The flow shop is easier to manage for reasons such as routing scheduling and control, all being facilitated because each output does not have to be individually monitored and controlled.

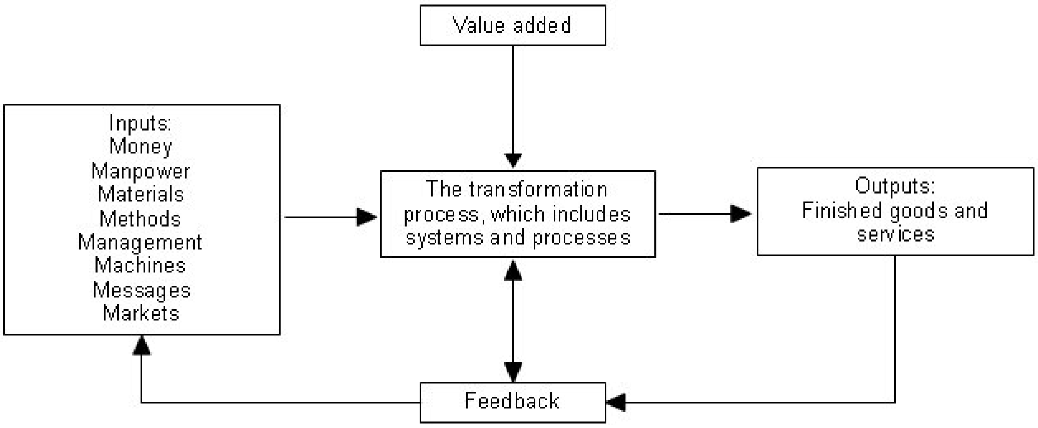

Figure 6.9: The transformation process in operations management adapted from (Kruger & Ramphal 2009)

A job shop is a typical shop where each output or each small batch of outputs, are processed differently (Meredith & Shafer 2011). Therefore the flow through the facility tends to be intermittent. The general characteristics of a job shop are grouping of staff and equipment according to function. There tends to be a large variety of inputs and large variation in system flow times. Typically each output takes a different route through the organisation, requires different operations with different inputs and hence takes a different amount of time to complete. The efficient management of a job shop is a difficult task. Managers should be sure that available resources are efficiently utilised while quality and delivery times are being considered. Because output varies in terms of function, processing, timing and quality, managerial control of the job shop is extremely difficult.

Adendorf & De Wit (1999) further concluded that to be competitive in the global market today, there could be no alternative but to have the best possible product quality. They further concluded that the operations manager's most important contribution to the business strategy is identifying the business's strong points in relation to the following four factors, quality, cost effectiveness, reliability and flexibility where quality is measured in terms of product performance.

To achieve the objectives of the operations management, the operations manager role can be described in broader terms with the following functions of management namely planning, organising, leadership and control (Adendorf & De Wit 1999:7). The planning function is concerned with the planning of the operations function in the long, medium and short term where long-term planning involves aspects such as fixed capacity planning. Medium to short-term planning involves aspects such as forecasting, master scheduling and inventory management.

The operations manager organises the operations function by allocating responsibilities and arranging departments and sections as well as setting up chains of authority which include supplier networks. The leadership function involves motivating the workers within the operations function, for example to be committed to the implementation of a quality improvement programme. Activities included are typically keeping track of defects by means of proper documentation and monitoring changes. Control is the final function which is included in the operations manager's responsibility. Some control functions experienced by the operations manager may include quality control which may also include monitoring the quality improvement programme for progress and status.

An operations manager should have a wide range of skills if he or she wants to succeed in managing the operations function. Skills include managing productivity, efficiency, satisfying the needs of the customer, customer service and global competition. Being part of the global competition means that the operations manager should also be able to manage quality improvement programmes such as lean manufacturing, six sigma, lean six sigma and design for six sigma (Meredith & Shafer 2011:128).

These different functions of operations management require time management by the operations manager and therefore requires a balance between objectives of the organisation and resources to meet these objectives (De J Cronje et al 1987:70). Typical allocation of time spent on the four elements of management for the different layers of management is represented in Table 6.1, adapted from (De J Cronje et al 1987:80). These allocations are typical and should not be seen as a true reflection of how operations management's time should be allocated but rather as a function of the type of organisation.

From Table 6.1 it is clear that top management would typically spend more time, (28%) on the planning function of management while middle management and lower management spend progressively less time on the planning phase. The leadership function is the most prominent function for lower management and could typically be 22% for top management. It is during this phase where lower management requires more technical skills. Control is the final phase and balance of how managers spend their time. It is during the leadership and control phase where operations managers may spend their time to manage the quality improvement programmes from a support and corrective actions perspective.

Good time management by a manager is a function of management effectiveness where management effectiveness is concerned with 'doing the right things', and relates to the outputs of the jobs and what the manager actually achieves (Mullins 1996:458). Mullins (1996) further states that for some management jobs it might be possible to identify more quantitative factors which may give an indication of managerial effectiveness such as accuracy of work carried out by the department, perhaps measured by the number of recorded errors or adherence to quality standards, for example the number of defects in a newly introduced six sigma process. Mullins (1996) further states that managerial effectiveness is about meeting the requirements of the organisation and is difficult to define and measure.

Mullins (1996) continues to say that the criteria for assessing the effectiveness of a manager should be considered in terms of measuring the results that the manager is supposed to achieve. However, such results can be influenced by broader organisational and environmental considerations, such as poor job security due to the economic climate which is outside the direct control of the manager. Manager's effectiveness may be assessed by factors such as (a) the strength of motivation and morale of the staff, (b) the success of the training and development of the staff and (c) the creation of an organisational environment in which staff work effectively.

Another possible indicator of managerial effectiveness is the management of their time (Mullins 1996:459). It is about finding a balance between their managerial responsibility through an open-door policy or the management-by-walking-about (Coates 1990). Time management should not be viewed in isolation from related activities of management such as leadership and delegation where a key aspect of leadership is visibility as stated by (Mullins 1996:461). Time management therefore needs to be balanced against potential benefits from maintaining an open door policy or the management-by-walking-about (MBWA). Monitoring departmental boards and cell boards, introduced during a quality improvement programme, are typical examples of management-by-walking-about.

Functional element	Top management	Middle management	Lower management
Planning	28%	18%	15%
Organising	36%	33%	24%
Leadership	22%	36%	51%
Control	14%	13%	10%

Table 6.1 Typical time spent by operations managers per functional element of management (De J Cronje et al 1987:80)

During the control phase of operations management, emphasis is placed on the exchange of information feedback and comparison of actual results against planned targets, therefore completing the cycle of managerial activities (De J Cronje et al 1987). Managerial control systems are a means of checking progress to determine whether the objectives of the organisation are being achieved. One such objective could be to meet the targets of the quality improvement programme by managing the feedback from the measurement system. Feedback from the measurement system could lead to corrective actions to be taken in order to achieve the goals or targets of the quality improvement programme.

Different tools, from the continuous improvement domain, are being used to investigate the issues related to not achieving the targets or goals as per the measurement system. Some of these tools being used, but not limited to such, may be brainstorming and cause-and-effect diagrams (Meredith & Shafer 2011:153). Brainstorming may be one of the widely used techniques in business to facilitate identification of ways to improve the business. The operations manager typically uses this tool to facilitate the thinking process with his team to determine the reason for the gap between the actual measurement and the target measurement for the process during the quality improvement programme.

A cause-and-effect diagram or fish bone diagram, could be used to find and cure causes. The operations manager may use this tool to identify, explore and graphically identify, in increasing detail, all of the possible causes related to a problem or condition to discover its root cause or causes (Brassard et al 2002). This tool enables the operations manager with his team to focus on the content of the problem and creates a snapshot of the collective knowledge and consensus of the team around the problem.

Two major formats exist for which the cause-and-effect diagram could be constructed namely dispersion analysis type and process classification type. The process classification type uses the major steps of the process in place of the major cause categories. The major cause categories, used in the dispersion analysis type, are machinery / equipment, people, methods and materials. The output of the process in question is at the end of the cause-and-effect diagram. Refer to Figure 6.10 for a schematic of a typical dispersion analysis type format (Brassard et al 2002).

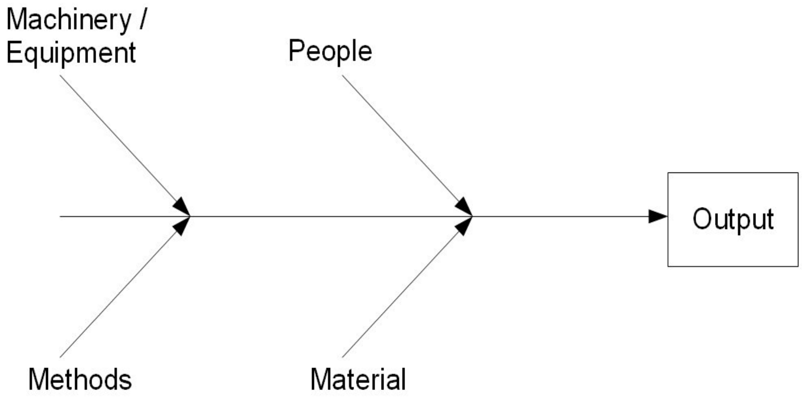

Figure 6.10: Cause-and-effect diagram in a dispersion type analysis. Format adapted from Brassard et al (2002)

Different corrective actions may follow from this analysis of which the implementation could be managed by the operations manager. Typical outcomes for corrective actions from this process could be if training of operators is inadequate which could lead to defects. It could also be raw material sub surface defects which only become visible after machining. It could also be machines used in the turning process which may not keep to the required tolerance for that specific operation. For all these possible causes that could lead to the output or defects of the process, corrective actions may follow with the primary goal to eliminate these probable causes.

However, cause-and-effect diagrams do not consider feedback from other factors in the system that could have an impact on the output of the system, generally referred to as feedback causality. System dynamics may solve this problem (Newton 2003).

An introduction to operations management and organisational behaviour has been discussed in this section. In the next section, the insights gained in this section from the literature on management feedback, managerial effectiveness and cause-and-effect diagrams used during problem solving, have been used to start to develop the theory of sustainability for quality improvement programmes grounded in the case study data. Also refer to Table A.3 and Table A.4 in Appendix A for the coding matrix. The case study data has been gathered during the polar type case study design through direct observations, archived data and semi-structured interviews. Refer to Chapter 4 for more detail.

6.1.5 Conceptual theory of a sustainability feedback loop

6.1.5.1 Introduction

No process is a perfect process and therefore defects may be part of the characteristics of any process. The defects increase through defect introduction and decrease through defect correction. Refer to Figure 3.3. Defects in a process can be late delivery if it is a service process or defective material if it is a manufacturing process. The primary goal of a quality improvement programme is to reduce the defects in a process by decreasing the rate of defect introduction. The rate of defect introduction is a function of process problems, where the process problem may not be visible to the manager of the process.

6.1.5.2 Theory of sustainability with feedback

Process problems within a process could typically be machines that are not calibrated, machine operators who are not fully trained on using measurement equipment correctly or a machine operator who needs glasses to read a measurement instrument accurately. The operational excellence manager recalled,

> " … we introduced process boards, visual performance boards …"

He continued saying that,

> " Opex *[operational excellence]* is wide, we looked at the different aspects of all processes as well … I have measurements … from these reject reports … we have a defect analysis … that will tell us first of all the machines, it will tell us the type of defect."

The process problem is typically the root cause of the defect and hence the origin of the defect. Refer to Figure 6.11 for a system dynamics model of defects and process problems.

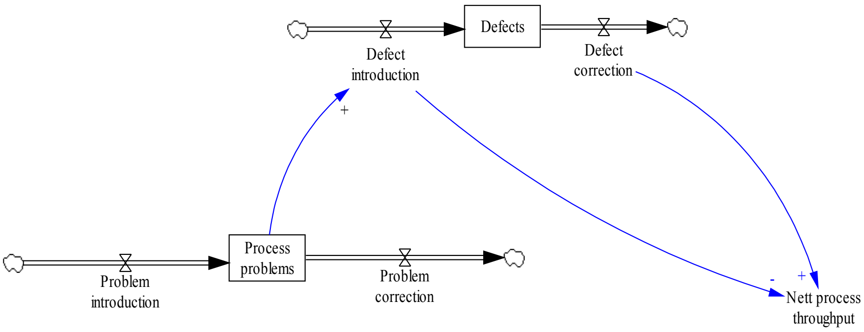

Figure 6.11: System dynamics model of process problems and defects. Extract from Figure 3.3

To find the root cause of the defect, may typically be one of the goals of a six sigma quality improvement programme, where a typical tool could be the fish bone diagram or cause-and-effect diagram. The business unit manager machine shop recalled,

> “ We try and track the defect at the point of the defect ...”

The business unit manager machine shop further recalled,

> “ Is it the operator, is it the machine, is it measuring equipment … and then we target that problem and fix it …”

To achieve the goal of the quality improvement programme, measurements are typically implemented across the process. Measurements could be used to compare the defects measured in the process to a target or desired defect level. The desired defect level is typically set by the quality department and may typically be measured and reported on, on a fixed frequency. Refer for Figure 6.12 for a system dynamics model depicting the measurement process. The defect gap is the difference between the actual number of defects in the process and the desired defect level.

The quality manager machine shop recalled,

> “ We are measuring the defects per unit every month. I *[quality manager]* capture the information and do the graphs *[DPU graphs]* and give it to management with root causes as well as cost ...we measure the process to make sure the defects per unit are not more than the target.”

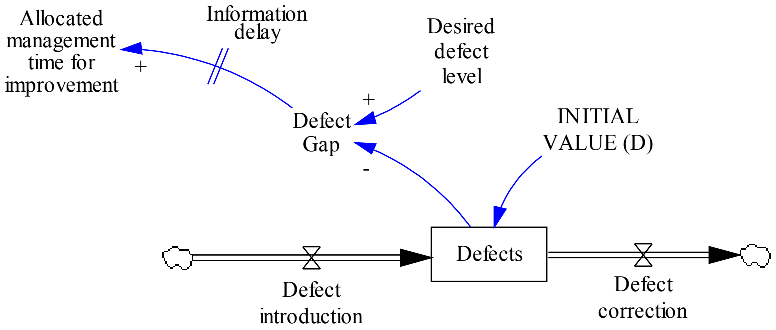

Figure 6.12: System dynamics model with defect measurement

The information on the defect gap is not immediately available but is reported to management on a monthly basis as recalled by the quality manager. This is described as a typical information delay depicted in Figure 6.12. Management typically allocate some of their time to use this information to determine if the manufacturing process is still capable to deliver the product at the desired quality level and also use this information to manage their respective processes to achieve the overall business goals.

If the information indicates that the respective processes are possibly not capable to deliver the product at the desired quality level, management time may be allocated to manage the defect gap. The business unit manager machine shop recalled,

> " I *[machine shop manager]* have measurements … from these reject reports … we do a defect analysis … we will zoom in and find exactly what the problem is ..."

The quality manager also recalled,

> “ We *[quality management team]* will measure the process to make sure the defects are not more than the target...”

Management would typically allocate some of their management time to investigate the root cause of the defects which prevents the process to deliver product at the desired quality level. Part of their management time allocation could be meetings with the production team and support to the team to investigate the defects typically using tools such as cause-and-effect diagrams. The technical supervisor for the machine shop recalled,

> “ We *[management]* sit and meet with the cell team members to find out what went wrong … then we will have physical interviews with the team leader and operator and ask what went wrong … we identify the problem and eliminate the problem going forward ...”

The quality manager commented on the question of management commitment to the quality improvement programme as follows,

> “ I never had any negative feedback from management ...”

Allocated management time for improvement is deducted from the total management time management has available per week to perform their normal managerial duties such as attending business related meetings, manage-by-walk-about, planning duties and following up typically on production output, state of the processes and human resource activities.

The team leader machine shop recalled,

> “ … I spend about 20% to 30% of my time on the shop floor … I also have meetings … discussing HR and IR issues … discussing the machines that are not working … making sure I get my recoveries”

When the defect gap is bigger than the desired defect level, managers typically allocate more time to the quality improvement programme compared to when the defect gap is equal or less to the desired defect level. The additional focus on the quality improvement programme could create managerial pressure, where a manager typically experiences time pressure to meet all his managerial requirements. The increase in management pressure typically has a negative impact on a manager's managerial effectiveness where the manager typically finds it difficult to manage his time (Mullins 1996). Refer to Figure 6.13 for the system dynamics diagram of the allocated management time required for improvement and the negative impact on management pressure and managerial effectiveness.

The business unit manager machine shop recalled,

> “ When we *[machine shop]* are not achieving our targets *[defect targets]*, it puts me under pressure … I get frustrated …”

He further recalled,

> “... I have to get more and more involved in their *[machine shop floor]* activities … it does happen sometime that my own work starts to lag behind, then I have to put extra effort in to catch up with my own work ...”

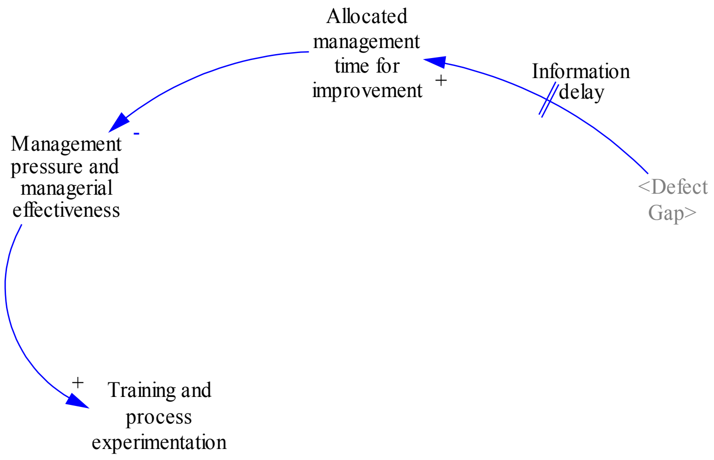

Figure 6.13: System dynamics model of management pressure and managerial effectiveness

The business unit manager tear down recalled,

> “ If I meet my target of cycle time *[defect target]*, I go back to 30% focus on the improvement effort *[quality improvement programme]*, but when I do not meet my target, I focus 70% of my time on the improvement effort”

The increased focus on the quality improvement programme could lead to management actions such as training and process experimentation, in order to fix the process problems and ultimately reduce the number of defects. The operational excellence manager recalled,

> “ … if there is something wrong on the machine, we stop the machine and do a machine capability study *[process experimentation]* in order to fix the machine”

The quality inspector commented as follows when he explained how they go about to find the process problems,

> “ We involved industrial engineering … to modify the method *[machining method of forgings]* in accordance to the operator's understanding. We also studied the geometry of the machine ...”

The link to training and process experimentation closes the feedback loop between defects and problem correction. Refer to Figure 6.14. The benefit from training and process experimentation is not immediately realised but only after some time and hence the delay. The problem correction reduces the stock of process problems which in turn reduces the rate of defect introduction, ultimately reducing the stock of defects. The feedback loop, sustainability loop, is a balancing feedback loop (B5) with the inherent behaviour of exponential decay with goal seeking. Refer to Figure 6.15.

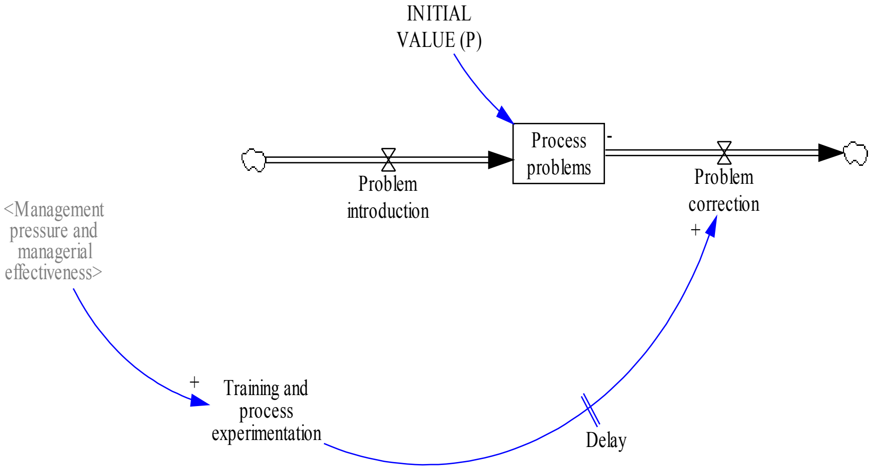

Figure 6.14: System dynamics model of training and process experimentation and problem correction

In this section the theory for sustainability has been developed, from a systems thinking perspective, and grounded in the literature and case study data. The system dynamics model, depicted in Figure 6.15, describes the sustainability feedback loop (B5), fundamentally developed from the case study data and based on the baseline structure of the theory developed by Repenning and Sterman (2002), fundamentally reconstructed in Chapter 3. This is another contribution of this research to the body of knowledge.

In the next section, the theory developed here for sustainability, has been further developed into a system dynamics simulation model to include the dynamic impact of the soft factors such as management support and management pressure. The system dynamics model has been grounded in the case study data gathered during the polar type case study design.

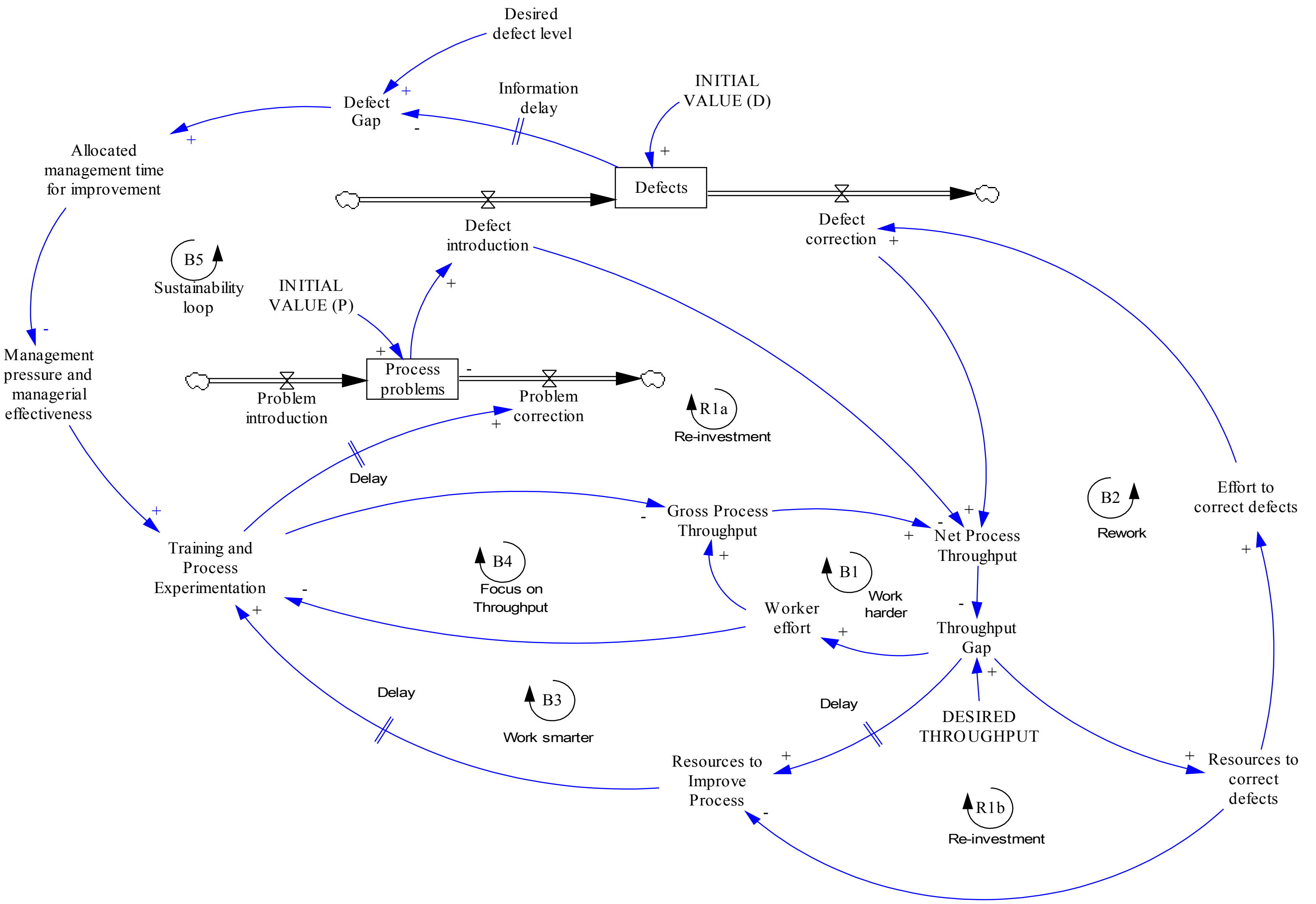

Figure 6.15: System dynamics model with a sustainability balancing feedback loop (B5), from a systems thinking perspective

6.2 System dynamics simulation model of sustainability for a quality improvement programme in a heavy engineering manufacturing environment

6.2.1 Theory of sustainability and management support

The sustainability loop, as depicted in Figure 6.15, is the closed feedback loop between defects and problem correction, where the main aim is to reduce the process problems and therefore the defects through measurement. Management support of the quality improvement programme is one of the key elements to ensure sustainability (Buchanan et al 2005), (Besterfield et al 2003). Management support could be demonstrated by the amount of time management allocates to the quality improvement programme that could lead to management pressure. The business unit manager, tear down recalled the following,

> " … but when I do not meet my target *[cycle time target]* … I am under pressure … I do feel pressure … focusing on priority managerial activities first."

Management support is therefore a function of management pressure and how well the manager manages his time or also referred to as managerial effectiveness (Mullins 1996).

6.2.2 Analogy between capacitated delay and management support

Management support could be compared to the shipments in the structure of a capacitated delay where the analogy is between the stock of backlog of orders and the stock of management time required to be allocated to the quality improvement programme. Refer to Figure 6.16 for a system dynamics model of a capacitated delay adapted from (Sterman 2000:554).

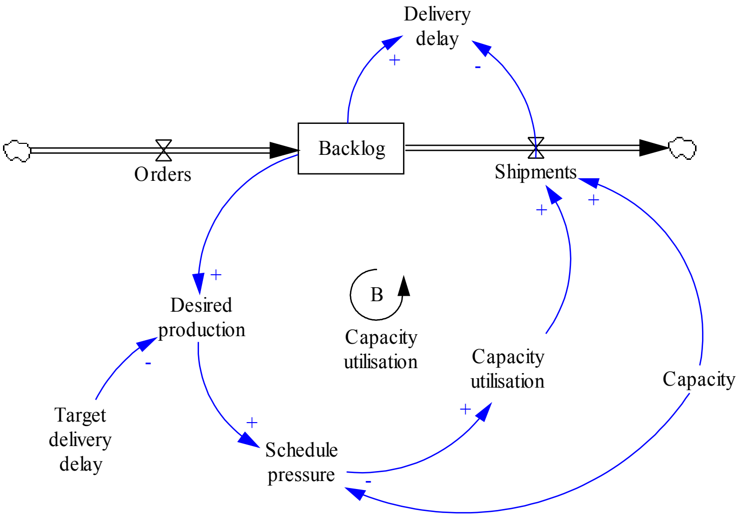

Figure 6.16: Structure for a capacitated delay adapted from Sterman (2000)

The structure in Figure 6.16 is a typical system dynamics model for a company that manufactures goods on a make-to-order basis. The orders accumulate in the back log until they are completed by the production facility and shipped. The size of the shipments is determined by the backlog but limited by the capacity of the production plant. Sterman (2000) further postulates that this structure could also be used for work in process inventory or the completion rate of tasks in a project. For the purpose of this research, the analogy between a capacitated delay and management support is demonstrated.

From Figure 6.16, the delivery delay is the average time for the orders in the backlog and is the ratio of the backlog to the current shipping rate. The desired production depends on the backlog and the target delivery delay. The shipments are a non-linear function of the desired production, saturating at high levels as capacity is reached. Refer to equation 6.2

$$Shipments = f\left(Desired\ production\right) \tag{6.2}$$

Data on the backlog and shipments might be used to estimate the function for the shipment rate. However, equation 6.2 only applies to a company's current capacity but if the capacity changes through productivity improvement programmes, the relationship changes.

Sterman (2000) rewrites this relationship where shipments are described as,

$$Shipments = Capacity * Capacity\,utilisation \tag{6.3}$$

Were capacity utilisation becomes a function of schedule pressure or the ratio of desired production to capacity.

$$Capacity\,utilisation = f\left(Schedule\ pressure\right) \tag{6.4}$$

Schedule pressure is a normalised function depicted by equation 6.5

$$Schedule\ pressure = \frac{Desired\ production}{Capacity} \tag{6.5}$$

The schedule pressure is defined as the pressure to produce above or below the normal rate and is dimensionless due to normalising it with the desired production and capacity. Capacity utilisation is therefore also dimensionless. Sterman (2000) further postulates that the plausible shape for this function can be determined from qualitative data gained from field work and interviews.

6.2.2.1 System dynamics structure for management support

The system dynamics structure for the management support loop (B7) is a balancing feedback loop as depicted by Figure 6.17. The analogy of each factor in the system dynamics model is discussed individually and grounded in the case studies done, historical data and literature reviewed, as discussed earlier in the research design and methodology in Chapter 4. The primary focus for the theory building process is from the case study data where there has been a dramatic success or failure, in the implementation of a quality improvement programme in a heavy engineering manufacturing environment.

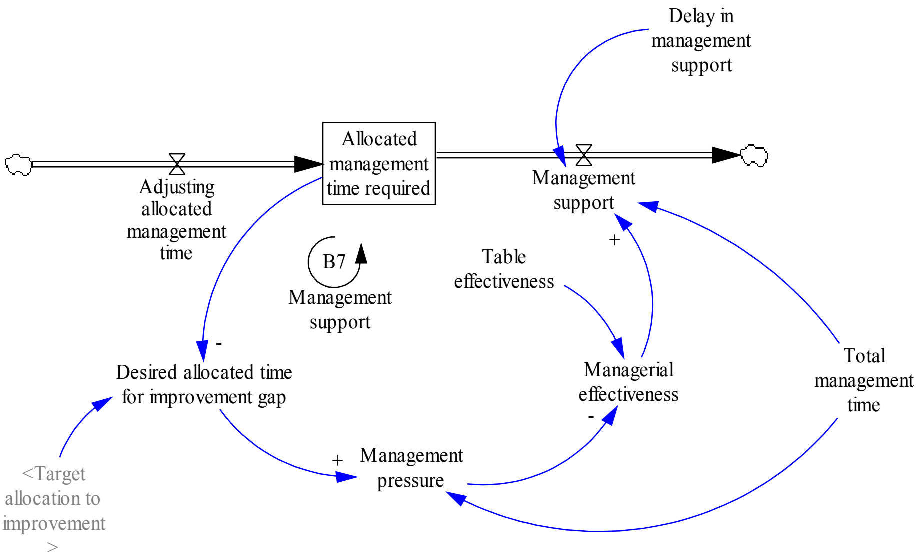

Figure 6.17: Stock and flow diagram for the management support balancing loop (B7)

The allocated management time required is the stock of management time to be allocated to the quality improvement programme. The output rate is the average rate at which the management time is allocated to the quality improvement programme in support of the programme's success. The management time to be allocated to the quality improvement programme is the management hours that are in backlog to the programme. Therefore the output rate, management support, is the average rate to satisfy this backlog. This output rate is similar to the shipments in the capacitated delay structure in order to satisfy the order backlog, as depicted in Figure 6.16.

Orders are the sales order intake or input rate to the backlog in a typical made to order process. The sales order intake is typically a goal or desired state of the system. The analogy with orders in the capacitated delay structure is the adjusted allocated management time required to support the quality improvement programme. This input rate seeks to adjust the state of the system until it equals a target state at an adjustment time which is the average time to close the gap between the target state of the system and the actual state of the system (Sterman 2000). Management time is measured in hours per week, which is adjusted per week, through the input rate of adjusting allocated management time.

The analogy with desired production in the capacitated delay structure is the desired allocated time for improvement gap. The desired production, at a target delivery delay, is the required production to satisfy the backlog which creates the schedule pressure. The desired allocated time for improvement gap is the difference between the actual allocated management time required for improvement and the target allocated management time required to support the quality improvement programme.

Management pressure is the analogy with schedule pressure. To produce above or below the normal rate creates schedule pressure while management pressure is created to support the improvement programme during or above normal management working hours. The total management time is the normal management hours plus additional management hours over and above the normal working hours. The analogy with the total management time is capacity, where capacity is the maximum capacity of the production plant to allow for capacity increase due to productivity improvement programmes.

Management support is a function of desired allocated time for improvement gap while the analogy with the capacitated delay structure is where shipments are a function of desired production. The quality improvement programme requires a certain amount of management hours for the successful implementation as well as to sustain the improvement effort (Buchanan et al 2005). The manufacturing director recalled,

> " My role is initiator as well as sponsor for operational excellence *[quality improvement programme]*"

The business unit manager commented the following on the question of management support towards the quality improvement programme,

> " … even today they *[the operators]* see management committed to the process …"

The quality manager responsible for the whole plant clearly indicated that the business unit managers and other supervision staff found it challenging to keep their focus on the quality improvement programme midst all the pressure on their time management to meet their production targets. He commented as follows,

> " The business unit managers are committed to achieve quality; the only obstacle is when the pressure comes they will push the production ..."

The relationship between management support and desired allocated time for improvement gap is captured in equation 6.6. Management support will saturate as soon as the managers desired allocated time for improvement gap reaches his normal available management time.

$$\begin{matrix}Management\\ support\end{matrix} = f\begin{pmatrix}Desired\ allocated & & Total & & Delay\ in\\ time\ for & , & management & , & management\\ improvement\ gap & & time & & support\end{pmatrix} \qquad (6.6)$$

It is not uncommon for managers to work extra hours beyond their normal working hours, also referred to as total management hours. The business unit manager, tear down recalled,

“ I do work overtime; I stay after five in the afternoon … to get certain things done.”

Management support is also a function of how well a manager manages his time or also referred to as managerial effectiveness. Management support is the rate at which management time is allocated to the quality improvement programme and is therefore the output rate of the stock of allocated management time required to support the quality improvement programme. The output rate is defined by equation 6.7 as follows,

$$Management\,support = \frac{Total\ management\ time * Managerial\ effectiveness}{Delay\ in\ management\ support} \qquad (6.7)$$

The delay in management support is the average time it takes for management to support the quality improvement programme. Some managers could take longer to support the programme while others might support it very quickly.

Managerial effectiveness, “is a difficult subject to define and measure” stated by Mullins (Mullins 1996). Mullins continued to argue that “Managerial effectiveness results from a combination of personal attributes and dimensions of the manager's job in meeting the demand of the situation, and satisfying the requirements of the organisation.” From the case study data the qualitative evidence demonstrated that managerial effectiveness is a function of management pressure with an inverse relationship, as explained next.

The more management pressure the manager experiences, the less effective he could be as a manager. One element of managerial effectiveness is how well the manager manages his managerial time (Mullins 1996). Managers experience a trade off between the different priorities that are required by the business at that point in time. The different requirements from the business could create management pressure which could have a negative impact on their managerial effectiveness such as the manager's management of their management time. The business unit manager, tear down recalled,

> "Improvements unfortunately at the moment are taking a back seat, because of all the work I have to do in my department … 30% of my time now is focused on improvement and 70% on production issues, but previously I focused 70% of my time on improvement and 30% of my time on production issues... it is also a function of my work load."

The business unit manager, machine shop also recalled,

> " The focus is not the same as it was two years ago … I focussed 80% of my day on the improvement programme and today I focus 40% on the programme."

From the evidence gathered during the case studies, the focus change came about when the gear strategy was rolled out which brought about new business requirements and hence created management pressure, as the one manager commented,

> " I am under pressure … therefore do feel pressure … focusing on managerial activities first."

The business unit manager, tear down commented as follows to the question of how his day turns out against how he planned it,

> " I get 60% done of what I plan to do."

The business unit manager, machine shop commented as follows on the same question,

> " About 60% of my day realised the way I planned it."

The business unit manager, machine shop further commented as follows,

> " My team leader mentioned that he is under pressure to get the operators trained on the new process ..."

He continued saying,

> " If we meet our targets, then I find it easy to manage my time and hence give attention to all aspects of my managerial activities. Other factors, such as the gear strategy, influence my management time, and then I have to increase my attention on certain details of activities. This causes a lack of my attention to the quality improvement programme."

The managerial effectiveness of the business unit manager machine shop, was impacted negatively by the extra management pressure due to environmental factors outside his control. Another element of managerial effectiveness is accuracy of work carried out by the manager's department that may be measured by the number of defects in his department (Mullins 1996). With reference to the reference mode depicted in Figure 6.4, the defects per unit show an exponential decay since the introduction of the six sigma quality improvement programme. However, from June 2011 the trend changed and the defects per unit approached a linear trend with randomness, instead of exponential decay.

The business unit manager, machine shop recalled,

> " In the beginning of the quality improvement programme we managed to maintain the improvements, but later on other dynamics *[rationalisation of the work force]* became part of the programme, like the gear strategy programme."

The gear strategy was a strategic decision the company took in order to consolidate all the global gear manufacture in one single global gear manufacturing facility, which inevitably led to rationalisation of the work force. The programme was officially announced in April

2011. From Figure 6.4 and paragraph 6.1.2 , the change in the trend in defects per unit from an exponential decay to a linear trend is explained from May 2011 onwards. The delay in the trend change could be due to the dynamics of the system. As stated by Mullins (1996:460) " such figures can be influenced by broader organisational and environmental considerations such as poor job security due to the economic climate, which is outside the direct control of the manager."

The business unit manager, machine shop commented as follows,

> " If we meet our targets, then I find it easy to manage my time and hence give attention to all aspects of my managerial activities. Other factors, such as the gear strategy, influence my management time, and then I have to increase my attention on certain details of activities. This causes a lack of my attention to the quality improvement programme."

The managerial effectiveness of the business unit manager machine shop was impacted negatively by the extra management pressure due to environmental factors outside his control. One could therefore express managerial effectiveness as a function of management pressure in equation 6.8 as follows,

$$Managerial\,effectiveness = f\,(Management\ pressure) \tag{6.8}$$

In equation 6.8, management pressure is defined as the ratio between the total management time and desired allocated time for improvement gap. The relationship can be described as follows in equation 6.9

$$Management\ pressure = \frac{Desired\ allocated\ time\ for\ improvement\ gap}{Total\ manangement\ time} \tag{6.9}$$

Equation 6.9 is normalised with the total management time and is therefore a dimensionless ratio. From equation 6.8, the relationship can be defined as a non linear relationship, also known as a table function (Sterman 2000:552). Sterman (2000) continues to say that this non linear relationship can be gathered from different sources for example fieldwork interviews, considerations of extreme conditions and physical laws, which could describe behaviour influences. The output from such a table function could be managerial effectiveness as a function of management pressure.

The desired allocated time for improvement gap is the difference between the target allocation to improvement and allocated management time required to support the quality improvement programme. The desired allocated time for improvement gap is therefore the discrepancy between the target and the actual state of the system. The behaviour of the balancing loop (B7) would be to close the discrepancy or gap to get the state of the system to be equal to the target. The desired allocated time for improvement gap is defined in equation 6.10 as follows,

$$\begin{matrix} \textit{Desired allocated time} \\ \textit{for improvement gap} \end{matrix} = \begin{matrix} \textit{Target allocation} \\ \textit{to improvement} \end{matrix} - \begin{matrix} \textit{Allocated management} \\ \textit{time required} \end{matrix} \qquad (6.10)$$

A typical manager's time allocation in this research is described in Figure 6.18. The total management time is the extra time managers typically work, which typically equates to 1.2 times normal working hours. Normal working hours is defined as the amount of hours managers typically work which are also the same hours the business pays its employees for a day's work. The target allocated management time required for improvement is the maximum percentage of the normal working hours managers typically allocate to a quality improvement programme where the minimum allocated management time required for improvement is typically the minimum percentage of the normal working hours a manager could allocate for the quality improvement programme. Evidence of these allocations were found during the case studies of this research as determined from fieldwork such as semi-structured interviews and direct observations.

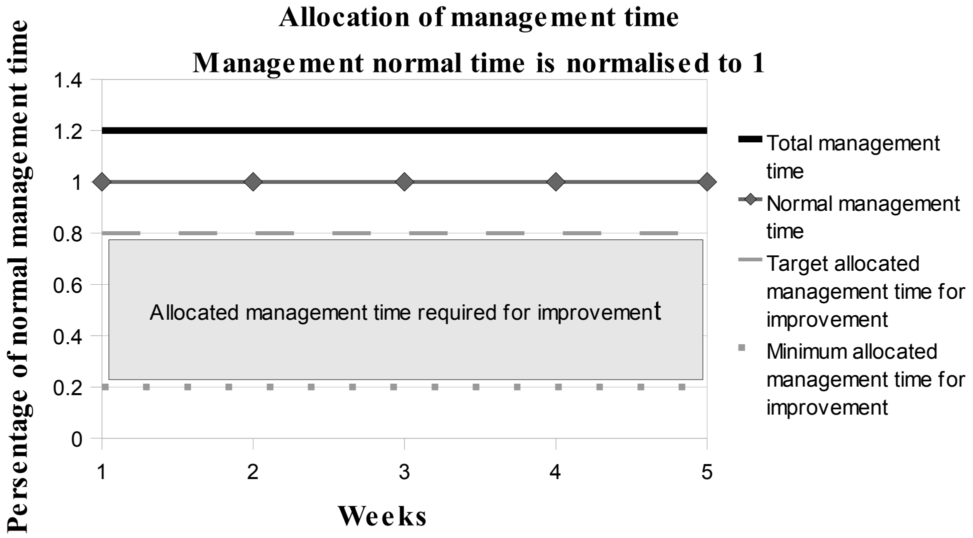

Figure 6.18: Allocation of management time for a typical manager as the background of this research

6.2.3 Soft factors - managerial effectiveness and management pressure

A table function is a table of values for the independent and dependent variables where linear interpolation is used for the values between the specified values. A table function is represented as follows in equation 6.11 (Sterman 2000:552).

$$Y = Effect\ of\ X\ on\ Y$$

$$\begin{aligned}&Where\\ &\quad Effect\ of\ X\ on\ Y = Table\ for\ Effect\ of\ X\ on\ Y\left(X\right)\end{aligned} \qquad (6.11)$$

Sterman (2000) further describes the steps for building such a relationship as follows, (1) normalise the input and the output, (2) identify the reference points, (3) identify the reference policies, (4) consider extreme conditions, (5) specify the domain for the independent variable, (6) identify the plausible shape for the function and (7) specify the values for the best estimate of the function.

Management pressure, input to the table function, is normalised to a reference value X', the total management time, and desired allocated time for improvement gap, as described in equation 6.9 and is therefore dimensionless. The output of the table function is a dimensionless effect modifying the reference value Y' (Sterman 2000:553) as described in equation 6.12. Managerial effectiveness is the output from the table function and is used in equation 6.7 to define management support.

$$Y = Y' f\left(X / X'\right) \qquad (6.12)$$

One element of managerial effectiveness is how well the manager manages his managerial time (Mullins 1996:459). Managers experience a trade-off between the various priorities that are required by the business at that point in time. The various requirements on the part of the business could create management pressure which could have a negative impact on managerial effectiveness such as their management of their management time. The business unit manager, tear down recalled,

> "Improvements unfortunately at the moment are taking a back seat, because of all the work I have to do in my department … 30% of my time now is focused on

> improvement and 70% on production issues, but previously I focused 70% of my time on improvement and 30% of my time on production issues... it is also a function of my work load."

The business unit manager, machine shop also recalled,

> " The focus is not the same as it was two years ago … I focused 80% of my day on the improvement programme and today I focus 40% on the programme."

The focus change came about when the gear strategy was rolled out which brought about new business requirements and hence created management pressure, as the one manager commented,

> " I am under pressure … therefore do feel pressure … focusing on managerial activities first."

The business unit manager, tear down commented as follows on the question how his day turns out against how he planned it,

> " I get 60% done of what I plan to do."

The business unit manager, machine shop commented as follows on the same question,

> " About 60% of my day realised the way I planned it."

In developing the table function, the reference points are defined first. When one describes the reference points, in the back ground of Figure 6.17, management pressure could be less than zero if the allocated management time required is more than the target allocation to improvement. Refer to equation 6.10. Management pressure could also be zero when the desired allocated time for improvement gap is zero when the allocated management time required equals the target allocated time for improvement. Refer to equation 6.9.

Management pressure as defined in equation 6.9 is not an absolute value but only an indication of increase or decrease. Management pressure is defined relative to zero where less than zero is merely a dimensionless indication of less management pressure relative to zero.

Managerial effectiveness is modelled between two extreme limits, maximum and minimum. The assumption for this study is that no manager is 100% effective or has a managerial effectiveness of 0%. The mere fact that the manager is already in a managerial position, could indicate that the manager cannot have zero effectiveness. For the purpose of this study, the managerial effectiveness is assumed to be between the extreme limits of a maximum 0.8 and a minimum 0.2.

During the field work for this research, managers reported an inverse relationship between management pressure and managerial effectiveness. Accuracy of work carried out by the department, which has been measured by the number of defects, could also be a quantitative indication of managerial effectiveness (Mullins 1996). The business unit manager, machine shop recalled,

> “ When we are not achieving our targets, it puts me under pressure ...”

The business unit manager, tear down recalled,

> “ If I meet my target, I go back to 30% focus *[on the quality improvement programme to reduce the cycle time]*, but when I do not meet my target, I go to 70% focus on the improvement project.”

He further commented that if he did not meet his quality improvement programme target, he feels under pressure. With time management of the managers also an indicator of managerial effectiveness, the business unit manager, machine shop commented as follows on his time management and his management pressure,

> " When the *[management]* pressure is low, I find my time management to be very well under control and have high focus levels on the quality improvement programme. When we were bringing work back from the sub contractors to fill the capacity *[spare capacity due to the gear strategy]* … the work complexity changed … this put pressure on my management time … I can now only focus on this problem. As the *[management]* pressure increases, my focus is more detailed on certain activities, as the *[management]* pressure decreases; my focus is broader on other management activities as well. If we meet our [*quality improvement programme]* targets, then I find it easy to manage my time …"

Managerial effectiveness function could therefore be described as an inverse relationship with management pressure bounded by two extreme limits Y max and Y min. Refer to Figure 6.19. There are three reference policy lines for this relationship. The first line is Y max which is the maximum limit for managerial effectiveness. Along this line managerial effectiveness is equal to 0.8 and is not a function of management pressure. The second line is the Y min line which is the minimum limit for managerial effectiveness. Along this line managerial effectiveness is equal to 0.2 and is also not a function of management pressure.

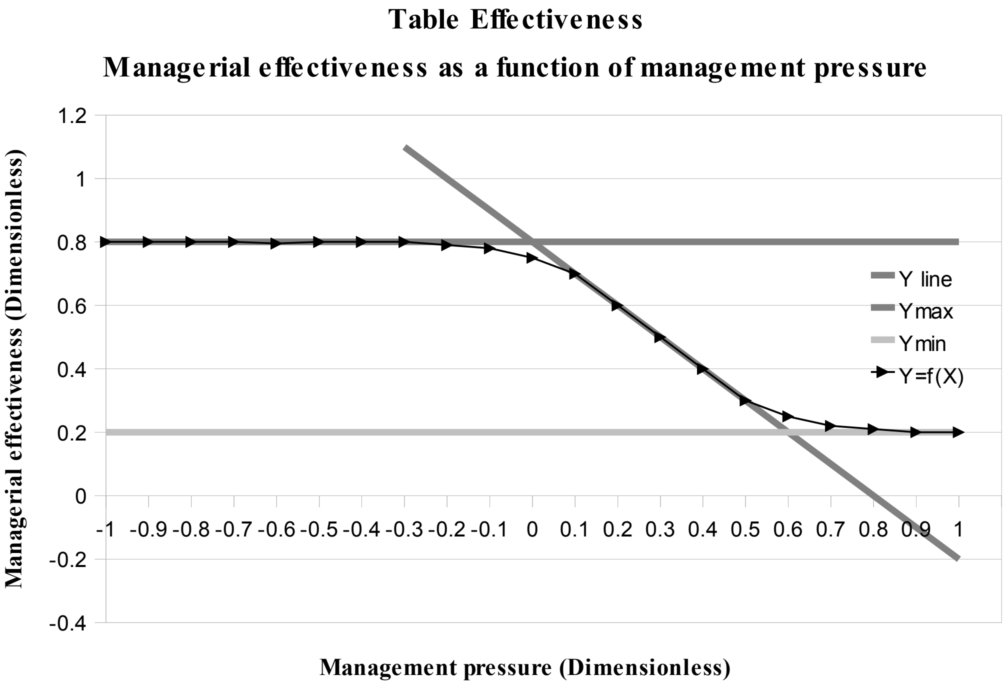

Figure 6.19: Inverse relationship of the function managerial effectiveness as a function of management pressure

The third Y = *f* (X) line is a -45° line which describes the inverse relationship between managerial effectiveness as a function of management pressure. This line represents the case where managerial effectiveness is fully determined by management pressure. Management pressure is the least when the target allocated time for improvement equals the allocated management time required. Refer to equation 6.10. The desired allocated time for the improvement gap is therefore zero. At this point managerial effectiveness is at its maximum and equal to Y max of 0.8. The reference point for the function could therefore pass through the point (0, 0.8). Assuming a direct inverse relationship, this line will intercept the x-axis at 0.8 and therefore pass through the point (0.8, 0).

The function Y = f (X) describes the relationship between managerial effectiveness as a function of management pressure bounded by the extreme limits of managerial effectiveness. As management pressure reduces, managerial effectiveness approaches the upper limit of Y max. As the management pressure increases, managerial effectiveness approaches the lower limit Y min.

6.2.3.1 System dynamics structure – defects and the management support loop

Figure 6.17 describes the system dynamics structure for the management support loop (B7) which includes the relationship between management support and managerial effectiveness. Adjusting the allocated management time required is the input rate at which the stock of management hours allocated to improvement is adjusted. This adjustment is at a frequency which is following the typical business reporting frequency. Managers seek to adjust the state of the system until it equals a goal or desired state of the system which is defined by equation 6.13 as follows (Sterman 2000:523),

$$R_I = \frac{Discrepancy}{AT} = \frac{(S' - S)}{AT} \tag{6.13}$$

The discrepancy is the gap between the desired state of the system S$'$ and the actual state of the system S. The adjustment time AT is the average time required to close the gap. Equation 6.13 is a typical equation for a negative feedback loop. Refer to Figure 6.20 for the system dynamics structure of the management support loop expanded to include the negative feedback loop (B6.)

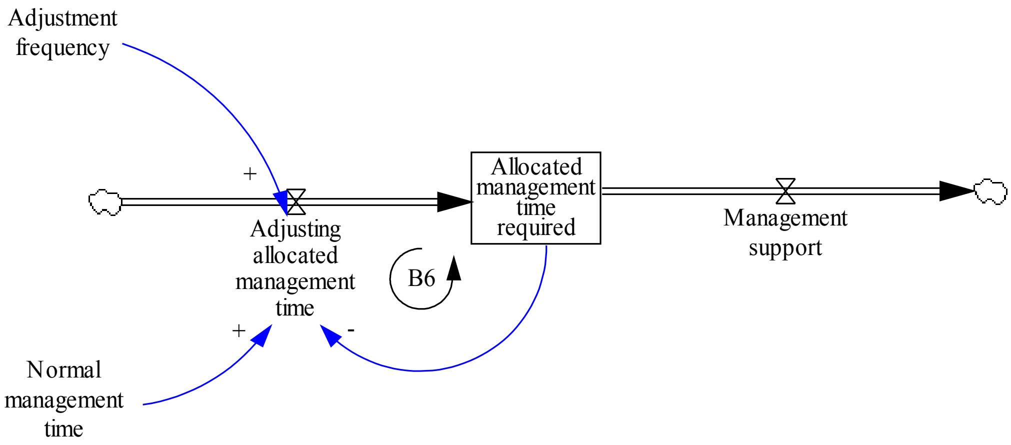

Figure 6.20: System dynamics structure for the rate input: adjusting allocated management time required

The time management has to allocate to the quality improvement time is designated by the stock of allocated management time required. The adjustment frequency could be per week or per month depending on the business reporting frequency. The target allocated management time required for improvement is management time, management's goal or target allocated to the quality improvement programme and is fixed as depicted in Figure 6.18 between a maximum and minimum level. From Figure 6.20, the input rate for the system can be defined as follows in equation 6.14.

$$\begin{matrix}\text{Adjusting allocated}\\ \text{management time}\end{matrix} = \frac{\left(\begin{matrix}\text{Normal}\\ \text{management time}\end{matrix} - \begin{matrix}\text{Allocated management}\\ \text{time required}\end{matrix}\right)}{\text{Adjustment frequency}} \tag{6.14}$$

The desired allocated time for improvement gap, (Figure 6.17), is the difference between the target allocation to improvement and the actual allocated management time required to support the quality improvement programme. Refer to equation 6.10. The desired allocated time for the improvement gap is part of the negative feedback loop (B7), Figure 6.17, and is the discrepancy between the target allocated management time required and the actual state of the system depicted by the allocated management time required. The goal seeking behaviour of a negative feedback loop, endeavours to close the gap and bring the system back in line with the target (Sterman 2000:112).

The level, designated by the allocated management time required, is the stock of time, management has to allocate to the quality improvement programme. The allocated management time for improvement is dynamic and could typically move between minimum allocated management time for improvement and target allocated management time for improvement. Refer to Figure 6.18. The stock of allocated management time required is determined from the following equation 6.15 (Sterman 2000:194).

$$Stock = INTEGRAL\left(Inflow - Outflow\right), Stock_{t_0}$$

$$Stock\ (t) = \int_{t_0}^{t} \left(Inflows(s) - outflows(s)\right) ds + stock\left(t_0\right) \qquad (6.15)$$

The stock(t_0) is the initial stock of the system at time t_0. The Inflow(s) and Outflow(s) are respectively defined as adjusting allocated management time required and management support respectively. The stock of allocated management time required is defined in equation 6.16 as follows,

$$\begin{matrix} Allocated \\ management \\ time\ required \end{matrix} = \int_{t_0}^{t} \left(\begin{matrix} Adjusting\ allocated \\ managment\ time \end{matrix} - \begin{matrix} Management \\ support \end{matrix}, \begin{matrix} INITIAL \\ MANAGEMENT \\ TIME \end{matrix} \right) dt \qquad (6.16)$$

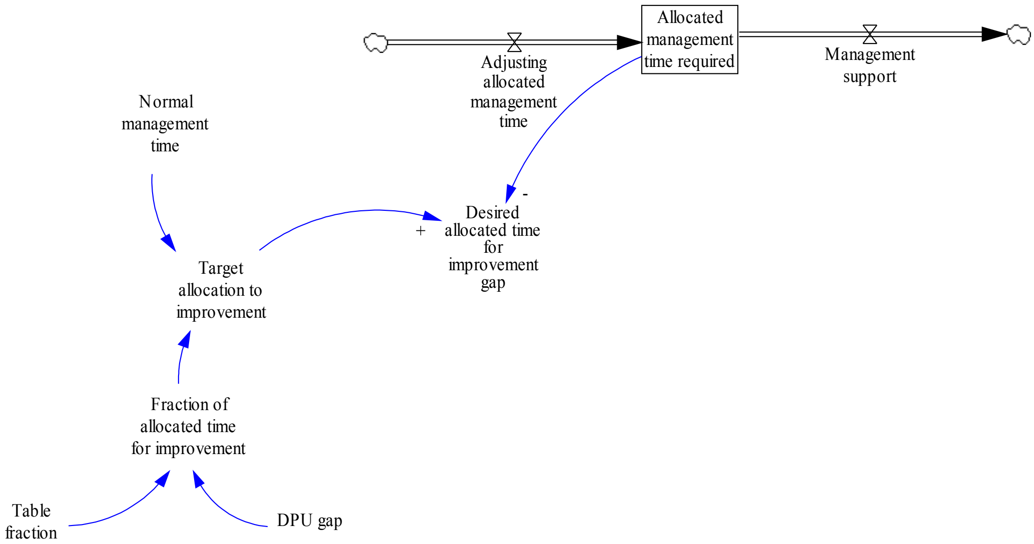

Figure 6.21: System dynamics structure - desired allocated time for improvement gap and DPU gap

The target allocated management time for improvement is described by target allocation to improvement. For the purpose of simulating the behaviour of the system dynamics structure of the management support model, target allocation to improvement is endogenous to the model but the DPU gap is exogenous and is a constant in the model. The target allocation to improvement is dynamic and is a function of the DPU gap as described in equation 6.17.

$$Target\ allocation\ to\ improvement = f\left(DPU\ gap\right) \tag{6.17}$$

When the defect gap is growing, more management time is allocated to the quality improvement programme in order to close the gap. When the gap decreases less management time is allocated to the quality improvement programme. The quality manager machine shop recalled,

> “ We measure the process to make sure the defects per unit are not more than the target. … identify the root cause for the problem that occurred, which means some analysis.”

The business unit manager, machine shop recalled,

> “ If we meet our targets … and hence give attention to all my managerial activities”

He further commented on not meeting the targets of the quality improvement programme as follows,

> “ … then we will zoom in and find out exactly what is the problem, machine or operator.

Managers typically increase their management effort when they do not meet the business targets, for example the number of defects produced by a manufacturing process. The business unit manager, assembly commented as follows on the question of meeting the targets of the quality improvement programme,

> “ We did improve on lead time and productivity from where we have been before, but we are still far from our targets.” and also “ Now they have to change all the planning again …”

The target allocation to improvement is a dynamic fraction between 0.2 and 0.8 of normal management hours. Refer to Figure 6.17. Target allocation to improvement could be defined in equation 6.18 as follows,

$$\begin{matrix} Target\ allocation \\ to\ improvement \end{matrix} = \begin{matrix} Fraction\ of\ allocated\ time \\ for\ improvement \end{matrix} * Normal\ management\ time \tag{6.18}$$

Fraction of allocated time for improvement is a function of defects per unit gap, and is the dimensionless output from the table function as described in Figure 6.22. The defect per unit (DPU) is a dimensionless number and calculated from equation 6.19 (Brassard et al 2002) as follows,

$$DPU = \frac{Defects}{Number\ of\ units\ produced} \tag{6.19}$$

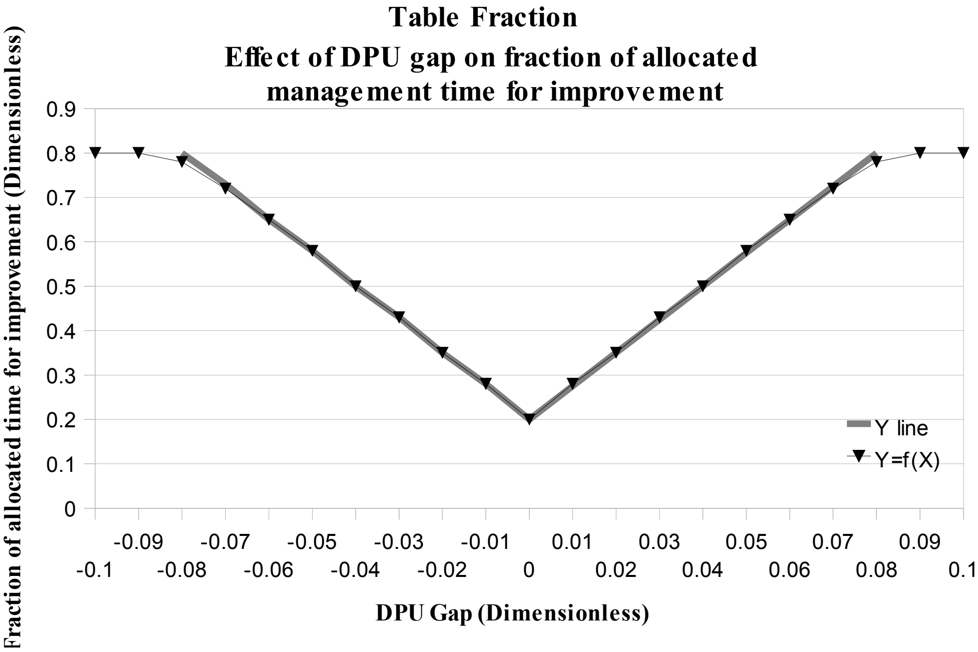

Figure 6.22: Table function describing the relationship between DPU gap and fraction of allocated time for improvement

Fraction of allocated time for improvement is proportional to defects per unit along the line (Y line) in Figure 6.22. The typical process sigma levels for the manufacturing industry are from 3 sigma level towards 4 sigma level (Ingle & Roe 2001). Typical process sigma values reported in the archive documents for this research were from 2.98 to 3.24 which equates to DPU values from 0.038 to 0.078 (Brassard et al 2002).

The relationship between the defects per unit and fraction of allocated time for improvement has been normalised so that most of the management time allocated to the improvement project is from a DPU gap level of 0 to 0.08, which equates to a process sigma level of approximately 2.98. The relationship is proportional between 0.2 and 0.8 of fraction of allocated time for improvement. For DPU gap values bigger than 0.08 and less than -0.08, the fractional allocated time for improvement approach 0.8. Refer to Figure 6.22 for the table function.

6.3 Simulation results for the system dynamics simulation model of the quality improvement programme

In this section the results for the dynamic simulation of the system dynamics simulation model for the quality improvement programme, fundamentally developed in the previous section and grounded in theory, are analysed and discussed. The system dynamics simulation models are programmed in Vensim®, a computer simulation software specifically designed to simulate system dynamics models. Vensim® is developed by Ventana Systems Inc. and is an integrated framework for conceptualising, building, simulating, analysing, optimizing and deploying models of dynamic systems (Ventana Systems Inc. 2012). The system dynamics model equations are contained in Appendix B for further reference.

In the first sub section (6.3.1), the simulation results for the management support model are analysed and discussed. In the following sub section (6.3.2), the system dynamics simulation model results are analysed and discussed for the the quality improvement model including the rework loop. The results for the dynamic behaviour of the system dynamics simulation model for the quality improvement programme including the sustainability feedback loop, are analysed and discussed in the last sub section (6.3.3).

6.3.1 Results from the simulation of the dynamic behaviour of the management support model

The complete structure for the system dynamics model of the management support model is described in Figure 6.23. The equations for the model are listed in Appendix B.2. The purpose of paragraph 6.3.1 is to test the behaviour of this system dynamics model with the initial and boundary conditions in order to study the behaviour of this model for stability, before expanding the model to include the structure for the theory of sustainability as fundamentally developed in section 6.1 of this thesis and described in Figure 6.15.

The DPU gap as described in the model in Figure 6.23 is exogenous to the model but endogenous to the sustainability system dynamics model as described in Figure 6.15. The variable, DPU gap is determined from the stock of defects and net process throughput. The variable, initial management time, is the initial value of the stock of allocated management time required at time t_o. Total management time, adjustment frequency and delay in management support are also constants in the model. Refer to Table 6.2 for a description of the constants in the model. The constants used in this simulation are typical constants and chosen for simulation purposes only.

Description	Constant value	Units
Initial management time	0	Hours/week
Total management time	48	Hours/week
Normal management time	40	Hours/week
Adjustment frequency	1	Week
Delay in management support	1	Week
DPU gap	Pulse	dimensionless

Table 6.2 Constants for the system dynamics model, management support

The first test is to investigate basic behaviour patterns of the system. The base line simulations use the parameter settings as described in Table 6.2. The first simulation run is related to the DPU gap producing a pulse input into the system. A pulse input is defined as an input which returns the value one for the duration of the pulse and zero for the rest of the time. A pulse input is typically used to test the dynamic response of a system in order to test if the system approaches a behaviour which resembles equilibrium (Sterman 2000). Refer to equation 6.20. Start is the time at which the function commences to return a value of one, while the width is the duration of the pulse function in time units. The pulse function in equation 6.20 returns the value one from time zero for a duration of one week and is dimensionless.

The dynamic behaviour of the system with the DPU gap pulse input is depicted in Figure 6.24. The DPU gap is described as a value of one from time $t = t_0$ at a duration of one week. The stock of allocated management time required to support the quality improvement programme increases when the pulse input is introduced into the system. The increase in allocated management time required is necessary in order to allocate enough required management time to the quality improvement programme to overcome the DPU gap of one. The amount of allocated management time that is required is determined by the target allocation to improvement. The target allocation to improvement returns to its maximum level when the DPU gap is at its maximum level as described by equation 6.17 and equation 6.18.

When the pulse input reduces to zero again, the allocated management time required to support the quality improvement programme reduces exponentially until it reaches equilibrium at 5.33 hours per week at approximately six weeks. The allocated management time required reduces accordingly with the reduction in the target allocation to the improvement programme. The target allocation to improvement is determined from the table function in Figure 6.22 and equation 6.18.

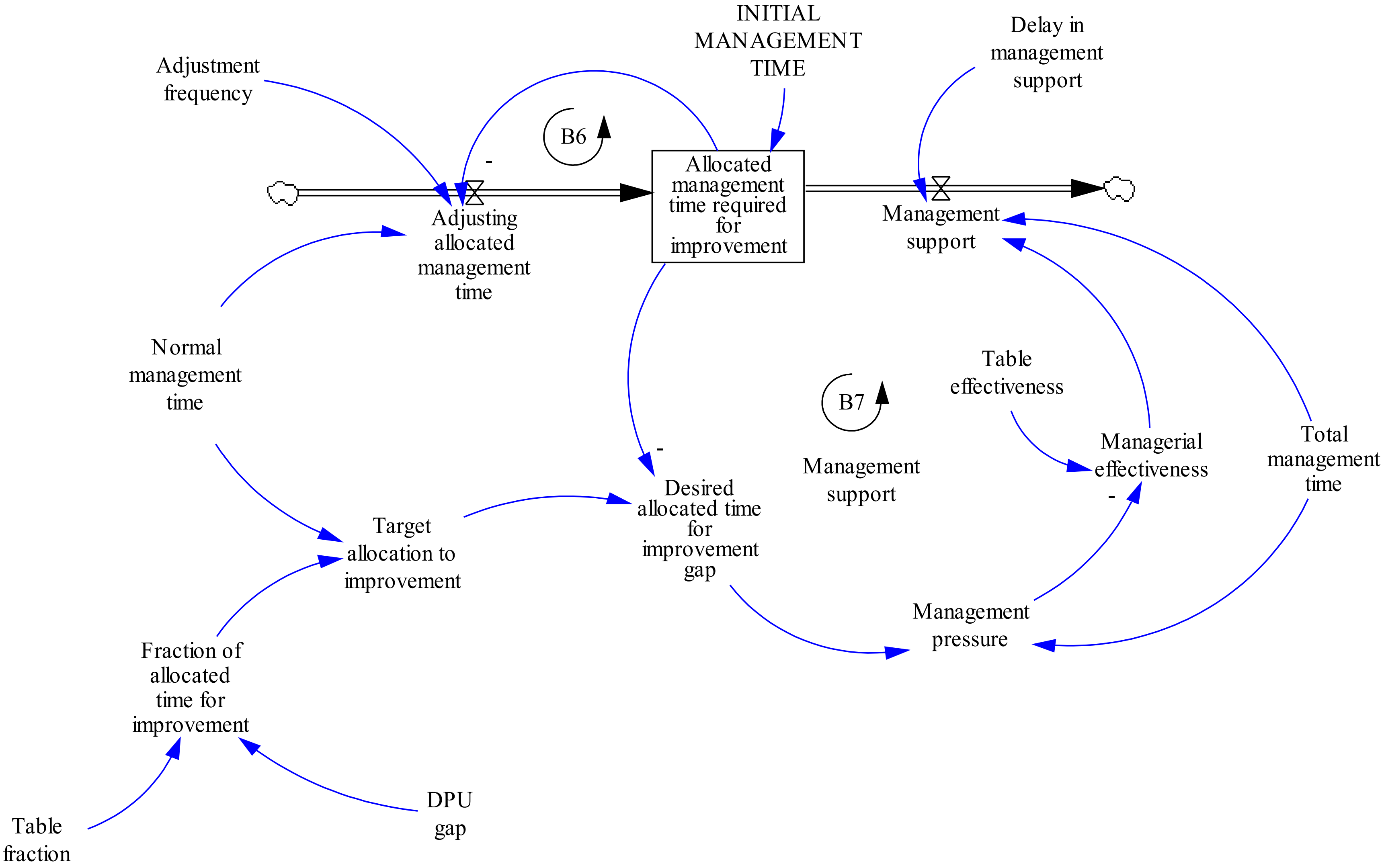

Figure 6.23: System dynamics structure of the complete management support model with the exogenous variable DPU gap

$$\begin{gathered} Pulse(start\,, width) \\ Pulse(0,\ 1) \end{gathered} \tag{6.20}$$

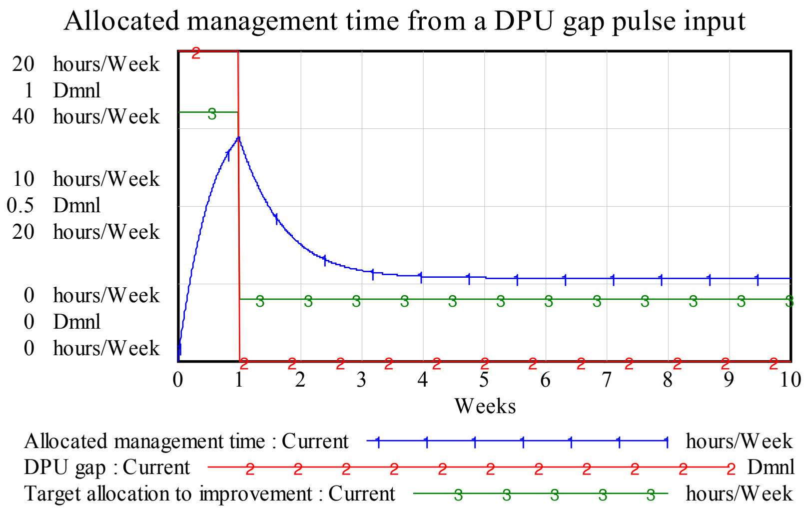

Figure 6.24: Allocated management time from a DPU gap pulse input compared to the target allocation to improvement

When the DPU gap returns a value of unity and zero respectively, the behaviour of management pressure is discussed. The manager typically experiences less management pressure when his business unit meet its targets for defects per unit and more management pressure when the business unit does not meet its target for defects per unit made. Management pressure starts off high due to the DPU gap being at a level of one and the target allocation to improvement also being high. Therefore, management pressure is high to close the desired allocation to improvement gap. It is a soft factor and is difficult to measure and is simulated as a dimensionless input into a table function. Refer to Figure 6.19 and equation 6.9. With the DPU gap pulse input at the level of one, the management pressure is at its maximum, reducing as more management time is allocated to the improvement programme and therefore closing the desired allocated time for the improvement gap. Refer to Figure 6.25.

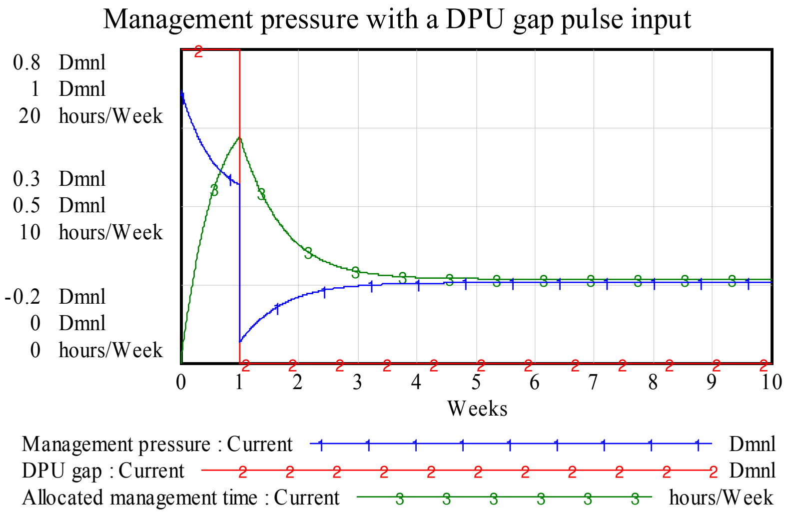

Figure 6.25: Management pressure and managerial effectiveness with DPU gap as a pulse input

When the DPU gap pulse input reduces to zero, management pressure reduces to its minimum. With less management pressure, less management time is required to be allocated to the improvement programme. Although the DPU gap is at its minimum, the target allocation to improvement is not zero due to the improvement programme that still has to be maintained as described in Figure 6.22. Management pressure therefore increases until it reaches equilibrium.

The simulation results for managerial effectiveness are now discussed when the DPU gap returns a value of one and zero respectively. Managerial effectiveness is the functional output from the table function in Figure 6.19, and is a soft factor, difficult to measure and dimensionless. Managerial effectiveness is at its maximum when management pressure is at its lowest and at its lowest when management pressure is at its maximum. The DPU gap at a level of one creates management pressure which in turn creates low managerial effectiveness.

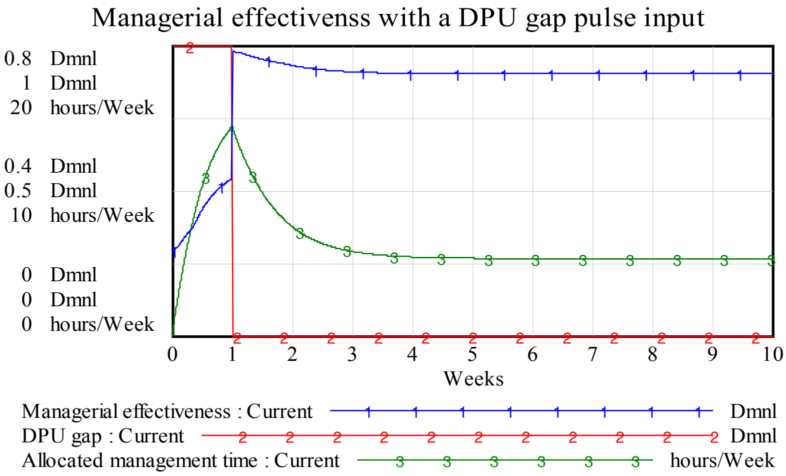

Figure 6.26: Managerial effectiveness and allocated management time required with a DPU gap pulse input

Managerial effectiveness is therefore at its minimum when the DPU gap pulse input is at its maximum. Managerial effectiveness increases while more focus is put on the quality improvement programme through the allocation of more required management time to the quality improvement programme. When the business unit meets its target, which could be when the DPU gap pulse input is zero, managerial effectiveness is at its maximum level.

Refer to Figure 6.26. The allocated management time required to the improvement programme reduces when the DPU gap pulse input is zero. Management pressure could increase until its equilibrium level where there is enough management pressure to support the quality improvement programme and the desired allocation to improvement gap is reduced. Managerial effectiveness therefore reduces accordingly as indicated in Figure 6.19. Managerial effectiveness reduces until it finds its equilibrium at a high level of managerial effectiveness which could indicate a high level of managerial effectiveness in order to support the quality improvement programme.

Management support is defined as the rate at which allocated management time required, is allocated to the quality improvement programme. The simulation results for the dynamic behaviour of management support with a DPU gap pulse input is discussed next. Management support is also a soft factor and difficult to measure. Refer to equation 6.7.

Allocated management time starts to increase when the DPU gap pulse input is one. This refers to Figure 6.27. Management time could typically be allocated until the desired allocation to improvement is at its minimum. At the same time management pressure will start at its maximum value with managerial effectiveness at its minimum level due to their inverse relationship as depicted in Figure 6.19. Management support is defined in equation 6.6 as a function of management pressure and also defined in equation 6.7 and could typically increase from its lowest level, with the DPU gap at a level of one.

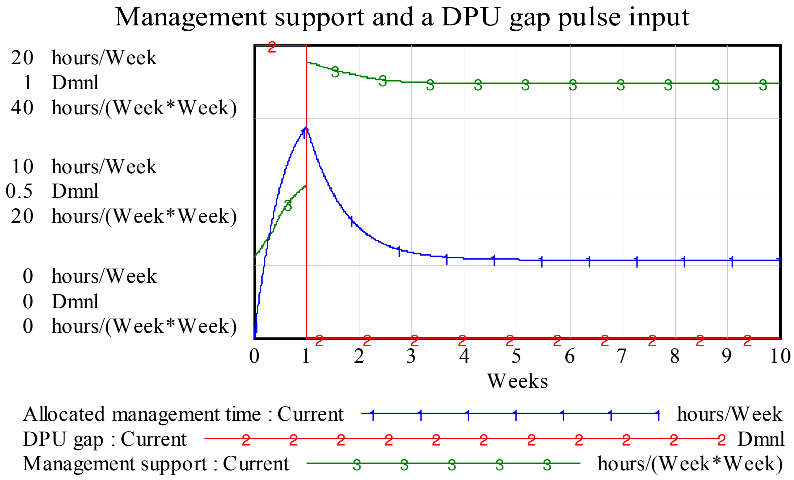

Figure 6.27: Management support and allocated management time required with a DPU gap pulse input

When the DPU gap reduces to zero level, management pressure to close the desired allocation to improvement gap also decreases. Enough management pressure is required to support the quality improvement programme and hence management support reduces to its equilibrium level in order to maintain the support for the quality improvement programme at an average adjustment time of delay in management support. Refer to Figure 6.27.

Management support goes hand in hand with managerial effectiveness. The better the manager's effectiveness is, the better his support for the quality improvement programme should be. The rate, of allocated management time required for the quality improvement programme, reduces until it stabilises at its equilibrium level as referenced in Figure 6.27. Although the rate reduces, management support should remain relatively high. This is supported by the case study data captured during the semi-structured interviews when the team leader, tear down commented as follows,

> “ Even today they *[the workers]* see management committed to this process ...”

The business unit manager machine shop commented as follows on the question of visibility of top managements' vision and goals regarding quality improvement programmes,

> “ Yes *[it is visible]*. It is in the quality manual. I also know what my responsibility is ...”

Management support is also visible at all levels in the organisation. The team leader, machine shop commented as follows on the question of visibility of management's vision and goals regarding quality improvement programmes,

> “ *[Business unit manager, machine shop]* and I discuss quality a few times per day and he will share information. He will also give recognition where needed. He makes us aware of these *[defects]* and asks us to make a difference in our department.”

Management support could differ between various managers and / or between various levels of management. The manufacturing director recalled,

> “ From top management … there is a lack of education and expertise and awareness of lean manufacturing principles ...it makes it difficult to roll it *[quality improvement programme]* out to the rest of the organisation.”

Delay in management support, refer to Figure 6.23, could be an indication of how management support typically differs between different levels of management in the organisation. The delay could be indicative of how various managers at different levels in the organisation accept the new quality improvement programme and how long they take to support it. The delay could be from one week to several weeks for different managers. Refer to Figure 6.28 for a comparison of the effect of different delays in management support for allocated management time required.

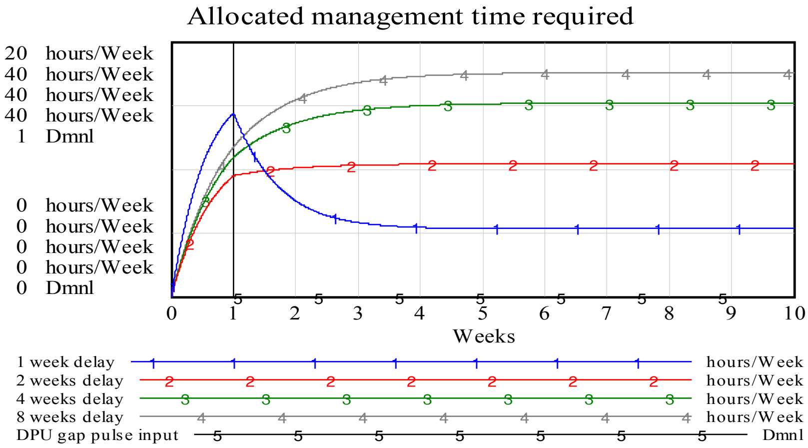

Figure 6.28: Allocated management time required at different levels of delay in management support with a DPU gap pulse input

When the delay is one week, allocated management time required for the quality improvement programme increases when the DPU gap pulse input is at a level of one. When the DPU gap input level drops to zero after one week, the allocated management time required starts to reduce until it reaches its equilibrium level after approximately four weeks. When the management support delay increases, the allocated management time required to support the quality improvement programme, continues to increase although the DPU gap pulse input reduced to zero after one week. This phenomenon can be attributed to the delay in management support.

The allocated management time required stock typically increases with a further increase in management support delay. The increase in the delay reduces the output rate, or management support, of the system. With a decrease in the management support, the allocated management time required to support the quality improvement programme, continues to rise to approach the target allocated management time for improvement if the adjustment frequency remains the same. Refer to Figure 6.29 for the output rate at different levels of delay in management support.

The output rate, management support, reduces by half as the delay in management support increases by a factor of two. The increase in the delay causes an accumulation of allocated management time that is required to support the quality improvement programme. Management support for the quality improvement programme would typically reduce when various managers take longer to accept the quality improvement programme. The delay in the acceptance could be due to lack of training on management's side or due to reluctance from management to accept the change in management that is required.

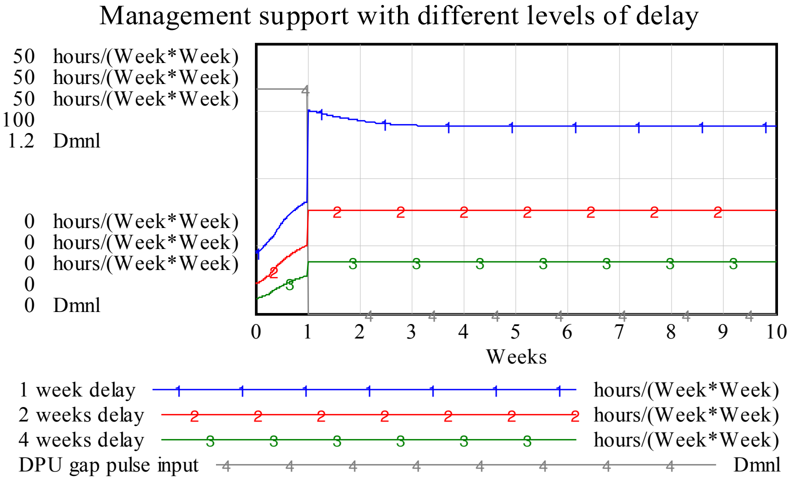

Figure 6.29: Comparison of management support with different levels of delay in management support with a DPU gap pulse input

6.3.2 System dynamics structure for the rework loop

In the previous paragraph, the structure and dynamic behaviour of the system dynamics management support loop model was analysed and discussed. In this paragraph, the structure of the system dynamics model for the rework loop is fundamentally developed and grounded in the literature and case study data gathered during the semi-structured interviews, archived data and direct observations, applicable to a heavy engineering manufacturing environment.

Rework is one of the actions a manufacturing facility could typically take to close the throughput gap in a typical manufacturing cycle where a quality improvement programme has been implemented. Refer to Figure 6.15 for the system dynamics structure of sustainability for a quality improvement programme, fundamentally developed and grounded in theory. The theory from Repenning and Sterman (2002) is the baseline structure. The business unit manager, final assembly commented as follows on the reason why he has to do rework on some of his upstream processes,

> " … if all the information and parts are not available to the people *[other departments in the value chain]* that are supposed to give me the finished product ... "

The quality manager, machine shop also recalled,

> " … when that happens *[defects are created]* they *[the operators]*, will find out if there are ways to rework it … "

The decision to rework the component or to scrap the component is not a decision that manufacturing typically would take but usually the request to re-use or scrap the component is handled through a concession from inside the quality department. The concession is approved or rejected by the engineering department in a form of a quality concession raised inside the business system. The business unit manager, machine shop commented as follows,

> “ The engineer comes once or twice a week … if he decides to scrap the component, it will go into the scrap bin. If he decides that it can be reworked, then we will rework the component.”

The engineering department issues a concession for rework or scrap within a maximum allowable time for the concession. Refer to Figure 6.30. For the purpose of this research the defects are defined as defective units. From direct observation, semi-structured interviews and historical data, it was evident that the parts that had defects are considered as defective parts irrespective of the number of defects per part.

Engineering concession [units/week] is described by equation 6.21 as follows,

$$Engineering\ concession = \frac{Defective\ units}{Maximum\ allowable\ time\ for\ concession} \qquad (6.21)$$

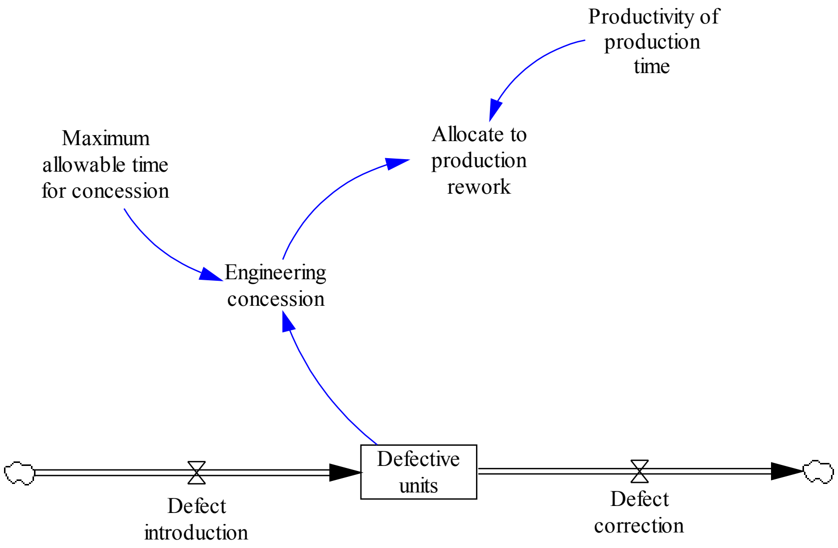

Figure 6.30: System dynamics structure for engineering concession within the maximum allowable time for the concession

When the concession is approved by engineering, the concession is allocated to production for rework. The amount of hours required per week to do the rework is a function of the productivity of the production work force. Refer to Figure 6.30. The equation, allocated to production rework [hours/week] is defined in equation 6.22 as follows,

$$Allocate\ to\ production\ rework = \frac{Engineering\ concession}{Productivity\ of\ \ production\ time} \tag{6.22}$$

The allocation to production for rework needs to be planned considering the available production time. The business unit manager, final assembly commented as follows,

> "... I sit with the rework. I have to rework it, because if I send it back, I will never get the machine out."

This function is typically performed by the production planner where he has to consider the total available production time as well as the time already allocated to production. The rework planning capacity is defined by a fuzzy MAX and MIN function where the fuzzy MAX function keep the variable to be non-negative and the fuzzy MIN function limit the rework to the model parameter, allocate to production rework (Sterman 2000:529). Refer to Figure 6.31 and equation 6.23.

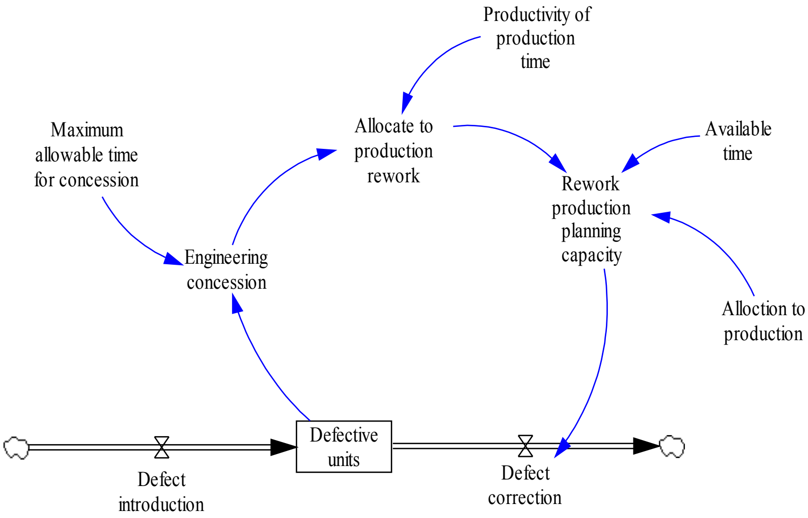

Figure 6.31: System dynamics structure of the rework loop

The rework production planning capacity [hours/week] is defined by equation 6.23 as follows,

$$\begin{matrix}Rework\\ production\\ planning\\ capacity\end{matrix} = MAX\left(0, MIN\left(\left(\begin{matrix}Available\\ time\end{matrix} - \begin{matrix}Allocation\\ to\ production\end{matrix}\right), \begin{matrix}Allocate\ to\\ production\\ rework\end{matrix}\right)\right) \qquad (6.23)$$

The rate at which the defective units are reworked, is defined as defect correction as depicted in Figure 6.31. The rate at which the rework is done is also a function of the productivity of the production facility, defined by the model parameter, productivity of the production time. The output rate, defect correction rate [units/week], is defined in equation 6.24 as follows,

$$\begin{matrix}Defect\\ correction\end{matrix} = \begin{matrix}Rework\ production\\ planning\ capacity\end{matrix} * \begin{matrix}Productivity\ of\\ production\ time\end{matrix} \qquad (6.24)$$

Refer to Figure 6.32 for the system dynamics structure of the rework loop including the output rate defect correction.

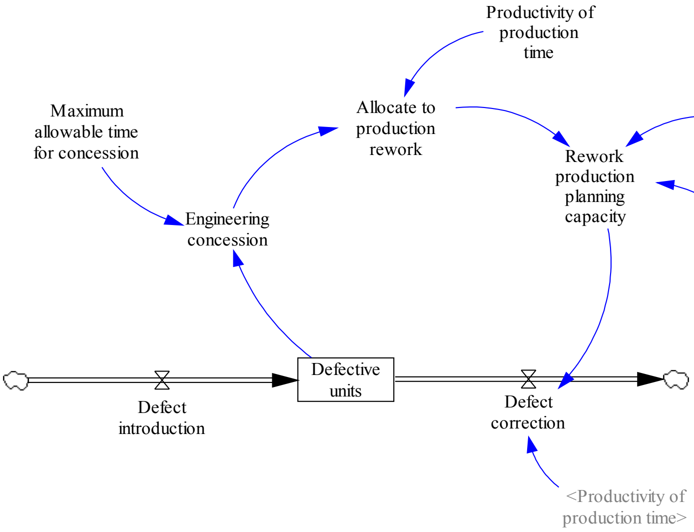

Figure 6.32: System dynamics structure of the rework loop including defect correction

6.3.2.1 Dynamic behaviour of the interaction of the first- and second-order improvement loops with the rework loop included

The model developed by Morrison (2007), refer to Figure 3.4, is expanded here to include the rework loop as depicted in Figure 6.32. The rework loop is a typical description of a process in a production facility where defects are reworked as one of the loops that could be used to close the throughput gap. Repenning and Sterman (2002) described this feedback loop as the rework loop (B2) and have also described the reinforcing or re-investment loops (R1a) and (R1b) which will reinforce the behaviour of the system at that point in time. Refer to Figure 3.3.

6.3.2.1.1 Description of the model with the different balancing and reinforcing loops

These loops are described respectively as follows from Figure 6.33. The work harder loop is described by desired allocation to production, indicated allocation to production, adjusting allocation, allocation to production, gross process throughput, throughput gap and resource gap. The rework loop is described by desired allocation to production, indicated allocation to production, adjusting allocation, allocation to production, gross process throughput, defect introduction, defective units, engineering concession, allocate to production rework, rework production planning capacity, defect correct, net process throughput, throughput gap and resource gap.

The work smarter loop is described by desired allocation to production, indicated allocation to production, adjusting allocation, allocation to production, allocation to improvement, problem correction effectiveness, problem correction, process problems, defect introduction, defective units, engineering concession, allocate to production rework, rework production planning capacity, defect correction, net process throughput, throughput gap, resource gap.

The re-investment loops are respectively described by the following loops. The re-investment loop is described by desired allocation to production, indicated allocation to production, adjusting allocation, allocation to production, allocation to improvement, problem correction effectiveness, problem correction, process problems, defect introduction, net process throughput, throughput gap and resource gap.

The re-investment loop can also be described by desired allocation to production, indicated allocation to production, adjusting allocation, allocation to production, rework production planning capacity, defect correction, net process throughput, throughput gap and resource gap. The re-investment loops described here can also be read in conjunction with the re-investment loops (R1a) and (R1b) as referenced by Figure 3.3 in Chapter 3 section 3.1.

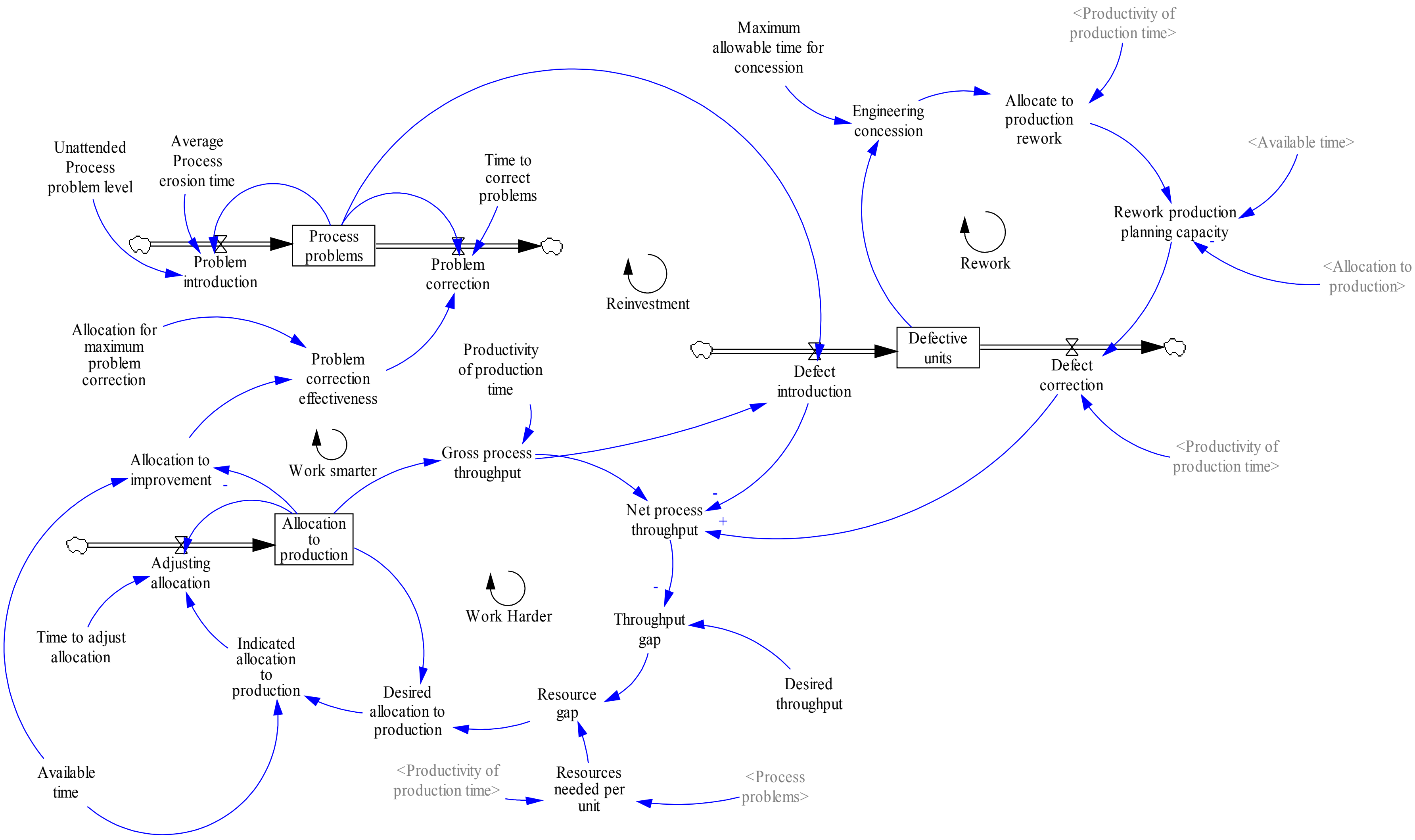

Figure 6.33: System dynamics structure for the interaction between the first- and second-order improvement loops with the rework loop included

6.3.2.1.2 Results of the simulation for the dynamic behaviour of the interaction of the first - and second-order improvement loops including the rework loop

The dynamic behaviour is investigated by simulating the desired throughput as a step input where the desired throughput is an exogenous goal and is typically a requirement of the business. A key assumption represented in this model is that the rework of defective units takes priority over improvement. Rework is therefore done with the time left after the allocation to production is complete, following the previous assumption that the worker's time is allocated between two activities. The first activity, first order improvement loop, pertains to production, which includes the rework of defective units, while the second activity pertains to problem correction or the second order improvement loop. Morrison (2007) further postulates the strict priority of first-order improvement also implies that second-order improvement takes place not as a direct response to the throughput gap but as an investment when resources are available.

To model the work harder loop, the workers' are assumed to respond to throughput pressure created by the throughput gap. The model further assumes that the allocation decision is made with full knowledge of the state of the system, which includes throughput rate, productivity of production time and current allocation to production (Morrison 2007).

The first simulation uses a step input for the desired throughput to investigate the dynamic behaviour of the model in terms of its stability under different conditions. The desired throughput is simulated by a step function with a height of 1100 units per week starting at week 10 with the base line parameters in Table 6.3. Refer to equation 3.20 for a description of the step function. The parameters tabulated in Table 6.3 are typical parameters chosen for simulation purposes only. The simulation is done with Vensim® with a list of the equations programmed in Vensim®, referenced in Appendix B.3

Parameter	Value	Units
Unattended process problem level	0.9	Dimensionless
Average process erosion time	36	week
Time to correct problems	16	week
Productivity of production time	1	unit/hour
Allocation for maximum problem correction	4000	hours/week
Available time	4000	hours/week
Time to adjust allocation	1	week
Initial process problems	0.4	week
Maximum allowable time for concession	2	week
Initial value for Defective units	0	units
Initial allocation to production	0	hours/week

Table 6.3: Base line parameter values for the dynamic simulation

The results from the dynamic simulation are displayed in Figure 6.34 and are analysed and discussed in the following paragraph.

The system responds on the desired throughput by adjusting the allocation in order to achieve the desired throughput. The allocation to production increases in response to the desired throughput, in allocating more hours to production. The net process throughput increases as a result of the increase in allocation to production. The net process throughput increases and approaches the desired throughput where it stabilises at the desired throughput level. The process problems decrease from the initial value of 0.4 and stabilises at a lower value in comparison to the initial value.

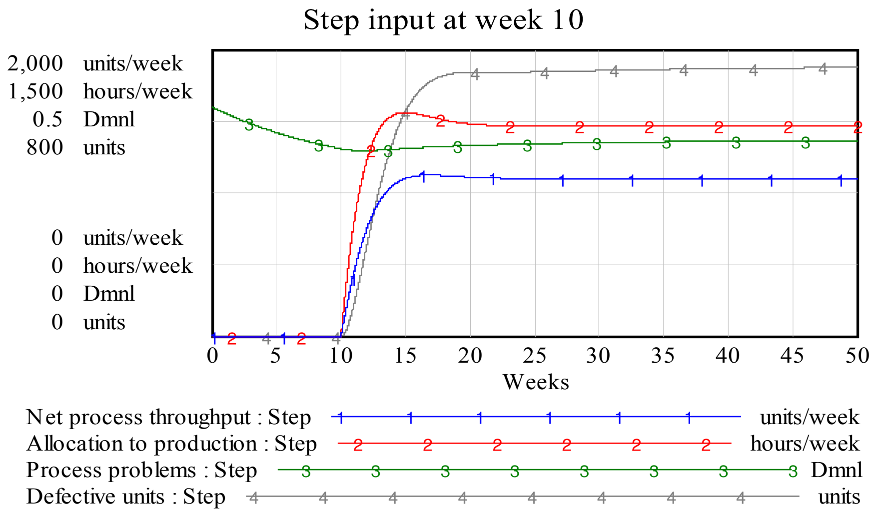

Figure 6.34: Dynamic simulation for the desired throughput as a step function from week 10

The defective units increase in response to the process problems in the system. Due to the allocation to production and rework, the defective units increase until the allocation to production stabilises. At this time during the simulation, the balance of the hours not allocated to production and rework, are used in the allocation to improvement as displayed in Figure 6.35. Due to this allocation to improvement, the process problems stabilise and hence the defective units also stabilise.

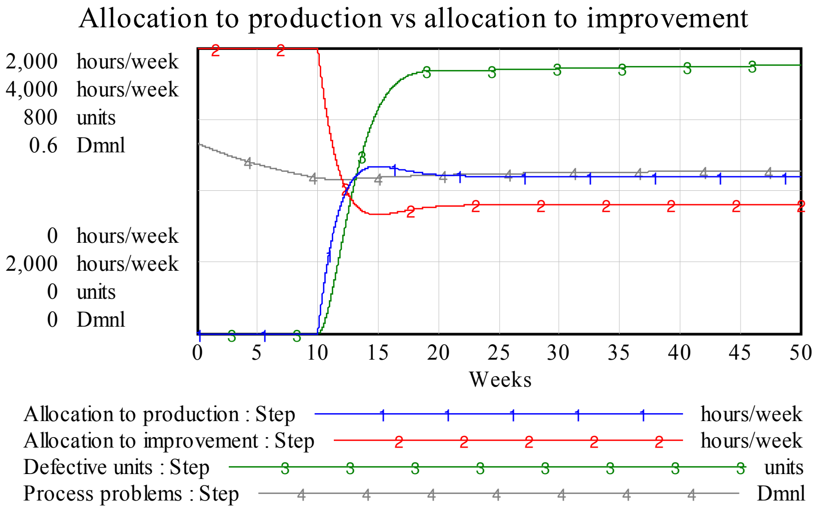

Figure 6.35: Dynamic simulation with the comparison of allocation to production and allocation to improvement with a step input of 1400 units per week at week 10

The interaction between the first-order and second-order improvement loops are depicted in Figure 6.35 as a shift from the first-order improvement loop to the second-order improvement loop (work smarter loop). The interaction is clearly visible in Figure 6.35 where the allocation to production increases after week 10 while the allocation to improvement decreases at the same time. When the system reaches the desired throughput level, the allocation to production stabilises. At this time in the simulation the allocation to improvement also stabilises which causes the process problems to stabilise at a level below the initial value.

6.3.2.1.3 Results of the simulation for the dynamic behaviour of the re-investment loop

The re-investment loop illustrated in Figure 6.33 and described in more detail in paragraph 6.3.2.1.1 , could act as a vicious cycle or a virtuous cycle (Repenning & Sterman 2002), (Morrison 2007). The re-investment loop re-confirms the current behaviour of the system at that point in time which could lead to a vicious or virtuous behaviour. When the system demonstrates such behaviour, it is referred to as a tipping point (Morrison 2007), (Sterman 2000), (Repenning et al 2001). Morrison (2007) defines a tipping point as an unstable equilibrium point where Repenning et al (2001) defines a tipping point in models of infectious diseases as the threshold of infective and susceptibility beyond which a disease becomes epidemic. A tipping point is therefore a critical threshold where if the system operates beyond this point, the system behaviour will display a better before worse pattern.

Application of a tipping point in this simulation, could lock the system behaviour in a vicious cycle or a virtuous cycle. The system behaviour could be locked in a downward spiral or vicious cycle where the allocation to production increases to overcome the increase in process problems. When the system passes the critical threshold, the net process throughput declines although the allocation to production continues to rise until all the available hours have been allocated to production.

The desired throughput is simulated with a step input of 2700 units per week from week 10. Refer to Figure 6.36 for the system dynamics results of this simulation. The allocation to production increases in order to meet the desired throughput. Although the net process throughput approaches the desired throughput, the process problems continue to rise. Defective units are manufactured due to the continuous increase in process problems which requires more allocation to production to do rework. From approximately week 45, in spite of the increase in allocation to production, the net process throughput starts to decline and could end at a lower level than the desired throughput.

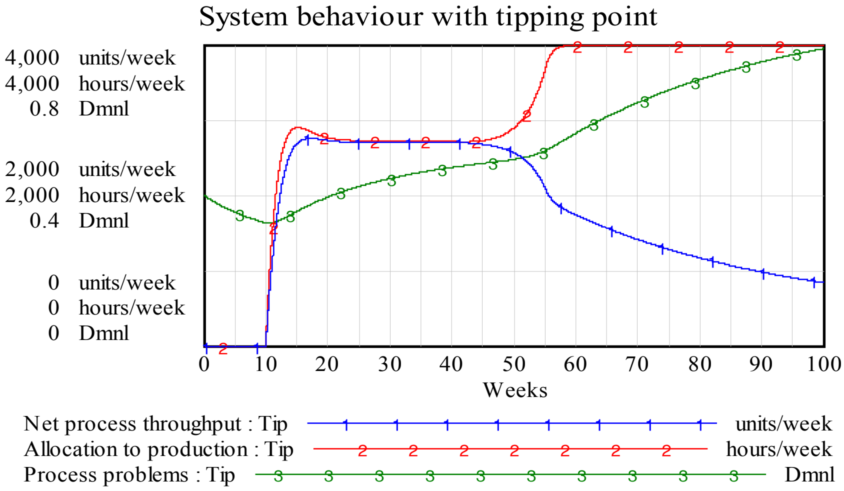

Figure 6.36: Simulating a tipping point from a desired throughput step function of 2700 units per week from week 10

The system behaviour in Figure 6.36 displays a typical tipping point. The increase in the desired throughput pushed the system beyond the critical threshold. The increase in the process problems had a direct impact on the creation of defective units. More hours had to be allocated to production in order to overcome the shortfall which meant less hours in allocation to improvement. Less hours allocated to improvement meant even more process problems and more defective units which required even more allocation to production until all the available time is allocated to production. The system is trapped in a vicious cycle which reinforced the behaviour at that point in time.

The tipping point of a system is typically not known to production managers and stretching production targets could push the system beyond the critical threshold. The optimal production level of the system is also unknown to the production manager. Morrison (2007) postulates that the optimal output for the system could be determined by factors such as, unattended process problem level, average process erosion time, time to correct problems, allocation for maximum problem correction and available time. Available time is the only factor that would be directly known to the production manager.

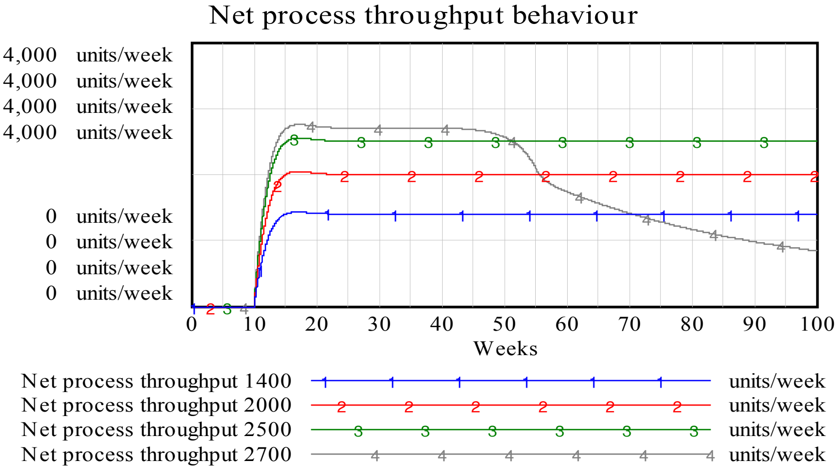

Figure 6.37: Sensitivity of the system behaviour towards an increase in desired throughput simulating a tipping point

Figure 6.37 displays the results of the simulation with an increase in the desired throughput from 1400 units per week to 2700 units per week. The results clearly illustrate that the system demonstrates a typical tipping behaviour between 2500 units per week and 2700 units per week. With desired throughput levels below 2700 units per week, the allocation to improvement is sufficient to keep the process problems in equilibrium.

Figure 6.38 displays the results for the simulation where the desired throughput is increased from 1400 units per week to 2700 units per week. From the results it is clear that the allocation to improvement stabilises for all the levels of desired throughput except for a desired throughput of 2700 units per week. At a desired throughput of 2700 units per week, all the hours available are allocated to production due to the continuous increase in process problems. Refer to Figure 6.38.

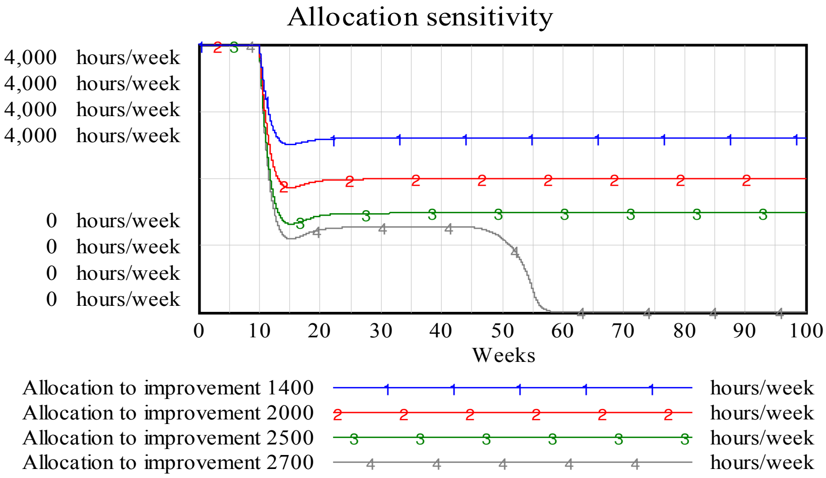

Figure 6.38: Sensitivity of allocation to improvement at different levels of desired throughput

At all levels of desired throughput, the process problems are in equilibrium except for a desired throughput of 2700 units per week. When the allocation to improvement decreases at approximately week 45, the process problems increase more from week 50. The offset between allocation to improvement and the increase in process problems could be due to several delays in the system. Refer to Figure 6.39.

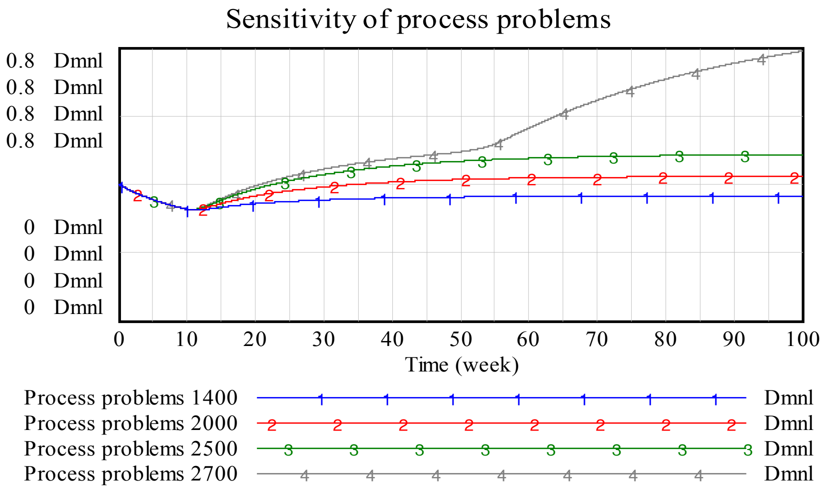

Figure 6.39: Sensitivity of process problems at different levels of desired throughput

The average process erosion time and time to correct problems could be factors that are unknown to a production manager in a typical manufacturing facility as discussed earlier. For the purpose of this simulation, the unattended process problem level is a target that could be between 0 and 1 and as also discussed earlier, is also an unknown parameter to a production manager in a typical manufacturing facility.

In Figure 6.40 the system was tested at different levels of unattended process problem level at a desired throughput of 2700 units per week, as displayed by simulation run 1, 2 and 3. Simulation run number 4 was run at a desired throughput of 3100 units per week. From the results it is clear that when the unattended process problem level is reduced from 0.9, the tipping point of the system is delayed to a higher desired throughput.

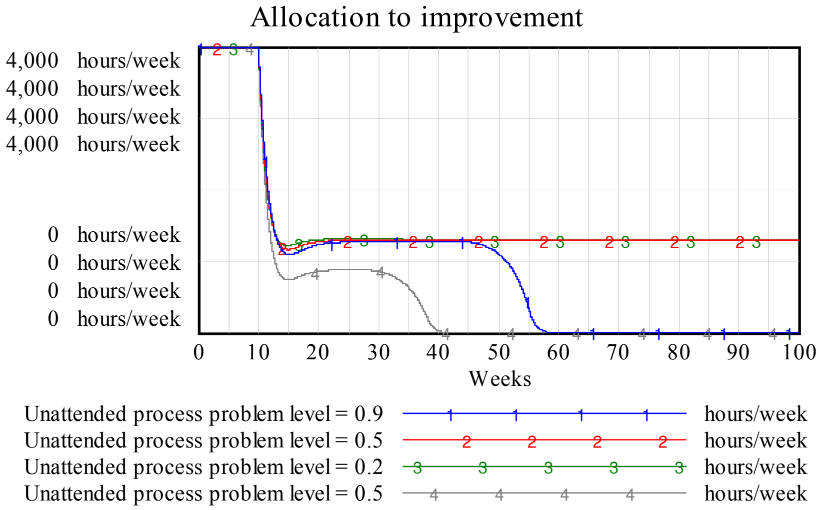

Figure 6.40: Allocation to improvement with different levels of unattended process problem level.

The system tipped at a desired throughput of 2700 units per week at an unattended process problem level of 0.9. Refer to Figure 6.40 simulation run number 1. When the unattended process problem level is set at 0.5 at a desired throughput of 2700 units per week, simulation run number 2, the system did not tip. However, when the unattended process problem level was set at 0.5 at a desired throughput of 3100 units per week, simulation run number 4, the system tipped.

When the unattended process problem level is lower, fewer process problems are introduced and the stock of process problems are less. Refer to Figure 6.33. With fewer process problems, less defective material is produced and hence less hours are to be allocated to production for the rework of the defective units in order to close the throughput gap. The balance of the hours available from the available time could be allocated to improvement which could delay the tipping point.

The average process erosion time is the average rate at which the stock of process problems approach and meet the unattended process problem level. In Figure 6.41 the system was tested at different levels of average process erosion time. The simulations, number 1, 2 and 3 were done for average process erosion time levels of 42, 36 and 30 weeks respectively. The results in Figure 6.41 clearly demonstrate that the stock of process problems stabilises at a higher level the shorter the average process erosion time is. In simulation run 1 at an average process erosion time of 42 weeks, process problems stabilises at a lower level than the initial level of 0.4 while simulation run 3 at an average process erosion time of 30 weeks, process problems stabilise at a slighter higher level than the initial level of 0.4.

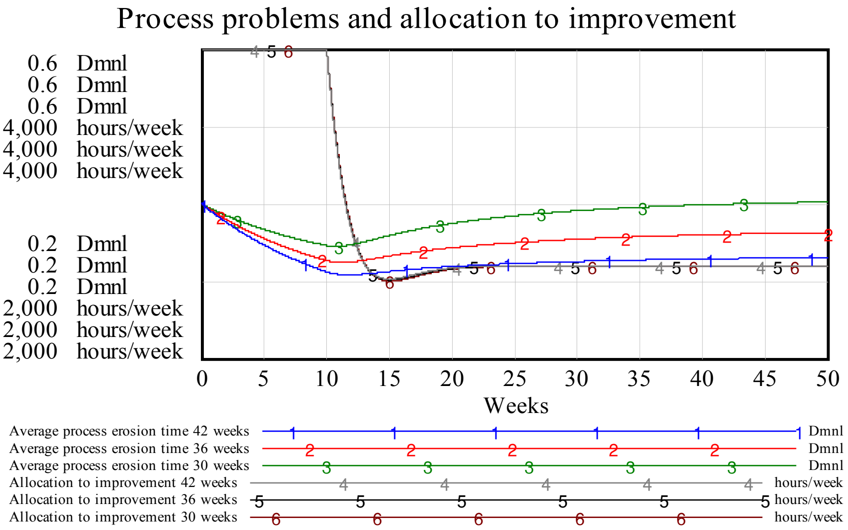

Figure 6.41: Dynamic behaviour of process problems and allocation to improvement at different levels of average process erosion time

When the process erosion time is shorter, the system could deteriorate at a quicker rate, and hence the stock of process problems accumulate quicker to stabilise at a higher level in the same time span than the longer average process erosion time. The results further demonstrate that the allocation to improvement, simulation run 4,5 and 6, at the different levels of average process erosion time, has an effect on the dynamics of allocation to improvement only during the transient condition of the system. The allocation to improvement stabilises at exactly the same level with slight differences in the undershoot before it stabilises. This could be attributed to the fact that allocation to improvement is the time left after allocation to production to meet the throughput target.

Time to correct problems is a delay in the system that could have an effect on the stock of process problems by influencing the output rate, problem correction. Refer to Figure 6.33 for the system dynamics model. Time to correct problems could be the time delay that a typical manufacturing facility could take to execute the quality improvement programmes in order to reduce the process problems.

It is clear from the simulation results that a shorter time to correct problems dynamically reduces the stock of process problems. Refer to Figure 6.42. A shorter time to correct problems increases the output rate, problem correction, of the stock of process problems which means that the problem correction happens more quickly compared to a longer time to correct problems. During the simulation run 1, time to correct problems set at 8 weeks, the process problems stabilised at a lower level than the initial level of 0.4. When the time to correct problems is set at 24 weeks, the process problem level stabilised at a level higher than the initial value of 0.4 as demonstrated by simulation run number 3. A longer time to correct problems dynamically increases the stock of process problems.

The different levels of time to correct problems have an impact on the dynamics of allocation to improvement only during the transient condition of the system. The model parameter, allocation to improvement, increases the level of undershoot with an increase in the time to correct problems. The allocation to improvement stabilises at the same level for the different levels of time to correct problems.

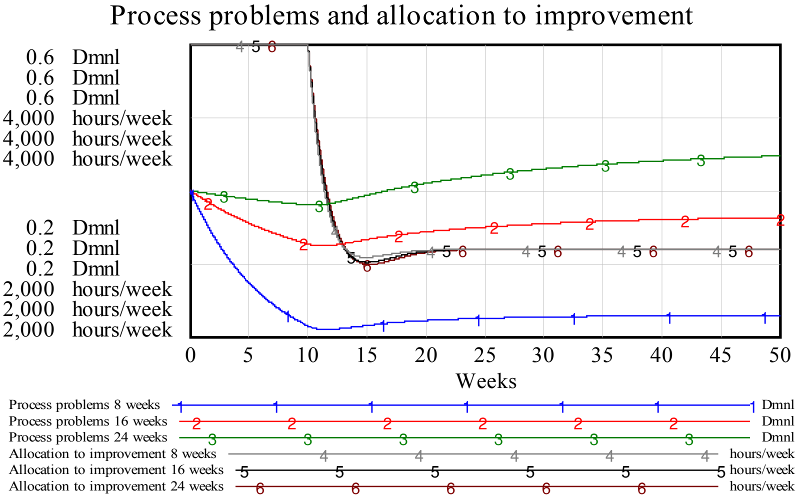

Figure 6.42: Dynamic simulation of process problems and allocation to improvement at different levels of time to correct problems

6.3.3 Results from the simulation of the system dynamics model with a sustainability feedback loop

In the previous section, the system dynamics simulation model for the quality improvement programme including the rework loop, was discussed. The results of the simulation demonstrating the tipping point, were also discussed. In this section, the description of the complete system dynamics structure of the quality improvement programme with the sustainability feedback loop, as described in paragraph 6.1.5.2 , is discussed. The system dynamics structure described here includes the rework loop as described in paragraph 6.3.2

as well as the management support loop depicted by the soft factors such as management pressure and managerial effectiveness, as described in paragraph 6.2.2.1 . The system dynamics simulation model discussed in this section, has been fundamentally developed and grounded in literature and case study data gathered during semi-structured interviews, direct observations and archived data. The results from the system dynamics simulation are also analysed and discussed. The simulation has been done with Vensim®, with a list of the equations referenced in Appendix B of this thesis.

6.3.3.1 System dynamics model assumptions and feedback loops

The parameter DPU is defined in this system dynamics simulation model as the number of defective units per unit produced. The reporting delay for the measurements to be made available for the next administration processes is indicated by the measurement reporting delay parameter. The defective units per unit produced [dimensionless] are defined in equation 6.25 as follows,

$$DPU = \frac{Defective\ units\ produced}{Gross\ process\ throughput} / (Measurement\ reporting\ delay) \tag{6.25}$$

Refer to Figure 6.43 and 6.44 for the system dynamics structure of the quality improvement programme developed and evaluated with the sustainability feedback loop, including the rework loop and the management support loop, respectively. The parameter, DPU, feeds into the management support loop at the model parameter DPU gap (Figure 6.44) while the parameter, managerial effectiveness, feeds into the parameter problem correction of the quality improvement programme (Figure 6.43). DPU gap [dimensionless] is defined in equation 6.26 as follows,

$$DPU\ gap = Desired\ defect\ level - DPU \tag{6.26}$$

The output rate of the stock of process problems, problem correction, is modified by two parameters, problem correction effectiveness and managerial effectiveness. Problem correction effectiveness is defined by equation 3.18, which describes the ratio between allocation to improvement and allocation for maximum problem correction, defined earlier in section 3.2 Problem correction effectiveness is a dimensionless ratio. Managerial effectiveness is also a dimensionless parameter which is the output from a table function as a function of the input, management pressure. The relationship between managerial effectiveness and management pressure was defined earlier in paragraph 6.2.3

System parameters often depend non-linearly on one or more other variables where the parameter could be a rate or an auxiliary that feeds into a rate (Sterman 2000:525). Sterman (2000) continues to state that the non-linear functions are often normalised by the normal or reference value of the input where one or more variables could have multiplicative or additive effects. Sterman (2000) further postulates that the additive formulation assumes the effects of each input to be strongly separable but could be incorrect in extreme conditions. Sterman (2000) recommends that multiplication formulation should be used when an extreme value of any input dominates all other effects.

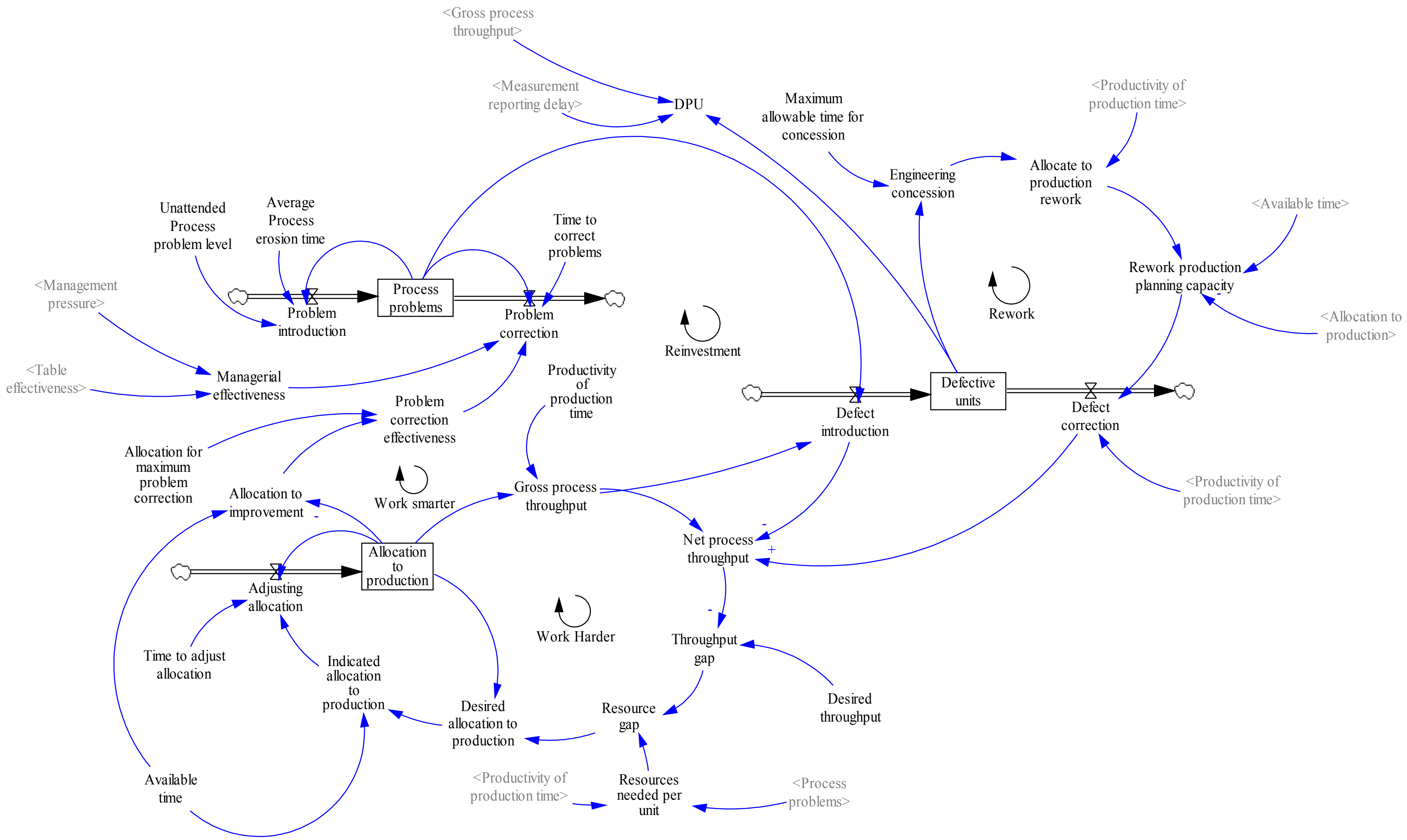

Figure 6.43: System dynamics structure of the complete quality improvement programme with the sustainability feedback loop. Part one – system dynamics structure for the quality improvement programme including the re work loop

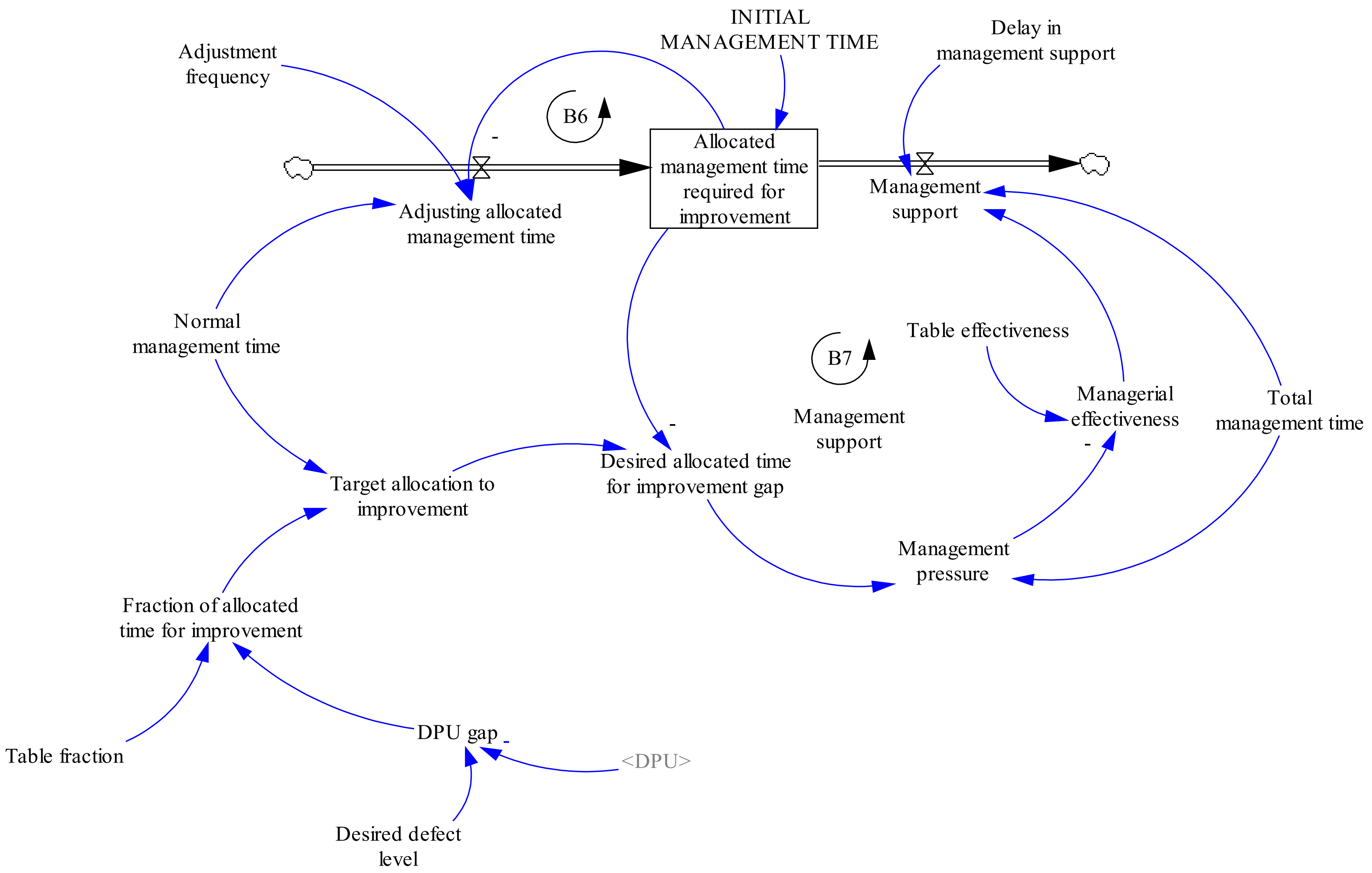

Figure 6.44: System dynamics structure of the complete quality improvement programme with the sustainability feedback loop. Part two - system dynamics structure for the management support loop

The output rate variable, problem correction [dimensionless/week] is defined in equation 6.27 as follows,

$$\begin{matrix}\text{Problem}\\ \text{correction}\end{matrix} = \left(\begin{matrix}\text{Managerial}\\ \text{effectiveness}\end{matrix} + \begin{matrix}\text{Problem correction}\\ \text{effectiveness}\end{matrix}\right) * \left(\frac{\text{Process problems}}{\text{Time to correct problems}}\right) \qquad (6.27)$$

The additive formulation is used for the two parameters, managerial effectiveness and problem correction effectiveness. The following two extreme conditions were considered, managerial effectiveness being zero and problem correction effectiveness being zero. From paragraph 6.2.3 , it is clear that managerial effectiveness cannot be zero but could be a minimal value. Although managerial effectiveness could be a minimal value, it could not dominate the problem correction effectiveness variable which is a function of the allocation of the balance of the labour hours to improvement.

Problem correction effectiveness can be zero when the allocation to improvement is zero. This is typically the situation when all the available labour hours are allocated to production. Although all the labour hours could be allocated to production, it could not dominate managerial effectiveness. One could still have management support that could lead to managerial effectiveness, even though all the labour hours are allocated to production. Managerial effectiveness and problem correction effectiveness are thus separable.

6.3.3.2 Dynamic behaviour of the quality improvement programme – system dynamics model with a sustainability feedback loop

The dynamic behaviour of the system dynamics model for the quality improvement programme is investigated by simulating the desired throughput with a step input where the desired throughput is an exogenous goal to the total system. The exogenous goal is typically the goal set by the production manager and is a requirement of the business. A key assumption represented in this model is that the rework of defective units takes priority over improvement by allocating the balance of the labour hours left after allocation to production to rework of the defective units before being allocated to improvement. The model further assumes that the allocation decision is made with full knowledge of the system, which includes throughput rate, productivity of production time and current allocation to production (Morrison 2007).

The desired defect level is another exogenous goal which could also be set by management. This goal is typically another business requirement which could stem from the goals and targets set by the quality improvement programme. Management support towards the quality improvement programme is determined by the stock of allocated management time required to support the improvement initiative and is a function of the desired allocated time for the improvement gap.

The variable defective units per unit produced, depicted by DPU, is part of the feedback loop which feeds into the management support loop via the variable, fraction of allocated time for improvement and target allocation to improvement. Target allocation to improvement is the fraction of management time required for the support of the improvement initiative and is a function of the DPU gap. The variable, desired allocated time for improvement gap, is determined from the variable, target allocation to improvement, and becomes the target of the management time to be allocated to support the improvement initiative, which ultimately could determine the management support towards the quality improvement programme.

6.3.3.2.1 Dynamic simulation of the information delay

Fraction of allocated time for improvement is the output from a table function depicted in Figure 6.22, with the DPU gap as the input for the table function. The information from the gap between the actual defects per unit and the desired level of defects per unit, described by the DPU gap, is not available immediately. The information could be available only after the quality data pertaining to manufacturing has been captured, analysed and reported with recommendations. These required actions in the system could create an information delay.

The simplest information delay and mostly used is called exponential smoothing or adaptive expectations where adaptive expectations is defined as a belief that gradually adjusts to the actual value of the variable (Sterman 2000:428). If the belief is consistently wrong, it could be revised until the error is eliminated. Sterman (2000) continues to argue that in adaptive expectations, a belief changes when it is in error, which is when the actual state of affairs differs from the perceived state of affairs. This structure is known as a first-order information delay.

Often a delay could involve multiple stages between the actual state of the system and the decisions that alter it (Sterman 2000:432). The current values of the input could be unavailable due to measurement and reporting delays. Delays could be administrative delays where the data is captured and analysed and decision-making delays where the decision makers revise their beliefs and finalise their judgement to act on it. Sterman (2000) argues that a higher-order information delay could be modelled where the output is simply the input lagged by a constant time period (D) or reporting delay, where one example could be measurement and reporting processes. This process is depicted in equation 6.28 (Sterman 2000:432).

$$Reported\ value(t) = Actual\ value(t-D) \tag{6.28}$$

A high order delay could be modelled by the SMOOTHn function, in the Vensim® platform, where the SMOOTHn function consists of n^{th} first-order information delays cascaded in series. The perceived value of each stage is the input to the next stage, and the output of the delay is the perceived value of the final stage where each stage equal to 1/n of the total delay time D (Sterman 2000:433).

To allow for the information delay in the measurement and reporting processes associated with the DPU gap, the fraction of allocated time for improvement is modified with the variable information delay. Refer to Figure 6.45 for a modified structure previously depicted by Figure 6.44 The fraction of allocated time for improvement is defined in equation 6.29 as follows,

$$\begin{matrix} Fraction\,of\;allocated \\ time\;for\;improvement \end{matrix} = Table\;fraction\left(Information\,delay \right) \tag{6.29}$$

Information delay is defined in equation 6.30 where the delay time (D) is defined by analysis time. Analysis time is the time delay in the system due to the measurement and reporting processes which could include the time taken to collect the data, analyse the data, reporting on the defects per unit produced with recommended actions and the time for management to discuss the data and recommended actions. The number of stages in this process could typically be four which is defined by the variable, measurement and reporting processes. DPU gap is the variable described previously in equation 6.26.

$$\begin{matrix} Information \\ delay \end{matrix} = SMOOTHN\left(DPU\;gap, \begin{matrix} Analysis \\ time \end{matrix}, 0, \begin{matrix} Measurement\;and \\ reporting\;processes \end{matrix} \right) \tag{6.30}$$

The initial information delay at t_0 is defined as zero in equation 6.30.

Managerial effectiveness closes the feedback loop, sustainability, which is the output from the non linear function depicted by table effectiveness and where management pressure is the input. Management pressure is the variable that describes the pressure management could experience when the DPU gap is more than the exogenous goal of desired defect level. The desired allocated time for improvement gap determines the pressure management could experience as a function of the total management time when the desired allocated time for improvement gap is more than zero.

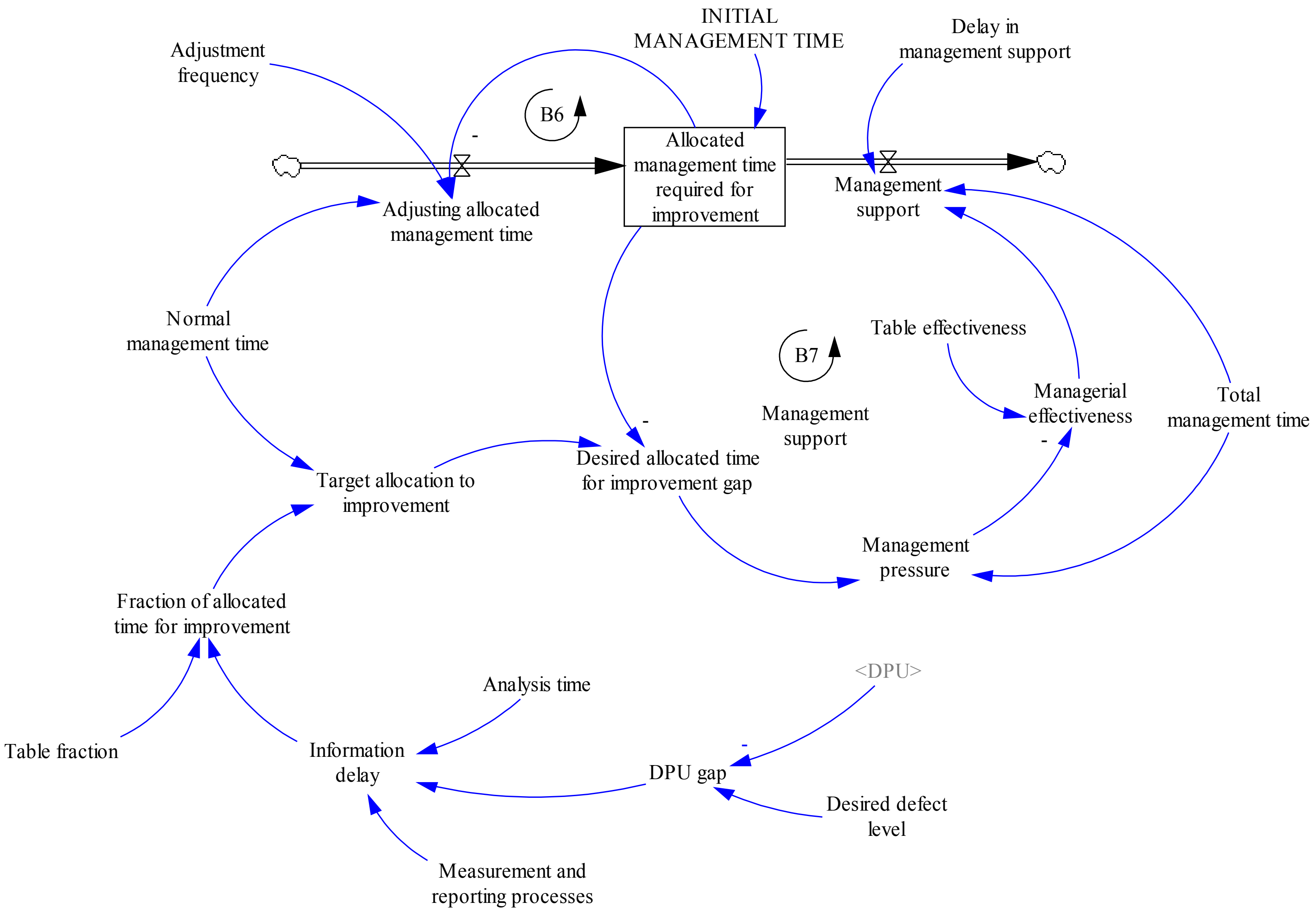

Figure 6.45: System dynamics structure of the complete quality improvement programme with the sustainability feedback loop. Part two - system dynamics structure for the management support loop with an information delay

6.3.3.3 Simulation results for the complete quality improvement system dynamics structure including an information delay

The main objective with the investigation of the behaviour of the structure for the complete quality improvement programme including the sustainability feedback loop, is to evaluate the effect of the management support loop on the dynamics of the parameter, defective units per unit produced (DPU) as well as to evaluate the stability of the structure at different possible management scenarios.

The system dynamics structure is simulated with a step input of 1400 units per week for the desired throughput from week 0 to investigate the stability of the system. The simulation is done with the base line parameters in Table 6.4. Refer to equation 3.20 for a description of the step function.

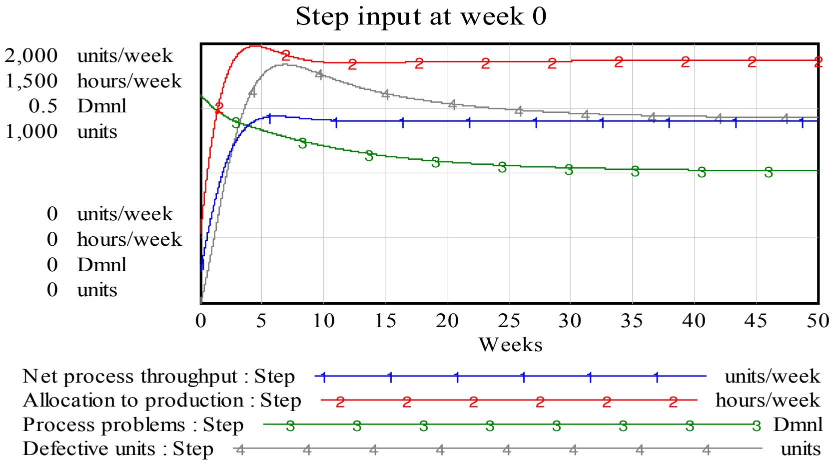

Figure 6.46: Dynamic simulation for the desired throughput as a step function from week 0 for the complete quality improvement structure

Parameter	Value	Units
Unattended process problem level	0.9	dimensionless
Average process erosion time	36	week
Time to correct problems	16	week
Productivity of production time	1	unit/hour
Allocation for maximum problem correction	4000	hours/week
Available time	4000	hours/week
Time to adjust allocation	1	week
Initial process problems	0.4	week
Maximum allowable time for concession	2	week
Initial value for Defective units	0	units
Initial allocation to production	400	hours/week
Analysis time	4	week
Measurement and reporting processes	4	dimensionless
Initial management time	0	hours/week
Total management time	48	hours/week
Normal management time	40	hours/week
Adjustment frequency	1	week
Delay in management support	1	week
Measurement reporting delay	1	week
Desired defect level	0.03	dimensionless

Table 6.4: Base line model parameter values for the dynamic simulation of the complete quality improvement system dynamics structure including an information delay

The system response to a step function of the desired throughput from week 0 is displayed in Figure 6.46. The allocation to production is adjusted in order to achieve the desired throughput of 1400 units per week. The net process throughput stabilises after approximately 10 weeks with the allocation to production displaying slightly oscillating behaviour but also reaching stability at approximately week 30. The increase in the net process throughput is due to the increase in allocation to production. The net process throughput approaches the desired throughput level of 1400 units per week after 10 weeks. The defective units start to rise as more time is allocated to production, until the required amount of hours to satisfy the desired throughput is reached. Refer to Figure 6.47. When the allocation to production stabilises, the balance of the hours are allocated for improvement.

The defective units continue to increase, due to the presence of process problems. As the allocation to production begins to stabilise, the allocation to improvement also starts to stabilise. When the allocation to improvement stabilises, the process problems continue to decline from the original value of 0.4. Due to a decline in process problems, defective units also continue to decline until the process problems stabilise after approximately 50 weeks. The effect of the sustainability loop is clearly visible in the results of the simulation displayed in Figure 6.46 and Figure 6.47 in comparison to Figure 6.34 and Figure 6.35, displaying the results of the simulation before the modelling of the sustainability loop. In Figure 6.35, the process problems reach equilibrium after the allocation to improvement has stabilised. The defective units also stabilised, as a function of the process problems. Process problems and defective units reduced, approaching exponential decay behaviour with the modelling of a sustainability feedback loop.

In Figure 6.47, the process problems did not stabilise after the allocation to improvement stabilised, but continue to decline to stabilise at a lower level than previously shown in Figure 6.35. The process problems stabilised at a level above 0.3, for a system dynamics structure without a sustainability loop and for a system dynamics structure with a sustainability loop, the process problems stabilised at a level well below 0.3. In both instances, it took approximately 50 weeks to stabilise. Refer to Figure 6.35 and Figure 6.47 respectively.

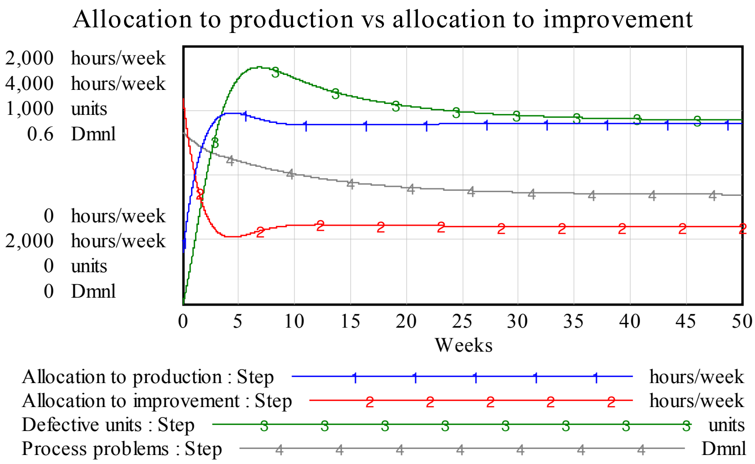

Figure 6.47: Dynamic simulation with the comparison of allocation to production and allocation to improvement with a step input of 1400 units per week from week 0

Although the process problems continued to decay, the allocation to improvement stabilised. In the real world one would expect the allocation to improvement also to decline while the process problems decline. The results displayed in Figure 6.47 are typical for the assumption that the balance of the labour hours after being allocated to production, are allocated to improvement. This is consistent with the field work done by Repenning and Sterman (2002) as well as the field work done during this research. Refer to paragraph 5.3.2 for the discussion of the results for the case study of the manufacturing and assembly plant.

The hours allocated to improvement are therefore not simulated as an independent stock of hours, as a function of process problems. This assumption is adequate for the modelling of the structure for the complete quality improvement programme with a sustainability feedback loop because the main objective of the simulation is not to investigate the dynamic interaction of the hours allocated to improvement and process problems.

The main objective with the modelling of the structure for the complete quality improvement programme with the sustainability loop, is to study the effect of the feedback of the sustainability loop on the dynamics of the defective units produced per unit produced (DPU). The dynamic behaviour of the defective units per unit produced (DPU), is following a decaying behaviour, previously described as the dynamic hypothesis in section 6.1.3 of Chapter 6. Refer to Figure 6.48, which displays the dynamic behaviour of the variable DPU.

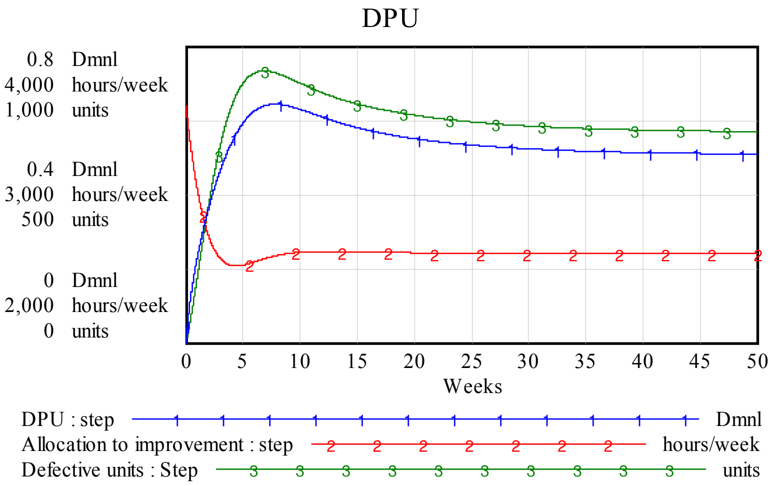

Figure 6.48: Dynamic behaviour of the defective units per unit produced (DPU) with an exponential decay behaviour

The defective units per unit produced (DPU) increase while the hours allocated for improvement decrease, due to the remaining balance of the hours not allocated to production. When the net process throughput approaches the desired throughput target, the hours allocated to improvement stabilise and level out as previously discussed. The defective units per unit produced (DPU), approaches its maximum value after the allocation to improvement has gone beyond its minimum value and stabilised at a higher level. The delay in the behaviour of the defective units per unit produced could be due to the different delays in the system such as the information delay. The defective units per unit produced (DPU), continue to decay, approaching the behaviour associated with an exponential decay.

As previously discussed in paragraph 3.2 process problem introduction is modelled with the analogy of entropy. If a process is left unattended, the process could deteriorate to that extent that the process problems could naturally increase (Morrison 2007). The parameter, unattended process problem level, describes the target level for the process if it is left unattended. The value for this parameter is not known and cannot be measured. It could also be a function of the state of the process. Different values for the unattended process problem parameter could impact on the behaviour of the system in different ways.

In Figure 6.49 the dynamic behaviour of the defective units per unit produced (DPU) is displayed with different values for the unattended process problem level. With the unattended process problem level at 0.3 and 0.1 respectively, the half life of the defective units per unit produced (DPU) is approximately 15 and 9 weeks. The data clearly demonstrates that for a lower value of unattended process problem level, the half-life of the process could be the less.

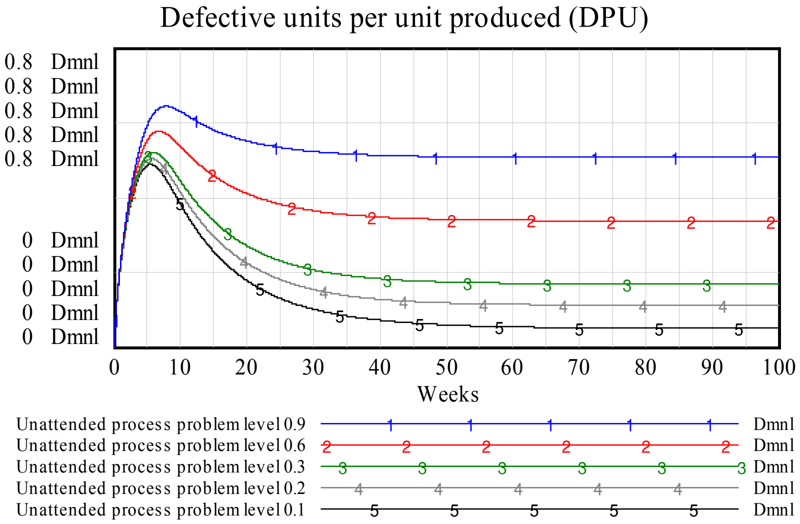

Figure 6.49: Dynamic behaviour of the defective units per unit produced for different values of unattended process problem level

The unattended process problem level is modelled as the potential target level for the stock of process problems if the system was left unattended. The stock of process problems is adjusted through the difference between the problem introduction rate and the problem correction rate. Refer to Figure 6.43. If the problem correction rate remains the same, the problem introduction rate could change through the unattended process problem level and hence the stock of process problems could have a different dynamic behaviour.

The defective units per unit produced (DPU) stabilise at different levels, progressively less for every reduction in unattended process problem level. Defective units per unit produced (DPU) stabilise at the highest level when the unattended process problem level is at its highest level of 0.9. Defective units per unit produced (DPU) stabilise at the lowest level with the unattended process problem level at 0.1.

Problem correction is the output rate at which the stock of process problems is reduced at a rate of time to correct problems. Refer to Figure 6.43. The parameter, time to correct problems, is the time that it takes the management to correct the process problems. The process problems are measured and investigated depicted by the sustainability feedback loop (B5) as depicted in Figure 6.11 and Figure 6.43. The outcome from these investigations rolls over into actions that could be process experimentation and training in order to solve the process problems identified earlier and ultimately reduce the defective units produced per unit (DPU).

The parameter, time to correct problems, could be a function of the complexity of the system's process problems and can typically be measured. It is therefore a parameter that is known to management over which management could have some control. This is consistent with the field work done in this research. The behaviour of the system dynamics structure for the complete quality improvement programme including the information delay, can be researched paramatically by simulating the impact of this parameter on the defective units per unit produced (DPU).

The first simulation is done with the unattended process problem level set at 0.3 and the time to correct problems varied respectively between 6 weeks and 12 weeks. Refer to Figure 6.50. The half-life for the exponential decay for defective units per unit produced (DPU) with a time to correct problems equal to six weeks is approximately seven weeks. The half-life for the exponential decay for the defective units per unit produced (DPU) is approximately 12 weeks with a time to correct problems equal to 12 weeks.

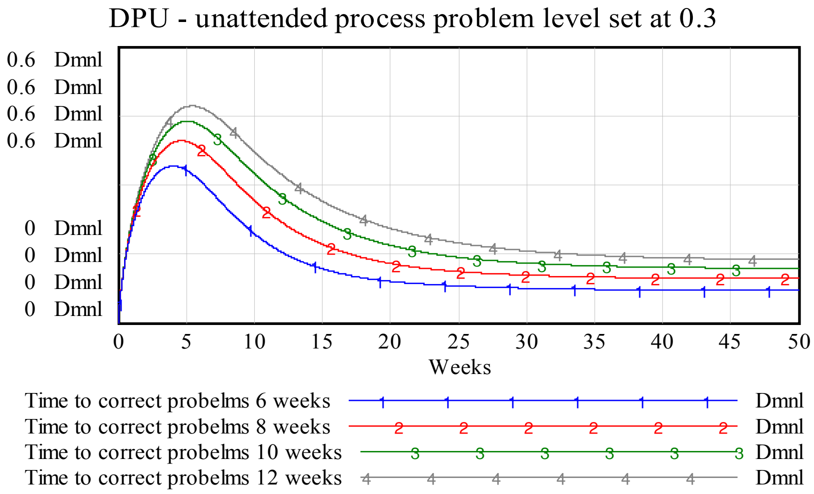

Figure 6.50: Dynamic behaviour of DPU with unattended process problem level set at 0.3 Time to correct problems is varied between 6 and 12 weeks

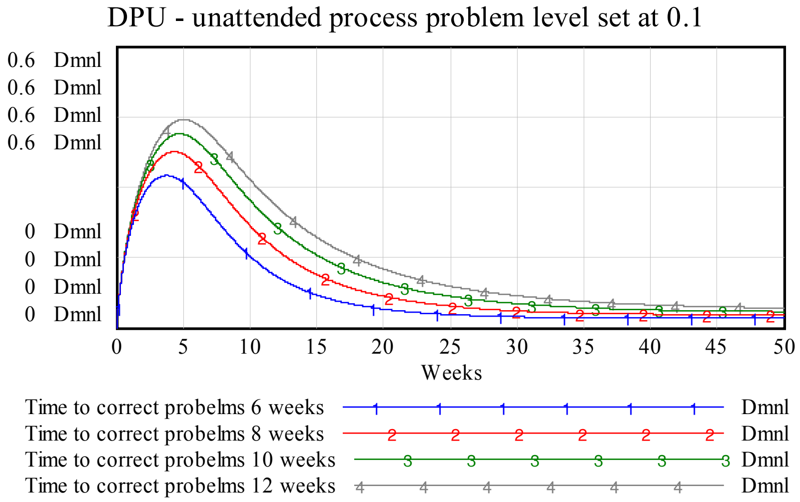

Figure 6.51: Dynamic behaviour of DPU with unattended process problem level set at 0.1 Time to correct problems is varied between 6 and 12 weeks

The next simulation is done with the unattended process problem level set at 0.1 with varying levels of time to correct problems between six weeks to 12 weeks. Refer to Figure 6.51. The results clearly demonstrate that the half life for the exponential decay increases as the time to correct problems increases. The exponential decay half-life is approximately six weeks for the parameter time to correct problems equal to six weeks. When the time to correct problems is increased to 12 weeks, the exponential decay half-life increases to approximately nine weeks.

The results further demonstrate that the defective units per unit produced (DPU) exponential decay half-life is more tolerable for an increase in time to correct problems when the unattended process problem level is set at 0.1 compared to an instance where the unattended process problem level is set at 0.3. The results also demonstrate that the defective units per unit produced (DPU) stabilise at a lower level for the same value for the model parameter, time to correct problems. Refer to Figure 6.52.

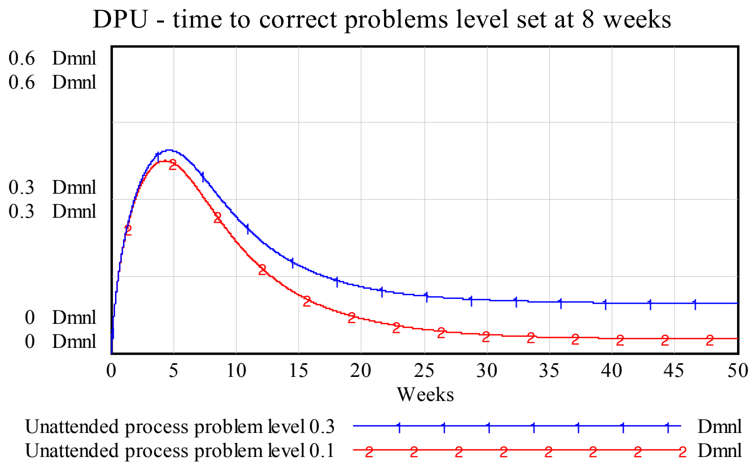

Figure 6.52: Dynamic behaviour of defective units per unit produced (DPU) with time to correct problems set at 8 weeks. Unattended process problems is set at 0.3 and 0.1 respectively

6.4 Summary

The dynamic hypothesis, formulated from the reference mode and archived data gathered during the case studies, is explained and clearly demonstrates the link, with behaviour associated with a structure of a negative feedback loop, with goal seeking behaviour. The dynamic impact of conditions outside the control of a manager is also demonstrated. The theory for the sustainability feedback loop is also explained through the description of operations management and organisational behaviour, grounded in the literature and case study data.

Management support is recognised in the literature as one of the key elements for sustainable quality improvement programmes. A management support model is developed based on an analogy with a capacitated delay structure. The management support model is further expanded to include managerial effectiveness as a non-linear function of management pressure. The system dynamics model of the quality improvement programme is fundamentally developed and expanded to include the management support system dynamics model, as part of the sustainability feedback loop.

Different sensitivity analysis studies demonstrate the dynamic impact of the sustainability feedback loop on the system dynamics model of the quality improvement programme. The simulation studies further demonstrated the exponential decay behaviour which is typical for a negative feedback loop. The decay in the simulation results for the quality improvement programme including the sustainability feedback loop, confirmed the dynamic hypothesis.

During the next chapter the system dynamics model of the complete quality improvement programme, developed and initially assessed in this chapter, is tested and validated against real system data gathered during the polar type case study design applicable to case study one for the machine shop. Refer to section 5.2.1 in Chapter 5 for more detail.

CHAPTER 7

MODEL TESTING AND VALIDATION OF MANAGEMENT DECISION POLICIES FOR QUALITY IMPROVEMENT PROGRAMMES IN A HEAVY ENGINEERING MANUFACTURING ENVIRONMENT

7 Introduction

The system dynamics model from Repenning and Sterman (2002) has been expanded to include a sustainability feedback loop, refer to Figure 6.15, to model the balancing feedback behaviour of a quality improvement programme. The model depicted by Figure 6.15 has been further developed into a system dynamics simulation model to simulate the behaviour of the complete system dynamics model, as depicted in Figure 6.43 and Figure 6.45, with the desired throughput estimated from the desired throughput of the real system. The desired throughput of the real system has been determined from data gathered during the the polar type case study design through semi-structured interviews and archived data.

The purpose of Chapter 7 is first to describe the model testing for this model to build confidence in the model for the purpose of this research. A second aim is to calibrate the model by optimising the model parameters in order to assess quantitatively the model's fit to the historical data obtained during the case study. The third purpose with this chapter is to model different scenarios which could impact the sustainability of a quality improvement programme, and lastly to propose possible management decision policies that could lead to sustainable quality improvement programmes in a heavy engineering manufacturing environment.

The goal is therefore to model the behaviour of the system and not necessarily to model exactly the reality and setting in which the study was done. There is no known method for proving a model to be correct (Forrester & Senge 1980). Modelling the behaviour could assist to make better decisions, informed by the best available model (Sterman 2000). Sterman (2000) continues to say that " Instead of seeking a single test of validity models either pass or fail, good modellers seek multiple points of contact between the model and reality by drawing on many sources of data and a wide range of tests."

Numerical, written and mental data are examples of three types of data used to develop system dynamics models (Forrester 1980) For the purpose of this research, the numerical data is represented by time series records gathered from various databases researched during the polar type case study design. The written data gathered during this research from these case studies include records such as operating procedures, quality procedures, emails, presentations on implementation of quality improvement programmes and other archival material.

Mental data has been determined from interviews and observations during these case studies. Refer to Chapter 4 for more detail on the research design and methodology used during this research. Also refer to Chapter 5 where the theory developed by Reppening and Sterman (2002), applicable to a automotive manufacturing environment, has been proven to be valid for a heavy engineering manufacturing environment. From this mental data, a system dynamics model for sustainability of quality improvement programmes, has been fundamentally developed. Refer to Figure 6.15 and section 6.1 for more detail.

Tests conducted during this research include those for the dynamic hypothesis which is defined as "A theory that explicitly articulates how structure and decision policies generate behaviour." (Oliva 2003). Oliva (2003) continues to argue that model calibration – the process of estimating the model parameters (structure) to obtain a match between observed and simulated structures and behaviours – is a stringent test of a dynamic hypothesis. According to Bunge, as quoted by Oliva (2003), a well formulated hypothesis should be (1) logically sound, (2) grounded in previous knowledge and (3) empirically testable.

The formulation of the system dynamics model with consistent units, positive time constants, at least one stock in the feedback loops and computer simulation help to ensure that the dynamic hypothesis is logically sound (Oliva 2003), (Sterman 2000). Oliva (2003) continues to argue that system dynamics is grounded in previous knowledge where the system dynamics academic community has endeavoured to ground system dynamics work in findings from other fields.

In this research the dynamic hypothesis is grounded in theory as already explained in more detail in paragraph 6.1.5 Finally Oliva (2003) argues that to fully confront the model with a piece of reality, that it is supposed to represent the essence of the real system, the real system should be captured through a series of observations, measurements or facts. During these research observations, measurements and facts were captured, of the structure and behaviour for the system of a heavy engineering manufacturing environment, through data gathered from the field work and observations, during these case studies.

7.1 Validation and model tests to gain confidence in the model

Specific tests and procedures should be followed to investigate the suitability of a model for a specific purpose (Sterman 2000). Sterman (2000) continues to say that these tests could include inspection of boundary assumptions to a quantitative assessment of the model's historical fit. However, there is no single test to “validate” a system dynamics model, but confidence is rather accumulated as the model passes more tests when more points of correspondence between model and empirical reality are identified (Forrester & Senge 1980), (Sterman 2002)

Tests are defined as the comparison of a model to empirical reality for the purpose of corroborating or refuting the model (Forrester & Senge 1980). Forrester & Senge (1980) continue to say that empirical information for testing a model includes the model structure which is compared to descriptive knowledge of the real system structure and model behaviour compared to observed system real behaviour. Also refer to Chapter 6, section 6.1 where the descriptive knowledge of the real system has been used to develop the system dynamics model from a systems thinking perspective, for the sustainability of quality improvement programmes in a heavy engineering manufacturing environment. Validation is defined as the process of establishing confidence in the soundness and usefulness of the model through confidence that accumulates as the model behaves plausibly and generates problem symptoms or modes of behaviour seen in the real system (Forrester & Senge 1980).

Oliva (2003) proposes model calibration as a form of model testing and argues that model calibration is a stringent test of a hypothesis linking structure to behaviour. Oliva (2003) defines model calibration as " … the process of estimating the process parameters to obtain a match between observed and simulated behaviour." He continues to argue that confidence in a particular structure, with reasonable model parameter values, is a valid representation if the structure is capable of generating the observed behaviour. According to Graham, as quoted by Oliva (2003), model parameter values for system dynamics models are normally estimated from direct observations and other sources of data below the levels of aggregation of model variables. Through an iterative process, the model parameters are estimated, to match the real system's dynamic behaviour.

Model parameters could also be determined by automatic model calibration algorithms. Oliva (2003) proposes a model reference optimisation method based on non-linear optimisation algorithms that search across the parameter space. Refer to equation 7.1 for such a calibration equation (Oliva 2003).

The optimisation is achieved by adjusting the system parameters ($\boldsymbol{p}$), to minimise a function of the differences between the available data series ($\boldsymbol{d_t}$) and the corresponding model variable ($\boldsymbol{y_t}$). Multiple data series could be available and therefore the relative weighting ($\boldsymbol{w}$) for each series must be specified. The model variables are a function of the model's state variables (***s**$_t$*), parameters (***p***) and the known inputs (***u**$_t$*). The feasible range for the system parameters is defined by [***ll***, ***ul***]. Oliva (2003) states that there is a range of options for defining the error function *f* and the weight of each error series w_i . The constraint function *c*, however is directly determined by the model equations and could be non-linear.

$$\underset{p}{Min} \quad \sum_{i=1}^{n} w_i \sum_{t=T_0}^{T_f} f(y_{it} - d_{it}) \tag{7.1}$$

Subject to

$$\boldsymbol{y_t} = c(\boldsymbol{s_t}, \boldsymbol{p}, \boldsymbol{u_t}), \quad \boldsymbol{ll} \leq \boldsymbol{p} \leq \boldsymbol{ul}$$

where
w_i = *weight of ith error series ,*
y_{it} = *model variable i at time t ,*
d_{it} = *data for variable i at time t ,*
s_t = *model state variables ,*
$\boldsymbol{p}$ = *model parameters ,*
$\boldsymbol{u_t}$ = *known inputs (data series) ,*
$\boldsymbol{ll}$ = *lower limit of parameter feasible range ,*
$\boldsymbol{ul}$ = *upper limit of parameter feasible range ,*
T_0 = *initial simulation time ,*
T_f = *final simulation time ,*
n = *the number of variable − data pairs in error function*

Forrester and Senge (1980) postulated that confidence in system dynamics models can be increased by tests of model structure, model behaviour and models' policy implications. Sterman (2000:852) proposes several tests that could also be used to answer the fundamental questions such as: What is the purpose of the model? What is the boundary of the model? What is the time horizon relevant to the problem? Does the model conform to basic physical laws? Are the simulated decisions based on information the real decision makers actually have? What types of data were used to develop and test the model? Adapted and extended from Forrester and Senge (1980), Sterman (2000) proposes twelve tests to assess system dynamics models. Refer to Table 7.1 for more detail.

In the next section, the system dynamics model developed in section 6.3.2 and depicted in Figure 6.33, has been tested and validated against Table 7.1 and the method proposed by Oliva (2003) and equation 7.1. The model behaviour has been compared with the real time behaviour determined from the data gathered during the case studies for a heavy engineering manufacturing environment.

7.1.1 Model tests and validation of the interaction of the first- and second-order improvement loops including the rework loop

The interaction of the first- and second-order improvement loops including the rework loop, refer to Figure 6.33, depicts the system dynamics simulation model of the quality improvement programme before the implementation of a six sigma quality improvement programme. The system dynamics model depicted by Figure 6.33, describes the structure of the of the quality improvement programme that has been derived from the case studies done for this research as described in paragraph 6.3.2 .

The model is validated by comparing the dynamic behaviour of the model to the measured behaviour of the manufacturing system for the machine shop, represented by the polar type case study design. The actual measured behaviour of the manufacturing system is gathered from field work, interviews and archived data. Refer to Figure 7.1 displaying the behaviour of the desired throughput and defective units in months while Figure 7.2 displays the same behaviour in weeks.

Test	Purpose of test
Boundary adequacy	Are the important concepts for addressing the problem endogenous to the model?
Structure assessment	Is the model structure consistent with relative knowledge of the system?
Dimensional consistency	Is each equation dimensionally consistent?
Parameter assessment	Are the parameter values consistent with the relevant descriptive and numerical knowledge of the system?
Extreme conditions	Does the model respond plausibly when subjected to extreme shocks?
Integration error	Are the results sensitive to the choice of time step or numerical integration method?
Behaviour reproduction	Does the model reproduce the behaviour of the system (qualitatively and quantitatively) Does the model generate the various modes of behaviour observed in the real system?
Behaviour anomaly	Do anomalous behaviours result when assumptions of the model are changed?
Family member	Can the model generate the behaviour observed in other instances of the same system?
Surprise behaviour	Does the model generate previously unobserved or unrecognised behaviour?
Sensitivity analysis	Numerical sensitivity – Do the numerical values change significantly? Behaviour sensitivity – Do the modes of behaviour generated by the model change significantly?
System improvement	Did the model process help change the system for the better?

Table 7.1 Tests for assessment of system dynamics models. Adapted from Sterman (2000)

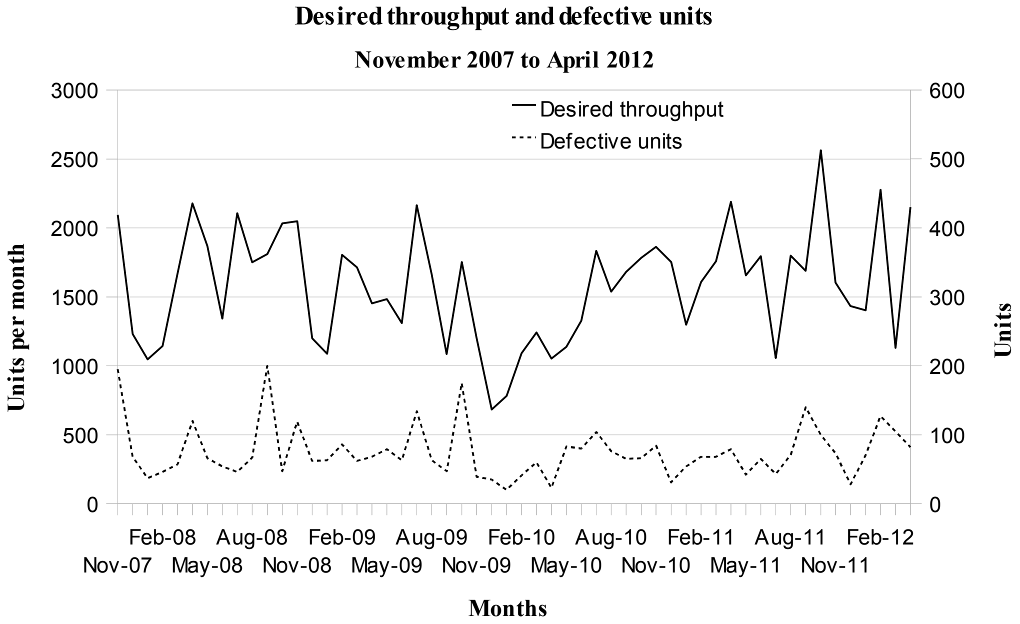

Figure 7.1: Desired throughput and defective units per month. Data displayed per month

The system dynamics model for the first- and second-order improvement loop including the rework loop, is modelled by using Vensim® DSS for Windows developed by Ventana Systems Inc. Vensim® is an integrated framework for conceptualising, building, simulating, analysing, optimising and deploying models of dynamic systems (Ventana Systems Inc. 2012).

From equation 7.1, the system dynamics model is calibrated by specifying upper ($\boldsymbol{ul}$) and lower limits ($\boldsymbol{ll}$) for specific model parameters ($\boldsymbol{p}$) to search across the range to find the best fit to the measured data ($\boldsymbol{u_t}$). The simulation is done in weeks with the desired throughput as an exogenous parameter as displayed in Figure 7.2. The function of the difference between the available data series ($\boldsymbol{d_t}$) and the corresponding model variable ($\boldsymbol{y_t}$) is assigned to the state variable, defective units, only. Because the function of the difference is assigned only to one model parameter, defective units, the relative weighting (***w***) is treated as a scale factor only in Vensim® simulations.

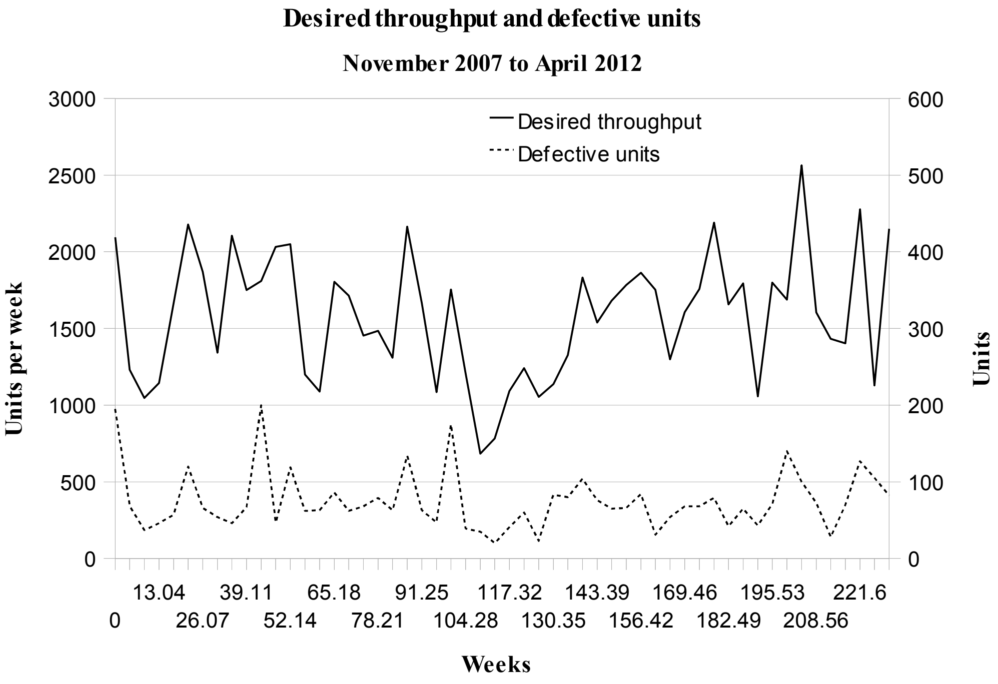

Figure 7.2: Desired throughput and defective units per month. Data displayed per week

The model is simulated and optimised to find the least difference between the measured defective units and simulated defective units. The difference is defined as the payoff value in Vensim® where it endeavoured to get the payoff value as close as possible to zero. The output from the optimised simulation, undertaken by Vensim® for this system dynamics model depicted in Figure 6.33, is tabulated in Table 7.2.

Model parameter	Upper and lower limit	Simulated model parameter value	Model parameter value to be used
Unattended process problem level	0.1 – 0.9	0.1168	0.12
Time to adjust allocation	0.01 – 1	0.0559	0.06
Initial process problems	0.1 – 0.9	0.1001	0.1
Maximum allowable time for concession	0.05 – 1	0.4443	0.44
Productivity of production time	0.1 – 0.7	0.6998	0.7
Average process erosion time	6 – 14	10.1000	10.1
Time to correct problems	13 – 35	34.9980	35

Table 7.2 Simulation output for specific model parameters at a payoff value of 0.0880407 for defective units and desired throughput as an exogenous parameter.

The behaviour of the manufacturing system, modelled by the system dynamics model of the interaction of the first- and second-order improvement loops including rework as referenced in Figure 6.33, is depicted in Figure 7.3. The model has been optimised through auto calibration, with the model parameters described in Table 7.2 for the best fit to the historical data of defective units gathered in field work, interviews and archived data during the polar type case study design.

The dynamic behaviour of the system dynamics model for the interaction between first- and second-order improvement loops including rework, with the model parameters tabulated in Table 7.2, are displayed in Figure 7.3. Desired throughput is an exogenous goal and is determined by the production manager. The defective units are endogenous to the model and is calculated from the model's state variable and model parameters during the simulation. This model's behaviour is representative of the jobbing shop manufacturing system for the heavy engineering manufacturing system, as determined from the case studies during this research.

Defective units are modelled as a function of the stock of process problems and gross process throughput. The actual measured defective units showed two distinct peaks at approximately 44 weeks and 100 weeks. Determined from fieldwork during the case studies in this research, in these two instances, the process problems have been compounded because the quality measurement process broke down. Due to this breakdown the defects were only discovered at the end of the process which led to scrapping the complete manufactured batch.

The business unit manager, machine shop recalled,

> “ We track the defect at the point of defect *[where the defect is generated]*. If there are 20 operations, the part gets rejected at operation 2 or 3… we try to find the defect at that stage and not at the end of the process.”

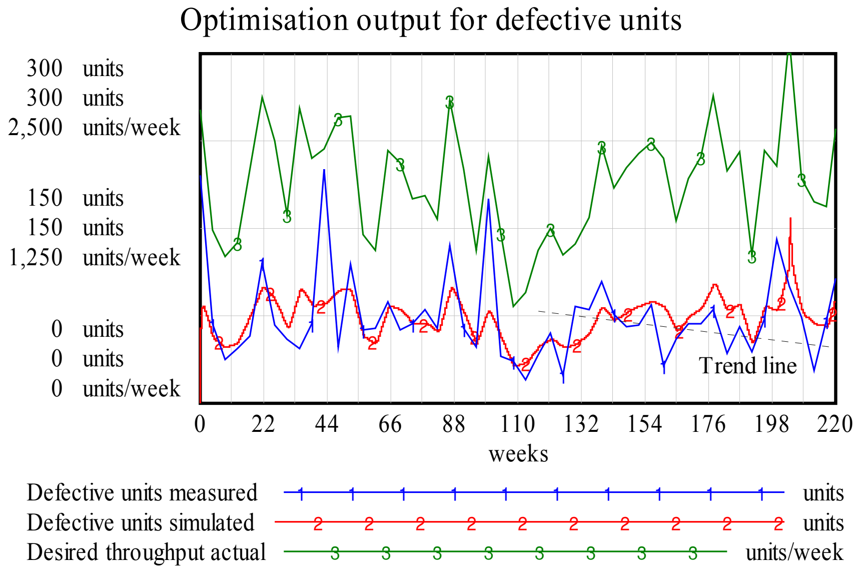

Figure 7.3: Simulation output for optimisation of model parameters for the least payoff value of defective units.

For the purpose of this research the model is built on the assumption that process problems are similar to the second law of thermodynamics, where the entropy of a system increases while left unattended. Refer to paragraph 3.2 for the full explanation. Problem introduction is therefore not modelled as a function of other parameters that could impact the stock of process problems. The simulation results depicted in Figure 7.3 indicate that the actual measured defective units show a negative trend from approximately 130 weeks to approximately 180 weeks. (The inclusion of a trend line in Figure 7.3 is for behaviour demonstration purposes only.) The negative trend is due to the dynamic impact of the implementation of a six sigma quality improvement programme on the defective units from week 130, compared to the dynamic behaviour before the implementation. The simulation of this model excludes the dynamic impact of a sustainability feedback loop, but will be simulated later in this chapter.

The model parameter, unattended process problem level, is the level to which a process would deteriorate if left unattended. This is an unknown model parameter in the manufacturing system to the production personnel. The model's behaviour demonstrates the best fit with this parameter at 0.12. Initial process problems also relate to an unknown model parameter and could be between 0.1 to 0.9. The model parameter that fits the historical data the best is 0.1.

The decision to allocate hours to production is taken by the production manager. This model parameter, time to adjust allocation, describes the rate at which the production manager can take the decision to allocate hours to production. The production manager could typically take the decision between one hour and one week. The value of the model parameter that fits the historical data the best is 0.06 weeks or approximately 2.4 hours based on a 40 hour work week. For a manager to take such a decision is indicative of the manufacturing system in this research as determined from the data gathered during the case studies.

Maximum allowable time for concession is the model parameter that describes the delay in time engineering could take to approve or reject quality concessions. From the interviews, observations and historical data, the time delay could be between once or twice a week. The business unit manager, machine shop commented as follows on the question of rework and scrap,

> “ The engineer comes once or twice a week past us *[machine shop]* and help us make a decision *[sign the concession]* ”

The value of the model parameter that fits the dynamic behaviour of the actual measured data the best is 0.44 or 17.6 hours, based on a 40-hour work week. Productivity of production time is a known model parameter to the production manager and is typically part of the month end reports, published one week after month end. From historical data gathered during the case studies in this research, the value of the model parameter productivity of production time is reported to be on average 0.52 units per hour for 30% over time. The value that fits the dynamic behaviour of the actual measured data best is 0.7 units per hour.

The model parameter, average process erosion time is the rate at which the process will deteriorate if it is left unattended. This model parameter could also be unknown to the production manager and his personnel. Typical process problems, determined from the field work are training, machine capability and material defects. A typical manufacturing cycle determined from this case study, is between six to eight weeks with machine maintenance once to every second month. The range for the average process erosion time is set between six to 14 weeks. The value that fits the dynamic behaviour of the actual measured data for defective units the best is 10.1 weeks.

The model parameter, time to correct problems, is the rate at which process problems are corrected. The value for this model parameter could typically also be unknown to the production manager and his personnel and could also depend on the complexity of the process problem that needs to be corrected. The business unit manager, machine shop indicated during his interview that it could take three to four months, which excludes monitoring after the operator(s) have been trained. The quality manager, machine shop recalled the following on the question of how long it takes to implement a six sigma quality improvement programme,

“ We took three months to implement and after six months the target was achieved.”

From the historical data gathered during the case studies on the implementation of six sigma quality improvement programmes, the first six sigma quality improvement programme started in October 2009 and was fully implemented in April 2010. A typical manufacturing lead time is six to eight weeks and therefore the positive impact in the trend of the defective units per unit produced (DPU) could typically be seen from May 2010 onwards. This model parameter could be a function of the complexity of the process problem and could also take nine months. The value of the model parameter that fits the actual measured data for defective units the best is 35 weeks or 8.12 months.

7.1.1.1 Discussion of the model tests for the system dynamics model of the a quality improvement programme including the rework loop

Sterman (2000) proposes a collection of tests; refer to Table 7.1 also, to build confidence in the system dynamics model. These tests are now briefly discussed.

The model is inspected for boundary adequacy to ensure that the parameters that are contributing towards the behaviour of the model are endogenous to the model. The only exogenous parameters to the model are the desired throughput which is determined by the production manager. The other exogenous model parameter is the desired defect level, typically determined by the quality department. The defective units, which are one of the key variables under study, are endogenous to the model.

The model structure conforms to physical laws such as the second law of thermodynamics. If the system is left unattended, the stock of process problems increases. The assumptions about information for decision makers are also appropriate. The model is dimensionally consistent and is one of the tests that are done in the Vensim® simulation platform. The model is also inspected for arbitrary scaling factors that have no real world meaning.

The model parameters are assessed against clear real life meaning and are also assessed against descriptive and numerical knowledge of the real heavy engineering manufacturing system. Model parameters are compared to quantitative data gathered during the field work, interviews, observations and historical data. The model is also inspected for extreme conditions such as the stock of process problems that are negative. A time step is chosen that yields continuous dynamics accurate enough for the purpose of the model.

The simulated results are inspected for reproduction of various modes of behaviour observed from the system. The method used for this analysis is the model calibration method which optimised the model to reproduce the observed behaviour of the real system for defective units for the best fit of the historical data. Specific parameters have been varied over a sensible range for which the behaviour of the system was studied and explained.

The system dynamics model for the interaction of the first- and second-order improvement loops including the re work loop has been optimised to simulate the best fit for the historical data for the behaviour of the defective units in the real system. This model does not include the sustainability feedback loop which models the impact of the implementation of a quality improvement programme. These issues are addressed further in the next sub section of this thesis.

7.1.2 Model tests and validation of the complete quality improvement programme model including the sustainability feedback loop and management support loop

The system dynamics model for the complete quality improvement programme is depicted in Figure 6.43 and Figure 6.45. The model simulates the dynamic behaviour of the defective units per unit produced (DPU) with the impact of the implementation of a six sigma quality improvement programme. The dynamic impact of this system dynamics model of the quality improvement programme is simulated with the sustainability feedback loop and the management support loop. An information delay is also included in the model to simulate the dynamic impact of the measurement processes and reporting which is part of the sustainability feedback loop.

The dynamic behaviour of the system dynamics model for the complete quality improvement programme, is simulated from May 2010 or week 130 for the field data shown in Figure 7.1 and Figure 7.2. From the field work, interviews and historical data, May 2010 is the point in time when the six sigma quality improvement programme was fully implemented as indicated in case study 1 for the machine shop. The six sigma quality improvement programme was completed during April 2010, where the process problem pertaining to raw material, was rectified with the six sigma intervention. The lead time for raw material to be procured was six to eight weeks.

The purpose for this model test and validation is to compare the simulated data for defective units per unit produced (DPU) to the actual calculated DPU for the manufacturing system researched in the polar type case study design. The actual calculated data for the DPU for the manufacturing system has been gathered from field work, interviews and historical data. Refer to Figure 7.4 and Figure 7.5 for a graphical presentation of the actual calculated DPU as well as the desired throughput. Figure 7.4 displays the data in months while Figure 7.5 displays the same data in weeks. The simulation run for the system dynamics model of the complete quality improvement programme is done in weeks in the Vensim® simulation platform.

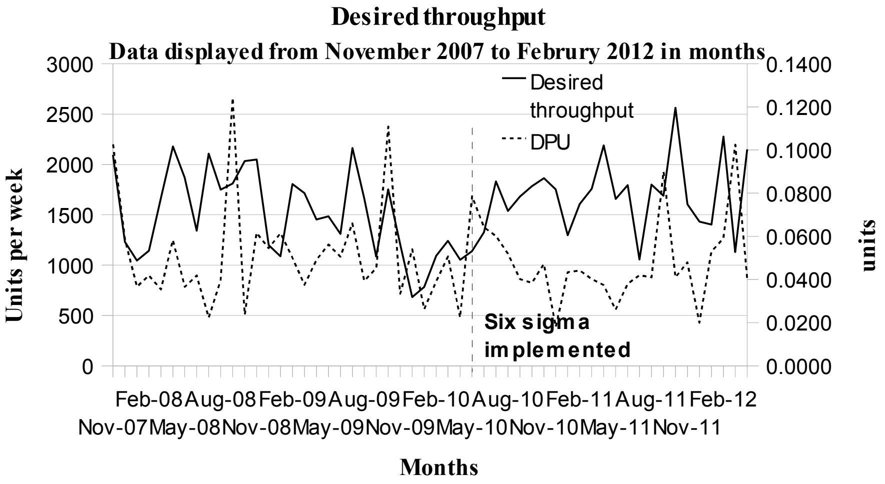

Figure 7.4: Time series plot for desired throughput per month and defective units per unit produced (DPU)

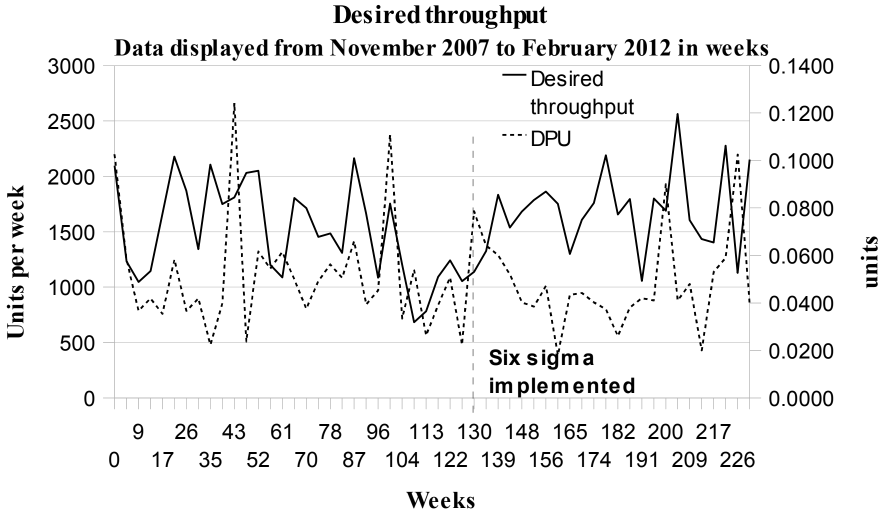

Figure 7.5: Time series plot for desired throughput per week and defective units per unit produced (DPU)

The implementation of a six sigma quality improvement programme is indicated on Figure 7.4 and Figure 7.5 from May 2010 or week 130. The exponential decay of the defective units per unit produced (DPU) is clearly visible and continues for approximately 50 weeks after which the DPU value returns to its dynamic behaviour before the implementation of the six sigma programme. External influences, for example implementation of the gear strategy from week 180, had a direct impact on the dynamic behaviour of the DPU. This phenomenon is explained in more detail in paragraph 6.2.2.1

The system dynamics model of the complete quality improvement programme including the sustainability feedback loop is an extension of the system dynamics model, depicted by the interaction of the first- and second-order improvement loops with the rework loop. The system dynamics model of the complete quality improvement model is a description of the structure of the system after the implementation of a six sigma quality improvement programme. The model parameters derived from the model calibration of the system dynamics model before the six sigma quality improvement programme implementation, Refer to Table 7.2, are used for the same model parameters in the system dynamics model of the complete quality improvement programme except for the model parameters, time to correct problems and initial process problems.

The model parameter, initial process problems, is an indication of the process problems at the point in time when the six sigma quality improvement programme was implemented. The value for the model parameter, initial process problems, is set at 0.2 at time t_{130}. One of the advantages of a quality improvement programme is to reduce the time it could take to correct process problems that could lead to defects (Bessant et al 1994), (Bhuiyan et al 2005), (Brassard et al 2002), (De Feo & Barnard 2005). The model parameter, time to correct problems, could be different before and after the implementation of the six sigma quality improvement programme.

From the data gathered during the case studies of this research, the model parameter, time to correct problems, could be between five to six months while the implementation of the first six sigma quality improvement programme took up to eight months. For the purpose of this simulation, time to correct problems is set at 35 weeks, determined from the calibration of the model already discussed in section 7.1.1 of this chapter. Refer to Table 7.3 for the model parameters which are used in the system dynamics simulation model for the complete quality improvement programme including the sustainability feedback loop, as developed and discussed before in section 6.3.3 of Chapter 6.

Model parameter	Exogenous or endogenous	Value	Unit
Unattended process problem level	Endogenous	0.12	dimensionless
Time to adjust allocation	Endogenous	0.06	weeks
Initial process problems	Endogenous	0.1	dimensionless
Maximum allowable time for concession	Endogenous	0.44	weeks
Productivity of production time	Endogenous	0.7	unit/hour
Average process erosion time	Endogenous	10.1	weeks
Time to correct problems	Endogenous	35	weeks
Desired defect level	Exogenous	0.03	dimensionless
Measurement and reporting processes	Endogenous	4	dimensionless
Analysis time	Endogenous	1	weeks
Delay in management support	Endogenous	6	weeks
Desired throughput	Exogenous	GET XLS	units/week

Table 7.3 Model parameter used in the simulation of the system dynamics model for the complete quality improvement programme.

The model parameter, desired defect level, is a goal and is an exogenous model parameter which is determined by the quality department. The DPU goal for the manufacturing system in this research is 0.03 confirmed from the interviews and historical data determined from the field work during the case studies.

Measurement and reporting processes is the model parameter which describes the number of processes involved to measure, analyse and report the DPU data to the management of the manufacturing plant, as part of the month-end manufacturing data. It is endogenous to the manufacturing system and determined during the field work to have four steps in total to calculate the DPU. Analysis time is the model parameter that determines the time it could take the quality department to measure and analyse the measured number of defective units per unit produced or DPU and report on them.

The model parameter, delay in management support is the average time it could take for a manager to support the quality improvement programme. This parameter could be different for different managers. From the case study data, some managers could typically take up to three months to get on board with the implementation of a quality improvement programme. Typically managers have gained confidence in the new programme after they have monitored the implementation and execution of the quality improvement programme, and started to see success. The quality control manager machine shop, recalled the following,

> " Every time I walk on the shop floor, *[business unit manager]* will point out problems in the manufacturing process and ask for a six sigma project to be introduced to correct the process."

The gear strategy was implemented from week 180 which changed the focus of the machine shop and stopped the six sigma quality improvement programme. The business unit manager recalled the following,

> "The focus is not the same as it was two years ago. The QA manager's quality strategy *[six sigma quality improvement programme]* has also changed … This process started in the beginning of this month, May 2012."

The impact of the gear strategy is simulated by introducing a switch into the structure of the complete quality improvement programme. Refer to Figure 7.7 and Figure 7.6 for a description of the switch. The purpose with the inclusion of the switch into the structure of the complete quality improvement model was to simulate the effect of the introduction of a quality improvement programme such as six sigma, at a specified time for a specified duration. The switch is defined in equation 7.2 as follows,

$$Switch = Switch\ input * Managerial\ effectiveness \tag{7.2}$$

The switch input is a pulse function which returns the value one for the duration of the pulse and zero for the remainder of the time. Refer to equation 6.20.

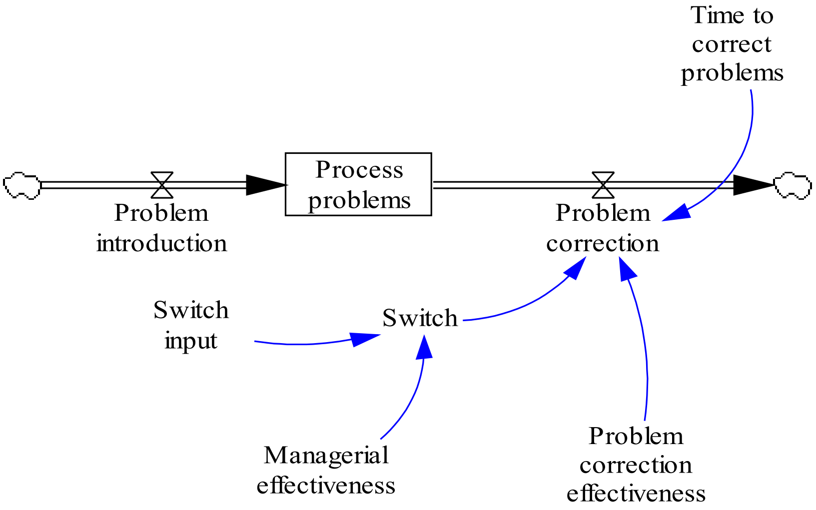

Figure 7.6: Structure and interaction of the switch with the complete quality improvement programme model. Extract from Figure 6.43

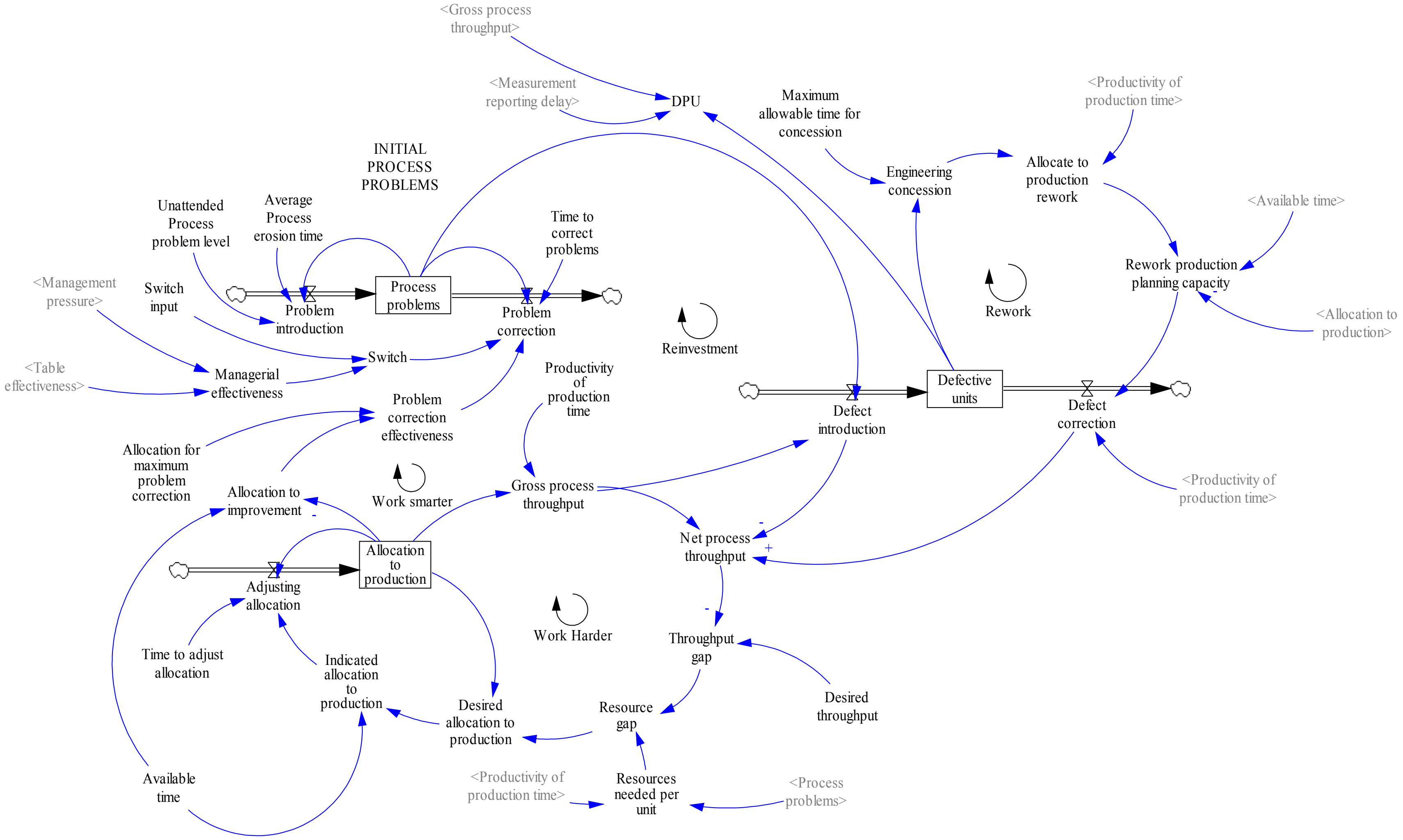

Figure 7.7: Structure of the system dynamics model for the complete quality improvement programme model with the introduction of a switch. Part one

Adapted from Figure 6.43

From equation 7.2 the model parameter, switch, returns a zero value while the switch input or pulse function returns a zero value or a value of one while the switch input returns a value of one. Equation 6.27 is adapted to define problem correction in equation 7.3 as follows,

$$\begin{matrix} \mathit{Problem} \\ \mathit{correction} \end{matrix} = \left(\begin{matrix} \mathit{Problem\ correction} \\ \mathit{effectiveness} \end{matrix} + \mathit{Switch} \right) * \frac{\mathit{Process\ problems}}{\mathit{Time\ to\ correct\ problems}} \tag{7.3}$$

If the switch returns a value of 1, the rate of problem correction, will be a function of both problems correction effectiveness and managerial effectiveness. However, if the switch returns a value of zero, problem correction is only a function of problem correction effectiveness, which models the instance where the quality improvement programme is not implemented. The quality improvement programme is defined by the sustainability feedback loop depicted by the model parameter, managerial effectiveness.

In order to simulate the implementation of the six sigma quality improvement programme, the switch input is defined for this case in equation 7.4 as follows,

$$\mathit{Swith\ input} = \mathit{Pulse}(130, 50) \tag{7.4}$$

The pulse returns a value of one from the time step 130 weeks and continues to return a value of one for a duration of 50 weeks. When the duration of 50 weeks has lapsed, the pulse returns a value of zero. Refer to Figure 7.8 for the graphical display of the switch, simulating the behaviour of the implementation of a six sigma quality improvement programme. The assumption is that the unattended process problem level does not change dynamically throughout the simulation except for the initial process problem level at time t_{130}, which could be at a different level before and after the implementation of the six sigma programme.

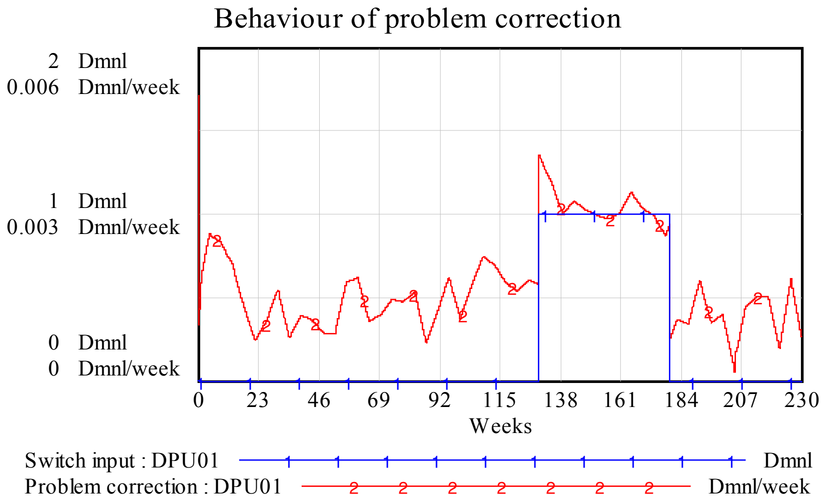

Figure 7.8: Dynamic behaviour of problem correction with a pulse input at t_{130}

The complete quality improvement model, refer to Figure 7.7, is simulated with the model parameters, as previously optimised and calibrated referenced to Table 7.3, in the Vensim® simulation platform. The simulation started at time t_{130} when the six sigma programme was implemented as determined from the field work during the case studies. The DPU behaviour of the complete quality improvement model was compared to the actual calculated behaviour of the defective units per unit produced (DPU) of the manufacturing system, after the implementation of the quality improvement programme such as six sigma from week 130. The actual behaviour of the manufacturing system with the impact of the six sigma quality improvement programme, has been determined from the polar type case study design done through data gathered during interviews and archived data.

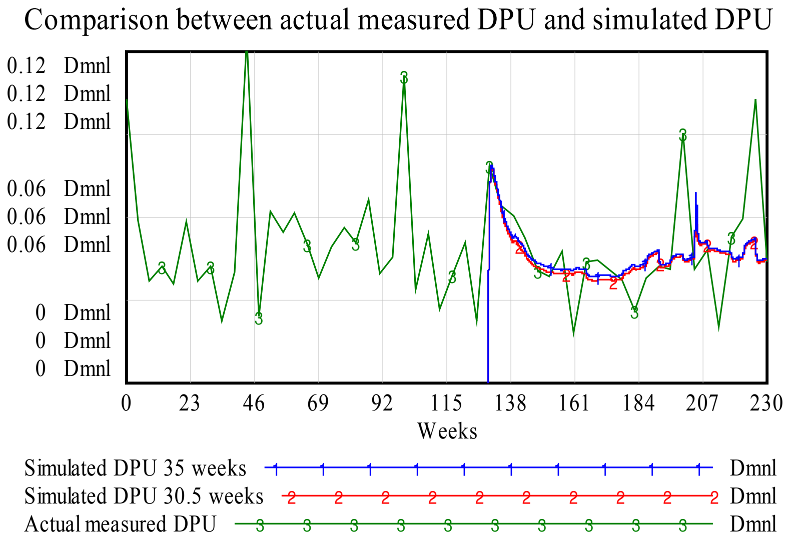

Figure 7.9: Comparison between the actual DPU and simulated DPU with the implementation of a six sigma quality improvement programme from week 130 to week 180

The dynamic behaviour of the complete quality improvement programme with the implementation of a six sigma quality improvement programme is displayed in Figure 7.9. The simulation results of the model for the complete quality system, generate the exponential behaviour of the manufacturing system, determined from the field work. Figure 7.9 displays two simulations where the time to correct problems is 35 weeks in the one instance and 30.5 weeks or 7.1 months in the other. In both instances the simulated behaviour follows the manufacturing system closely. From the data gathered in the field work, the exponential decay for the manufacturing system is determined to be 7.1 months or 30.5 weeks. Refer to equation 6.1. Schneiderman (1988) determined from his empirical studies that the exponential decay of the DPU for a typical manufacturing system is 32.7 weeks.

From week 180, the defective units per unit produced for the simulation of the complete quality improvement model, shows a general increase in the levels of the variable DPU. These results demonstrate the behaviour of the model compared to the behaviour of the real manufacturing system where the quality improvement programme is interrupted due to the implementation of the gear strategy. The gear strategy was announced in April 2011 and the gear manufacturing machines were transferred from August 2011 onwards. The quality improvement programme has been designed for gear manufacturing while the effect of the gear strategy moved the machine shop from a predominant gear manufacturing shop to a general machine shop.

The unattended process problem level, time to correct problems and other model parameters could change after the intervention of the gear strategy. The structure of the complete quality improvement model assumes that the model parameters remain the same before and after the intervention of the gear strategy. The intervention is modelled through the switch model variable where the sustainability feedback loop, through managerial effectiveness, is disabled with the switch input.

The behaviour of the complete quality improvement model is displayed in Figure 7.10. The behaviour of the real manufacturing system is described by, defective units measured, and is determined from data gathered during field work from the case studies. Defective units with the sustainability feedback loop, display the behaviour of the model after the implementation of a six sigma quality improvement programme. The model behaviour is simulated through the switch and pulse input, modelling the intervention of the gear strategy 50 weeks after the implementation of the six sigma programme. The results clearly demonstrate that the level of the defective units reduces after the implementation of the six sigma quality improvement programme.

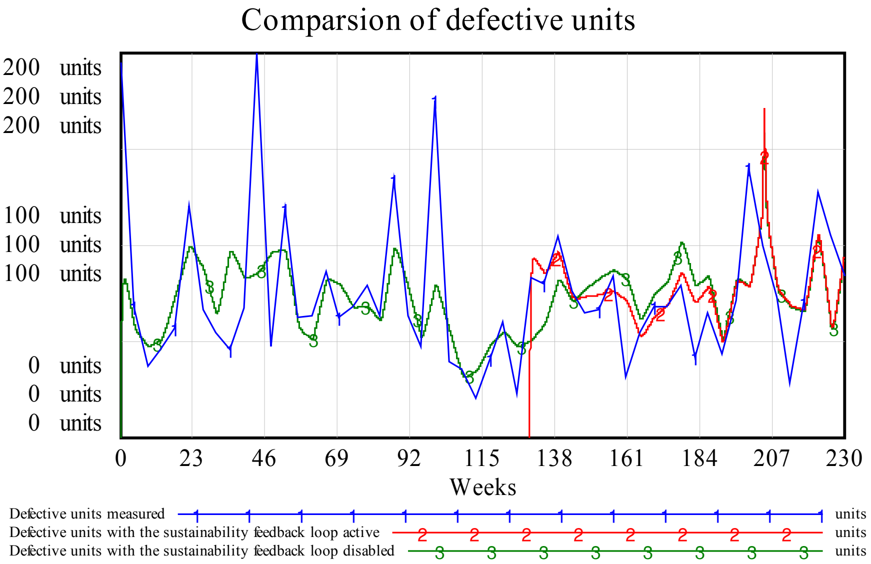

Figure 7.10: Comparison of defective units, before and after implementation of the six sigma quality improvement programme, and the actual system behaviour

The simulated behaviour returns to the model behaviour of the model without the implementation of a quality improvement programme, simulated by the switch and input function. A delay of a few weeks, after the sustainability feedback loop is switched off, is also visible in the results. The delay could be attributed to the time delay in the average process erosion time. The gear strategy was implemented at week 180, 50 weeks after the implementation of the six sigma programme in week 130.

The results from Figure 7.9 and Figure 7.10 have demonstrated that the model generated the various modes of behaviour observed in the real system and it endogenously generated the behaviours which motivated this research.

7.2 Modelling management decisions and decision rules – a sensitivity study

Decisions and decision rules are defined by Sterman (2000) as follows, "Decision rules are the policies and protocols specifying how the decision maker processes available information. Decisions are the outcome of this process." Sterman (2000) further postulates that every rate of flow in the stock and flow structure constitutes a decision point and that the decision rule determining the rate should be specified.

The decision process relies on different types of information. Refer to Figure 6.2 for a schematic diagram of the decision process. Decisions are the result of applying decision rules to the available information cues which are generated by the structure of the system from other areas in the model. These information cues could include measurement and reporting processes. The output from the decision process is the rate of flow that alters the state of the system (Sterman 2000:515). The assumption for the model in this research is that the decision maker understands the structure of the system very well, does not make errors in his inference about the future behaviour of the system and therefore makes optimal decisions.

Time delays and strength of feedback loops are a challenge for subjects that have to take decisions, specifically under conditions where the time delays could grow and the strength of feedback loops increase (Diehl & Sterman 1995). Studies also indicated mis-perceptions of feedback from subjects involved in decision making processes; in particular subjects are shown to be insensitive to the feedback from their decisions to the environment (Sterman 1989).

Four decision points have been identified in the complete quality improvement model. Refer to Figure 7.7 and Figure 6.45 for the system dynamics structure of the complete quality improvement model including the sustainability feedback loop, part one and the system dynamics structure of the complete quality improvement model, part two, respectively. The first decision point is the decision rule for, management support, which could be determined from information on the delay in management support, analysis time, measurement and reporting processes, and DPU gap. All the information is available to the decision maker except for delay in management support which is not instantaneously known to the decision maker. For the purpose of this research, delay in management support is determined from historical data, interviews and observations and is assumed to be known to the decision maker without a delay.

The second decision point is the decision rule for problem correction which has been determined from information on the state of the system, allocation to production and management pressure. The exact value of management pressure is not quantitatively known to the decision maker but the parameters of which management pressure is a function, is known to the decision maker. These factors could be normal management time, analysis time, measurement and reporting processes, DPU gap and the state of the system allocated management time required for improvement.

The third decision point is the decision rule for defect correction which has been determined from information on the productivity of production time and maximum allowable time for concession. The fourth decision point is the decision rule for adjusting allocation. This decision rule determines the rate of changing the state of the system, allocating hours to production. The decision rule could be determined from the model parameters, time to adjust the allocation, throughput gap and resource gap.

A manager would typically adjust his allocation to production in order to close the throughput gap. He could also experience management pressure due to not meeting his desired defect level as reported by the DPU gap after the information delay. This could determine the rate at which the state of the system, process problems, is changed.

Management support could be indicative of the support for the quality improvement programme, determining the state of the system of allocated management time required for improvement.

Different scenarios on information for decision rules towards the sensitivity of the defective units per unit produced (DPU) and defective units, are simulated in the next section using the previously developed models on a Vensim® simulation platform. The purpose with this scenario study was to propose possible policies that could lead to sustainable quality improvement programmes in a heavy engineering manufacturing environment.

7.2.1 Decision rule for management support, information from model parameter - information delay and delay in management support

The information delay is the time taken to measure and analyse the results from the DPU gap and report on the measurements. The management team uses this report and analysis to create actions to close the DPU gap through allocation of labour hours to improvement by adjusting allocation. This information could also determine allocated management time required for improvements, which could have an impact on management pressure.

The model parameter, analysis time, is varied between one to eight weeks where eight weeks is the extreme. In the real system the analysis time to take all the measurements and report on them, is typically one week. The dynamic behaviour of management pressure indicates oscillatory behaviour with a longer analysis time. Refer to Figure 7.11. With an analysis time of one week, the management pressure the production manager could experience would stabilise in one week while with an analysis time of four weeks the manager would experience a varying management pressure beyond one month.

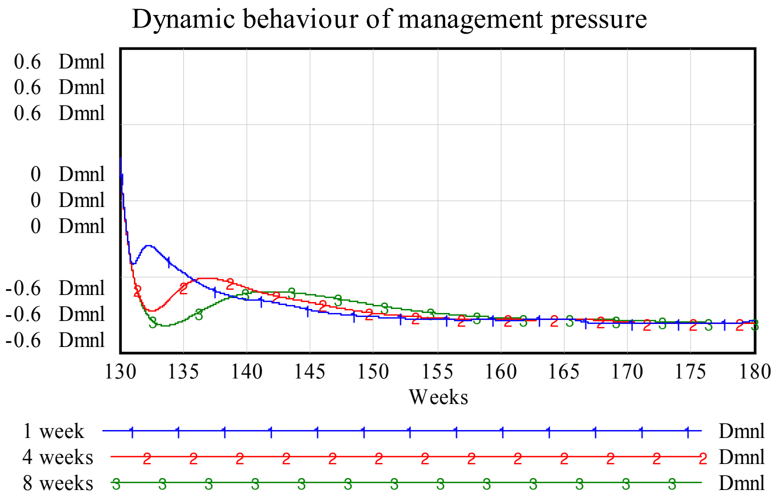

Figure 7.11: Dynamic behaviour of management pressure with varying analysis time between 1 to 8 weeks. The model parameter values are as per Table 7.3

In all these instances, management pressure is below zero and therefore would lead to maximum managerial effectiveness as referenced by the Table function effectiveness, displayed by Figure 6.19. Following from the Table function effectiveness, the varying of the analysis time between one to eight weeks has no impact on the dynamic behaviour of the model variable, DPU. Refer to Figure 7.12.

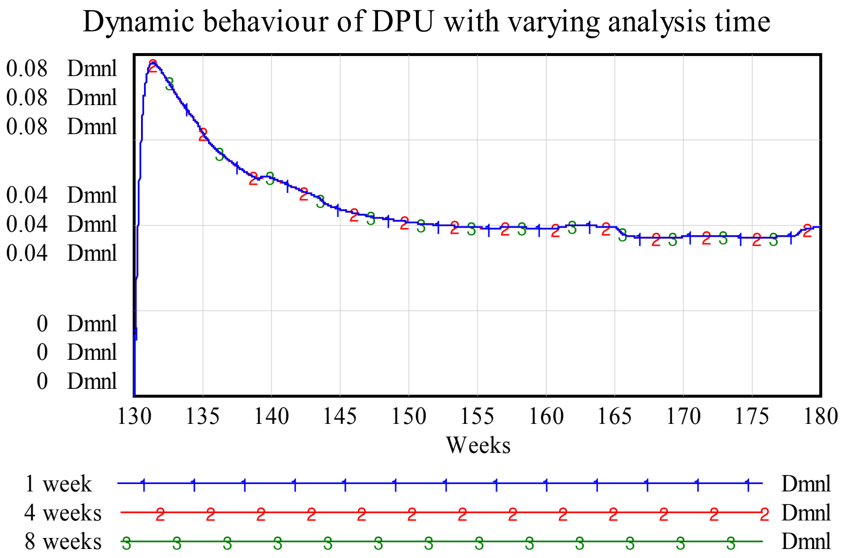

Figure 7.12: Dynamic behaviour of DPU with varying analysis time. The model parameter values are as per Table 7.3

Delay in management support is the average time it could take for various managers or levels of management to support the quality improvement programme. The delay in time to support the quality improvement programme could be more than one week, depending on the individual manager. For the purpose of this research the model parameter, delay in management support is varied between one week to six weeks to simulate the sensitivity of defective units per unit produced (DPU). Refer to Figure 7.13 for the simulation results for the dynamic behaviour of management support.

The longer the delay in management support, the less the management support for the quality improvement programme. When the delay in management support increases, the output rate of the stock of allocated management time required for improvement, decreases which in turn increases the level of management time required for the quality improvement programme. With an increase in the stock of management time required for the improvement programme, the desired allocated time for improvement gap could be less than zero. An increase in the level of allocated management time required for improvement is indicative of a back log of management time and is not visible to the manager.

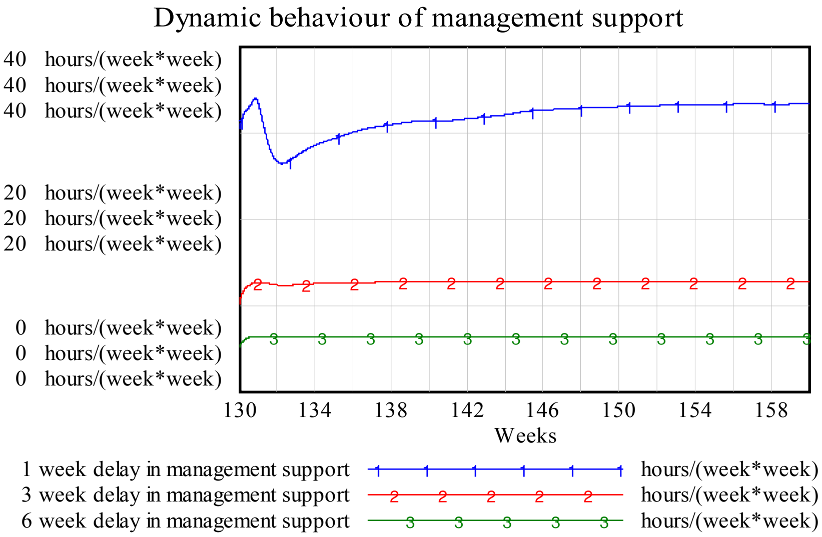

Figure 7.13: Dynamic behaviour of management support varying the model parameter, delay in management support. The values for the model parameters are as per Table 7.3

With an increase in backlog of management time required for the improvement programme, management pressure reduces and could become negative. From Figure 6.19, managerial effectiveness is high due to management pressure being less than zero. The longer delay in management support could create a false impression with the manager, which in spite of the back log of management time required for the improvement, he might experience little management pressure. Refer to Figure 7.14 for the dynamic behaviour of management pressure.

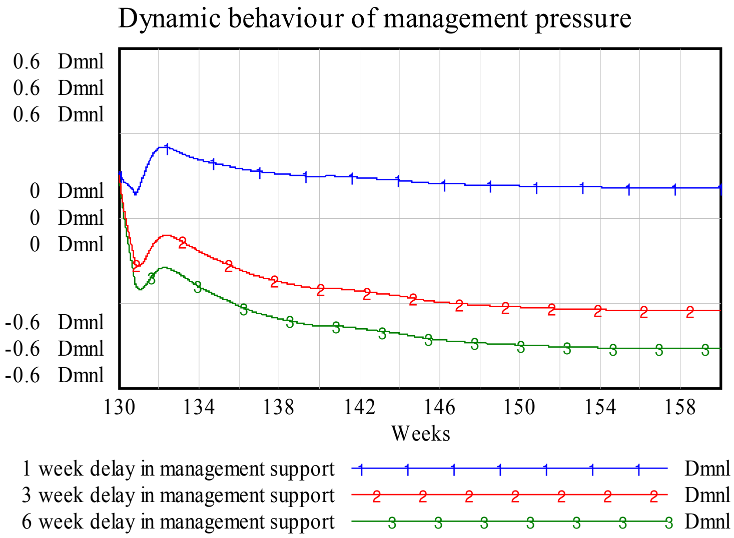

Figure 7.14: Dynamic behaviour of management pressure with varying delay in management support. The values for the model parameters are as per Table 7.3

With a short delay in management support, management pressure reaches equilibrium in a shorter time interval relative to a longer delay in management support. In all the simulated values for delay in management support, management pressure decreases from the initial level attributed to the initial management time at t_0, until the information feedback from information delay measures the defective units per unit produced (DPU) to be different to the desired defect level. Management pressure starts to rise to close the DPU gap until the defective units per unit produced (DPU) value starts to decline. Management pressure follows the DPU behaviour after a short delay as indicated in Figure 7.14. Refer to Figure 7.15 for the dynamic behaviour of the model parameter, DPU

From Figure 7.15 the simulation results for the dynamic behaviour of defective units per unit produced (DPU) indicate that DPU has little sensitivity towards varying delay in management support. Varying delay in management support could change the dynamic behaviour of management support as well as management pressure but managerial effectiveness remains between the upper and lower limit of 0.8 and 0.2 respectively as depicted by the table function in Figure 6.19 and Figure 7.16 for the dynamic behaviour of managerial effectiveness. A longer delay in management support could indicate a false sense of managerial effectiveness.

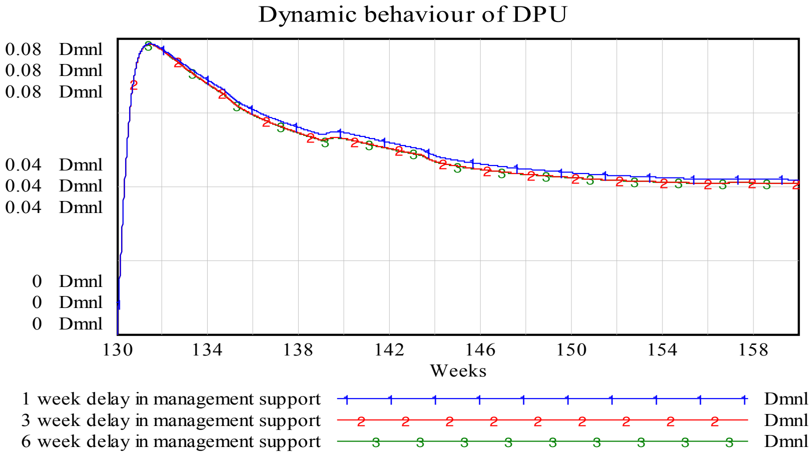

Figure 7.15: Dynamic behaviour of defective units per unit produced (DPU) with a varying delay in management support. The value of the model parameters are as per Table 7.3

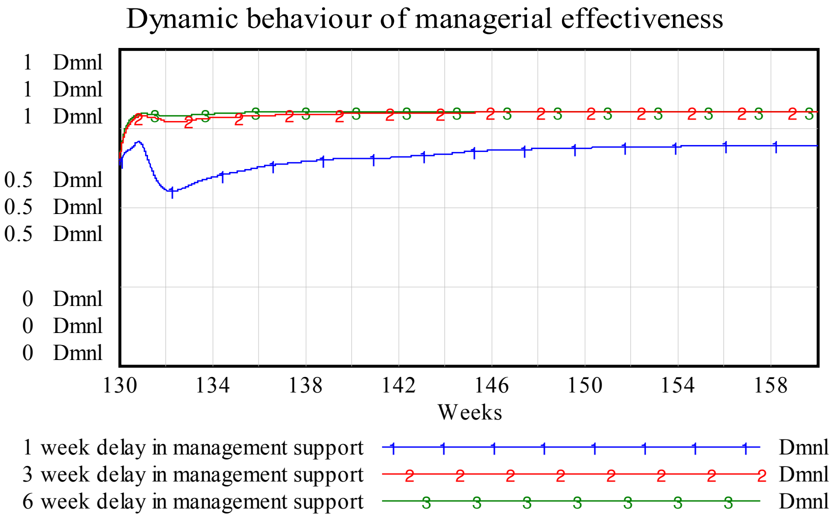

Figure 7.16: Dynamic behaviour of managerial effectiveness with a varying delay in management support. The model parameter values are as per Table 7.3

7.2.2 Decision rule for defect correction, information from model parameter - maximum allowable time for concession and productivity of production time

The defective units are reworked at a rate of defect correction. Productivity of production time is one of the model parameters in the information cue and is not immediately known to the manager. The productivity of production time is calculated at month end with the month's production data and production hours only available at month end. For the purpose of this research, productivity of production time is determined as an average productivity measure from interviews, archived data and direct observation. The assumption for the simulation is that the productivity of production time is known to the production manager. Typically, any manufacturing facility strives to be as productive as it possibly can be. The impact of productivity of production time on defective units per unit produced (DPU) in regard to its sensitivity, is displayed in Figure 7.17.

The level of defective units per unit produced (DPU), is typically halved when the productivity is approximately doubled. The response time of the system is also higher when the manufacturing system is more productive. The results in general confirm the productivity drive for manufacturing facilities.

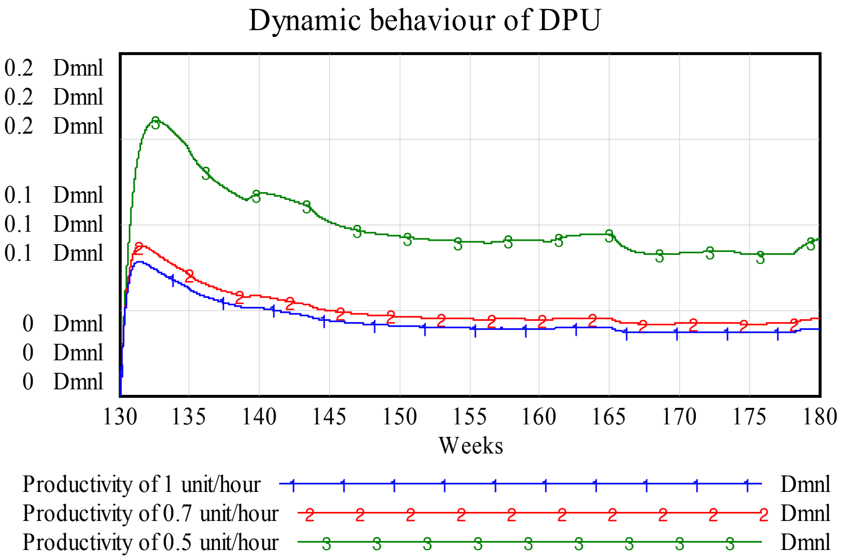

Figure 7.17: Dynamic behaviour of defective units per unit produced (DPU) with a varying model parameter, productivity of production time. The value of the balance for the model parameters are as per Table 7.3

Maximum allowable time for concession is the time it could take for engineering to give a concession on defective units to be reworked. In the real heavy engineering manufacturing system, determined from the case studies, this value is typically 0.44 weeks or 17.6 hours based on a 40-hour work week. For this simulation, the model parameter is varied between 0.1 week and 1 week. Refer to Table 7.3.

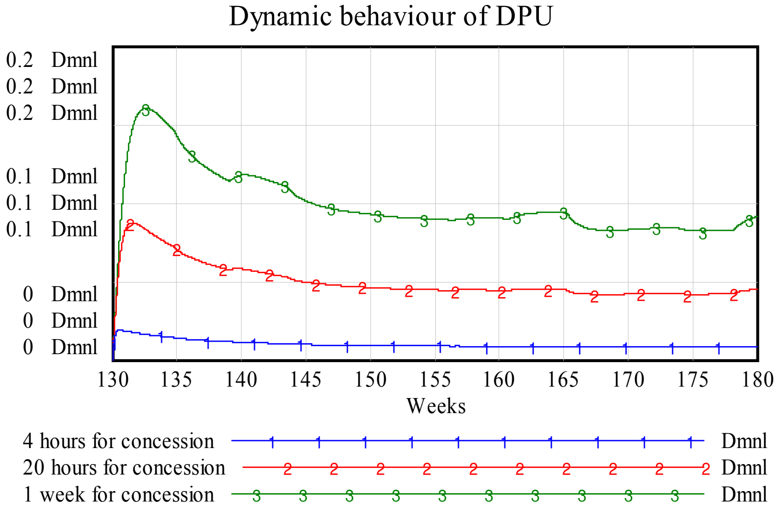

Figure 7.18: Dynamic behaviour of DPU with a varying maximum allowable time for concession. The model parameters used in this simulation are as per Table 7.3

The simulation results in Figure 7.18 indicate that a shorter maximum allowable time for concession, reduces the level of the defective units per unit produced (DPU) and also reduces the response time of the system. The increased delay in correcting the defects, increases the stock of defective units. Refer to Figure 7.19. From a dynamic impact on behaviour point of view, the maximum allowable time for concession should be kept as low as possible to have the system behaviour for DPU and defective units at an optimal low.

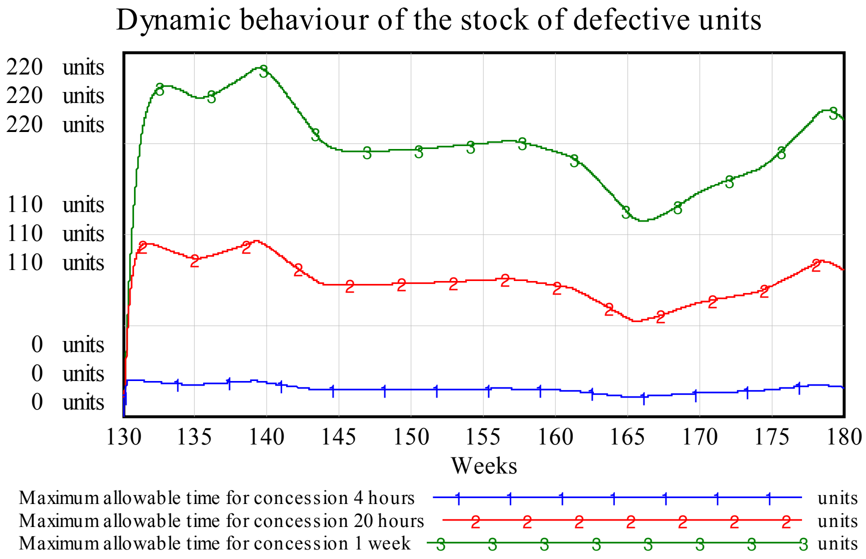

Figure 7.19: Dynamic behaviour of defective units with varying maximum allowable time for concession between 0.1 week and 1 week. Model parameter values are as per Table 7.3

7.2.3 Decision rule for adjusting allocation, information from model parameter – throughput gap and time to adjust allocation

Adjusting allocation is the average rate at which the allocation to production is adjusted. The time to adjust allocation is the time a manager typically takes to adjust his allocation to his production based on the information from the throughput gap. The assumption with this model is that the value of the throughput gap is available to the production manager without a delay. The decision to allocate hours to production could be taken in one hour to one day upon receipt of information from his manufacturing plant. The model parameter, time to adjust allocation is simulated with a value from one hour to eight hours. Refer to Figure 7.20.

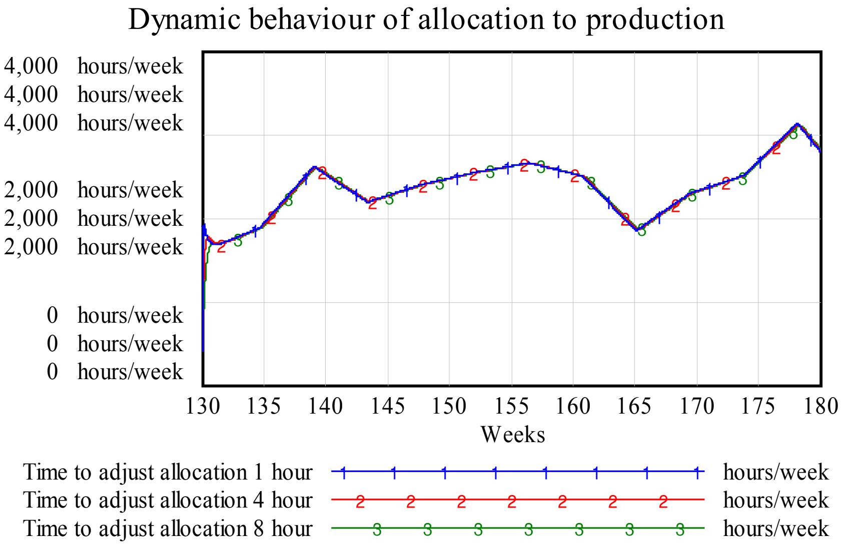

Figure 7.20: Dynamic behaviour of allocation to production with varying time to adjust allocation. The values for the model parameters are as per Table 7.3

The dynamic behaviour of the allocation to production is not sensitive for a variance in the model parameter, time to adjust allocation. With a varying time to adjust allocation within the simulated range, the system reacts and closes the throughput gap to meet the desired throughput. The results from the simulation displayed in Figure 7.21 also demonstrate that defective units per unit produced (DPU) is also not sensitive to time to adjust allocation.

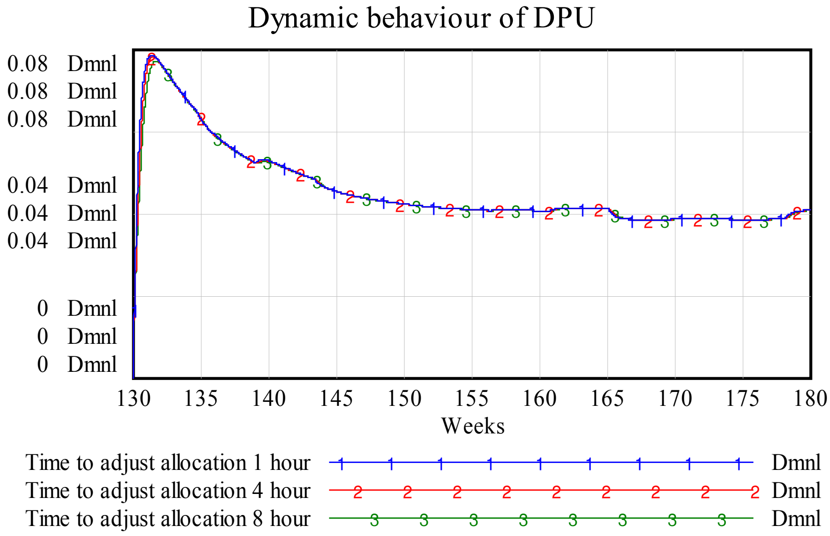

Figure 7.21: Dynamic behaviour of defective units per unit produced (DPU) with a varying time to adjust allocation. The model parameter values are as per Table 7.3

7.2.4 Decision rule for problem correction, information from model parameter – time to correct problems

Time to correct problems is the average time taken for the output rate, problem correction, to adjust the level of the stock of process problems. The model parameter time to correct problems could be different for different process problems and also depends on the type industry and complexity of the process problem (Schneiderman 1988). The manager does not have immediate knowledge of the time to correct problems for his particular manufacturing system, but for the purpose of this research the model assumes that the manager does have knowledge of the model parameter, time to correct problems.

The output rate of problem correction is also a function of problem correction effectiveness and managerial effectiveness, for this case of a heavy engineering manufacturing environment, where managerial effectiveness closes the sustainability loop. From interviews and archival data gathered during the field work for this research, the time to correct problems could be between five to eight months. The complete quality improvement model is simulated with the above range of time to correct problems with the balance of the model parameters set at the values in Table 7.3.

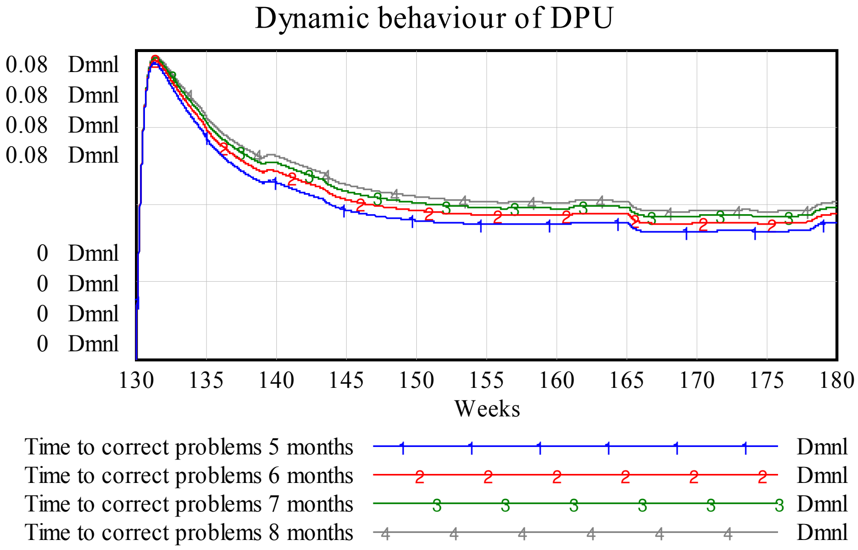

Figure 7.22: Dynamic behaviour of defective units per unit produced (DPU) with a varying time to correct problems. The value of the model parameters are as per Table 7.3

The rate of decay of defective units per unit produced (DPU) is 15% faster with time to correct problems at five months compared to eight months. Refer to Figure 7.22. The results also indicate that the range of the values of DPU is changed by approximately 0.005. A small variance in the DPU value could indicate that the manufacturing system has little sensitivity to a variance in the time to correct problems, as per the simulated value of time to correct problems.

The dynamic behaviour of the defective units also indicates that the manufacturing system is less sensitive for time to correct problems within the simulated range within 20 units. Refer to Figure 7.23

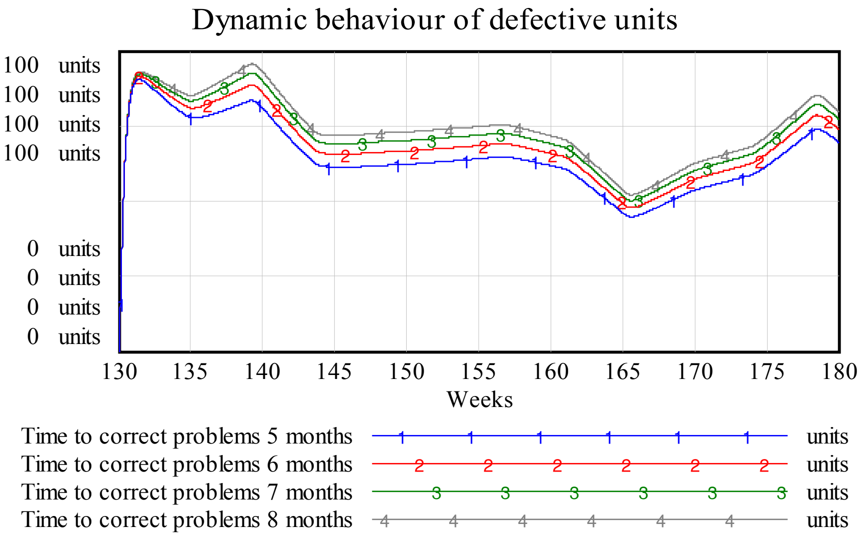

Figure 7.23: Dynamic behaviour of defective units with varying time to correct problems. The balance of the model parameter values are set as per Table 7.3

7.3 Possible management decision policies for quality improvement programmes in a heavy engineering manufacturing environment

7.3.1 Discussion of the results from the sensitivity analysis

The goal of management policies on quality improvement programmes such as six sigma, is to successfully introduce these programmes and also to implement programmes successfully to sustain the improvements (Besterfield et al 2003). These management policies or decision rules, as illustrated in the previous sub sections, are determined at every decision point that could determine the state of the system. These decision points could be determined from every rate of flow in the structure of the complete quality improvement model (Sterman 2000).

Data for defective units determined from field work from the real system, indicates peaks at 44 weeks and 100 weeks. Refer to Figure 7.2. Breakdown in the quality control measurement processes could have an impact on the dynamic behaviour of defective units. Sensitivity analysis results regarding defect correction did illustrate that the model, as depicted by defective units, is sensitive to a varying model parameter, maximum allowable time for concession. Refer to Figure 7.3 and Figure 7.19.

The decision point, defect correction is also a function of the model parameter, productivity of production time. The output rate, defect correction is the rate that defective units is reworked and determines the level of stock of defective units. The average productivity of production time impacts the defect correction rate and from the sensitivity analyses results, it indicates that the model is sensitive also for the model parameter, productivity of production time. Refer to Figure 7.17.

The level of defective units is dynamically impacted by defect introduction which is a function of the gross process throughput and the level of process problems. Process problems are not visible to the production manager but defective units are. The level of process problems is determined by the output rate problem correction and input rate problem introduction. For the purpose of this research, problem introduction is modelled from the second law of thermodynamics or entropy and the manager does not necessarily have knowledge of the rate of problem introduction and hence he might not know the rate at which the process could possibly deteriorate.

The results from the sensitivity analyses indicated that the system is less sensitive to a varying model parameter, time to correct problems. The effect on the response time of the system is more noticeable than the dynamic impact on the level of defective units and DPU. A longer time to correct problems dynamically causes defective units per unit produced (DPU), to take longer to approach the desired defect level and also increase the level of defective units. Refer to Figure 7.22 and Figure 7.23.

Increase in delay in management support reduces management support which has a negative impact on the stock of allocated management time required for improvement. The back-log in management time with an increase in delay in management support could create a false impression with the manager that he does not have management pressure. In spite of low management support, defective units per unit produced are not sensitive for a varying delay in management support. Refer to Figure 7.15.

The simulation results also demonstrated that since the implementation of the six sigma quality improvement programme, the level of defective units per unit produced (DPU) reduced exponentially. However, the roll out of the gear strategy at week 180 had a negative impact on the dynamic behaviour of the model variable DPU. The structure of the system returned to its previous state when the quality improvement programme was stopped and the focus of the machine shop changed. Refer to Figure 7.10.

Sustainability could be defined by persistent performance levels or stability of work methods which may also include consistent trajectory of performance improvement (Buchanan et al 2005). Buchanan et al (2005) further propose that factors such as managerial (style and behaviours) and processual (implementation methods), could affect sustainability of quality improvement programmes. The structure as proposed by Figure 6.43 and Figure 6.45 encapsulates management support as well as a balancing feedback loop, which models the use of quality improvement programme tools. The sustainability feedback loop also models measurement, which Zairi (2002) proposes as an important aspect for sustainable performance.

In this sub section, the results from the sensitivity analysis through a parametric study of the model parameters determining the information for the decision rules, have been analysed and discussed. During the next sub section, the insights gained from this parametric study have been incorporated into the simulation and analysis of possible decision policies for sustainable quality improvement programmes in a heavy engineering manufacturing environment.

7.3.2 Discussion of proposed decision policies for sustainable performance of quality improvement programmes

In this section a brief discussion follows on possible decision policies of sustainable performance for quality improvement programmes in a heavy engineering manufacturing environment.

Successful implementation of a quality improvement programme should include the introduction of a measurement system. Such a system should close the feedback loop between the desired defect level of the manufacturing system and the actual defective units. Defect correction is the average output rate that has an impact on the dynamic level of defective units. Decision rules for defect correction should strive to eliminate waiting time in the rework loop for engineering concessions. These decision rules should also strive to improve productivity of production time for the manufacturing system including the rework of defective units.

Problem correction is part of the feedback measurement system loop in Figure 7.7 of the system dynamics simulation model for the quality improvement model. Change in the output rate, problem correction, could dynamically impact the stock of process problems which in turn dynamically impacts on the stock of defective units. The decision rule for problem correction is to ensure that the rate is as large as possible. A decrease in time to correct problems could improve the decay of defective units per unit produced (DPU) in order to meet the exogenous goal of the system for the desired defect level where time to correct problems could be a function of the complexity of the process problem. Schneiderman (1988) empirically determined that the decay of DPU for a typical manufacturing facility is 7.6 months. During this research a typical decay of 7.1 months is measured in section 6.1.3 and depicted in Figure 6.7, from data gathered during case study one for the machine shop.

Information from managerial effectiveness could also impact on the rate of problem correction. For sustainable performance of the quality improvement programme the measurement feedback loop, should be maintained. External factors outside the control of the manager could have a negative impact on the maintainability of this feedback loop which could introduce a break in the feedback loop. Refer to sub section 6.2.2.1 for more detail on the gear strategy, determined from case study one for the machine shop.

Management support is the average rate that management time is allocated to support the quality improvement programme. Refer to Figure 6.45 for the system dynamics simulation model of the management support loop with an information delay. Also refer to section 6.2.1 for more detail on the system dynamics model of the management support loop. An increase in delay in management support could negatively impact the stock of management time required for improvement. With an increase in the delay in management support, management support could reduce. The decision rule for delay in management support could be to train managers in quality improvement programmes before hand, in order to keep the delay in management support as low as possible.

Information delay is the average time it could take for the organisation to measure the defective units per unit produced (DPU) to compare to the exogenous goal of desired defect level. The decision rule for information delay is to keep the analysis time as short as possible. The manufacturing system should strive to have an information delay to be less than a month by adjusting the analysis time to a minimum. Refer to sub section 6.3.3.2.1 for more detail on the information delay.

In the next sub section the proposed decision rules, as discussed in this section, are simulated using Vensim® as the simulation framework. Refer to Table 7.4 for the proposed model parameters, where the model parameters indicated by an asterisk are indicative of the model parameters for the new proposed management decision policies, for sustainable quality improvement programmes in a heavy engineering manufacturing environment.

7.3.2.1 Discussion of the results for simulating the complete quality improvement model with the proposed decision rules

The purpose with this sub section is to simulate the dynamic behaviour of the system dynamics simulation model for the complete quality improvement programme depicted by

Figure 6.45 and Figure 7.7. For the dynamic simulation, the model parameters tabulated in Table 7.4, have been used in the system dynamics model to simulate the impact on some of the model parameters such as defective units per unit produced (DPU). The model simulation is done from the point in time that the six sigma quality improvement programme has been introduced (week 130) up to the end of the desired throughput data or week 230.

Maximum allowable time for concession is reduced to 1.5 days from an average of 2.2 days which is possible to achieve in the real system. This model parameter is part of the quality management system of the manufacturing facility and could also be part of a typical total quality management programme or TQM. The concession process could typically be improved by including it into the business management system or material resource planning (MRP). Data gathered during the polar type case studies (case study one for the machine shop), indicated that the plant where the quality improvement programme was successfully introduced, is also the only plant where the concession process is included into the business management system of the company. This is a further indication of the consistent use of quality tools to ensure sustainable improvement. For this simulation, the model parameter, maximum allowable time for concession, is set at 0.35 weeks or 1.5 days.

The effective use of the measurement loop is modelled with the switch function. The switch input models the implementation of the quality improvement programme from week 130 until the end of the simulation. The switch input models the effective implementation of the measurement feedback loop as well as its successful maintenance.

Model parameter	Exogenous or endogenous	Current Value	New proposed value	Unit
Unattended process problem level	Endogenous	0.12	0.12	dimensionless
Time to adjust allocation	Endogenous	0.06	0.06	weeks
Initial process problems	Endogenous	0.2	0.2	dimensionless
Maximum allowable time for concession	Endogenous	0.44	0.35*	weeks
Productivity of production time	Endogenous	0.67	0.74*	unit/hour
Average process erosion time	Endogenous	10.1	10.1	weeks
Time to correct problems	Endogenous	35	30.5*	weeks
Desired defect level	Exogenous	0.03	0.03	dimensionless
Measurement and reporting processes	Endogenous	4	4	dimensionless
Analysis time	Endogenous	1	1*	weeks
Delay in management support	Endogenous	6	1*	weeks
Desired throughput	Exogenous	GET XLS	GET XLS	units/week
Switch input	Endogenous	Pulse (130,100)	Pulse (130,100)	dimensionless

Table 7.4: Current and proposed model parameters to simulate decision policies for a sustainable quality improvement programme (* Values are adjusted in accordance to the new proposed decision policy)

Analysis time is part of the information used for information delay and is simulated with an analysis time delay of one week. This is possible in the real world and is also part of the quality management system. Analysis time is part of the reporting process to report on the defective units per unit produced (DPU). Managers typically use this report to do further investigations if they did not meet the desired defect level. For this simulation, the model parameter, analysis time, is set at one week.

Productivity is simulated with an increase of 10% on the current value determined from the data gathered during the polar type case study design. It is a model parameter that management monitors closely and is being reported on monthly. For the purpose of this simulation, the model parameter, productivity of production time is set at 0.74.

Delay in management support is modelled with a delay of one week. When a quality improvement programme is introduced into the manufacturing facility, managers should be trained before hand in anticipation of the quality improvement programme introduction. This action could keep the delay to a minimum. A reduction in the delay in management support could have a favourable impact on management support. Delay in management support is set at one week for the purpose of this simulation.

The results from the simulations, with the above proposed model parameters, are discussed next during the following paragraphs.

With a maximum allowable time for concession at 1.5 days, the dynamic behaviour of defective units per unit produced (DPU), decays exponentially until it approaches the desired defect level of 0.03. Refer to Figure 7.24 for more detail. If the maximum allowable time for concession is exceeded, possibly due to a break down in the quality measurement process and it increases to three days, the dynamic impact on the DPU is clearly visible when it reaches equilibrium at a higher level compared to the instance when maximum allowable time for concession is 1.5 days. Figure 7.24 takes reference.

With the maximum allowable time for concession set at the proposed 1.5 days, the DPU gap increases from the initial state of the system until it starts to reduce to approach the desired defect level of 0.03. Refer to Figure 7.24 for more detail. Management pressure rapidly increases in reaction to the DPU gap not being equal to zero, as indicated in Figure 7.25 demonstrating the dynamic behaviour of the DPU gap, management support and management pressure on the same graph.

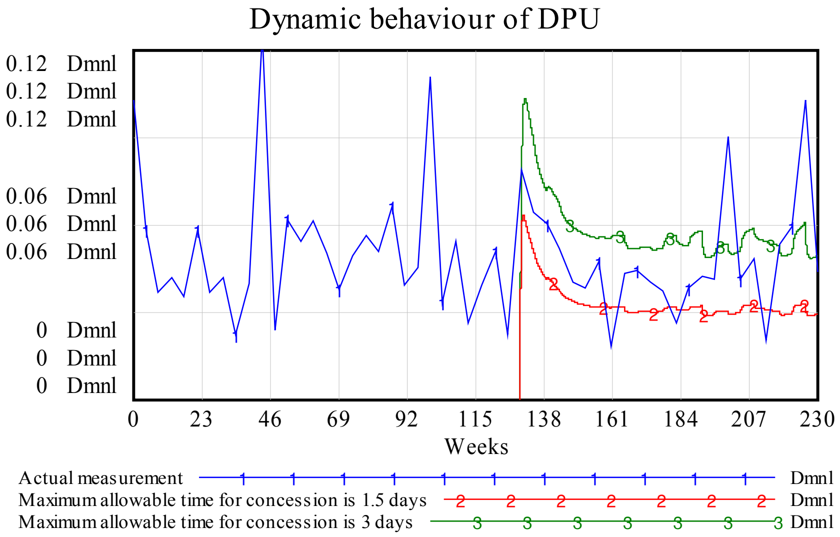

Figure 7.24: Dynamic behaviour of defective units per unit produced (DPU). The preferred maximum allowable time for concession is 1.5 days

Management support rapidly decreases in reaction to the increase in management pressure. Refer to Figure 7.25. When the DPU gap approaches zero, management support increases accordingly until it reaches equilibrium at a higher level compared to the level at time t_{130}. Managerial effectiveness reduces, following the dynamic behaviour of the DPU gap. Figure 7.26 takes reference. If the manager does not meet his targets, his managerial effectiveness reduces and his management pressure increases. When the DPU gap approaches zero, managerial effectiveness increases until it reaches equilibrium at a higher level compared to time at t_{130}. Refer to Figure 7.26.

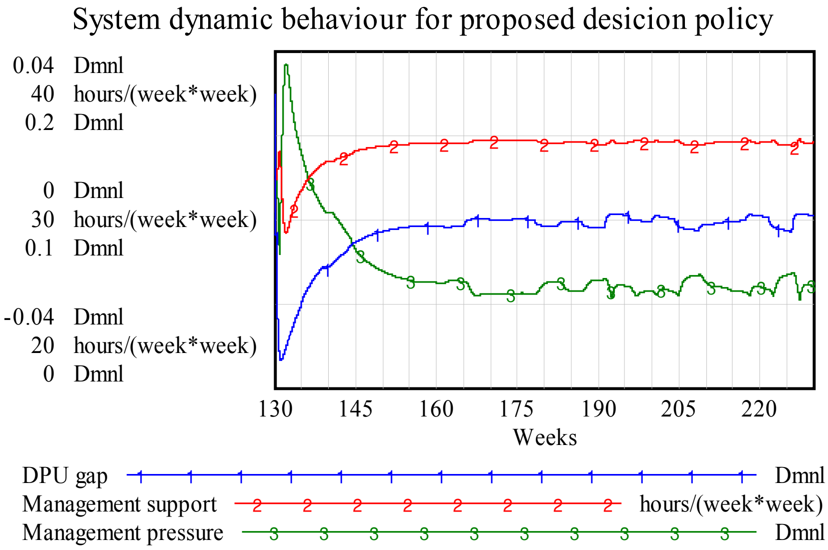

Figure 7.25: Dynamic behaviour of the management support and pressure

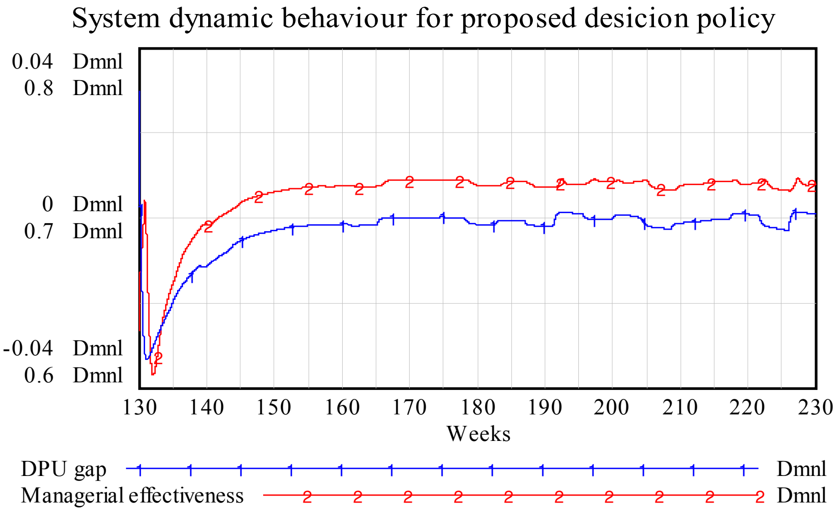

Figure 7.26: Dynamic behaviour of managerial effectiveness and DPU gap

7.4 Summary

The system dynamics model for the quality improvement programme, displaying the structure for the interaction between the first- and second-order improvement loops, including the rework loop, has been tested and validated. The model has been tested and accepted against twelve proposed tests. The model was also validated when the model parameters were calculated from a calibration algorithm in the Vensim® simulation platform, that reproduced the dynamic behaviour of the real system the closest. This is another novel contribution of this research to the body of knowledge.

These model parameters have been used in the dynamic simulation of the expanded system dynamics model describing the structure of the complete quality improvement programme including the sustainability feedback loop to study the sustainability theory developed earlier in section 6.1 .

The system dynamics model of the complete quality improvement model with the sustainability feedback loop has been used to study sensitivity of the decision points in the system dynamics model against varying model parameters determined from the information cues for the decision points. Four decision points have been studied, from which decision policies for sustainable quality improvement programmes in a heavy engineering manufacturing environment, have been proposed.

From the sensitivity analysis, policies for sustainable quality improvement programmes in a heavy engineering manufacturing environment have been simulated and discussed. The simulation results were compared to the behaviour of the real system from which the validity of these new proposed policies have been determined and tabulated in Table 7.4.

In the next chapter, the results and novel research contributions obtained from this research are summarised. The answering of the research questions, as previously discussed in section 1.3.1 of Chapter 1, is also explained. Ideas for future research are also discussed in more detail.

CHAPTER 8

DISCUSSION OF RESULTS AND FUTURE RESEARCH

8 Introduction

To stay competitive manufacturing operations may use quality improvement programmes such as six sigma (DMAIC) and DFSS to improve quality and reduce cost. One of the steps in DFSS is to use simulation and design of experiments (DoE) to find the transfer function between the voice of the customer (VOC) and the voice of the process (VOP). Design of experiments (DoE) defines the mathematical relationship between the process variables (X) and the process output (Y) to define the relationship, $Y = f(X)$. This equation could then be used to run simulations on the newly designed process to study the variation and probable failure modes (Ginn 2004).

During the simulations the influence of the different factors are simulated, but the influence of the soft issues such as policies, management support and other related issues are not fully simulated. Typical causality is studied using one of the six sigma tools, fish bone diagram, to study cause and effect. This tool does not allow the user to study and understand feedback from other factors in the improvement process system and generally the understanding is poor of the dynamic behaviour of the improvement process system with the soft issues as factors of the system.

From a system dynamics point of view, the effect of the soft issues with the interaction of the hard issues can be modelled and therefore studied in more detail. This provides a clearer view of the dynamic behaviour of the complete system in relation to the improvements made by a quality improvement process such as six sigma.

8.1 Purpose and objective of this research

The purpose with this research, stated in Chapter 1, has been to model the structure and behaviour of the quality improvement programme system, in order to simulate its dynamic behaviour, including the effect of the hard and soft factors. From this model, the dynamic behaviour of this structure and the effect on the long-term sustainability of the improvements made by the quality improvement programme initiatives, have been studied for a heavy engineering manufacturing environment. Revised policies and strategies based on this model have been designed, to ensure long-term sustainable quality improvement programmes in the heavy engineering manufacturing environment.

The theory developed by Repenning and Sterman (2002), a system dynamics model for process improvement for an automotive environment depicted in Figure 3.3, has been further tested intensively in the setting of operations management in a heavy engineering manufacturing environment. From the polar type case study design the theory has been generalised to be applicable for operations management in a heavy engineering manufacturing environment as described in more detail in Chapter 5. System dynamics of operations management in a heavy engineering manufacturing environment is not well researched. This theory-testing of the validity in a heavy engineering manufacturing environment, is the first contribution of this research.

The system dynamics model proposed by Repenning and Sterman (2002) has been fundamentally expanded to include the sustainability feedback loop, from a systems thinking perspective and grounded in the literature and case study data. The sustainability feedback loop depicted in Figure 6.15 has been developed in section 6.1 from the dynamic hypothesis and data gathered during the polar type case study design. The proposed theory as depicted by the system dynamics model in Figure 6.15, addresses the problem statement in section 1.2 on how gains from quality improvement programmes, after successful implementation, may be sustained over a long-term in a heavy engineering manufacturing environment. This is another novel contribution from this research to the body of knowledge. The theory developed here could be used to expand to other industries, such as the service industry or product development, where sustainability of quality improvement programmes is also a challenge.

Another objective with this research was to develop a system dynamics simulation model of a quality improvement programme. This objective was fulfilled by fundamentally reconstructing and adapting the model developed by Morrison (2007), to include the rework loop as depicted in Figure 6.33. The development of this system dynamics simulation model created the baseline framework from which the simulation model for sustainability has been developed. The development of this simulation model and simulated extensively in Vensim®, is another contribution to the body of knowledge applicable to sustainability of quality improvement programmes in a heavy engineering manufacturing environment.

From these new insights and the theory on sustainability of quality improvement programmes in a heavy engineering manufacturing environment, a system dynamics simulation model has been developed to propose new management policies that could contribute to sustainable quality improvement programmes in a heavy engineering manufacturing environment. The system dynamics simulation model is described in Figure 6.45 and Figure 7.7 with a list of the equations in Appendix B, where Vensim® has been used as the simulation software platform. This system dynamics simulation model for sustainability is another contribution to the body of knowledge on quality improvement programmes in a heavy engineering manufacturing environment. This simulation model could be used in future research to study sustainability in other industries.

In a study done by Baines & Harrison (1999), it was found that manufacturing system modelling does represent a missed opportunity for system dynamics modelling, especially at the higher levels of decision making. From this research it is demonstrated, at a fundamentally inductive and detailed level, that system dynamics is applicable and can be used to model the implementation and sustainability of quality improvement programmes in a heavy engineering manufacturing environment. The interaction of soft factors such as management pressure and management support, with the sustainability of quality improvement programmes in a heavy engineering manufacturing environment, has been successfully demonstrated. This is another contribution from this research that could be used for future work on sustainability of quality improvement programmes in other industries where soft factors are an issue.

8.2 Research questions

In this section the research questions, stated earlier in section 1.3.1 , are answered through a detailed discussion, drawing on information from results obtained during the different sections throughout this thesis. The different research questions are listed from (a) to (e) below.

a) *How can the dynamic behaviour of the manufacturing process be explained with system dynamics?*

Repenning and Sterman (2002) developed a system dynamics model which describes the structure and dynamic behaviour for the implementation of a quality improvement programme in an automotive environment. Morrison (2007) simulated the interaction of the first-order and second-order improvement loops, demonstrating through his results a tipping point in the dynamic system.

In this research, through the data gathered from the case studies, the system dynamics simulation model from Morrison (2007) was fundamentally adapted to include the rework loop applicable to a heavy engineering manufacturing environment, depicted in the theory developed by Repenning and Sterman (2002) for an automotive environment. The rework loop describes a typical concession process where engineering decides on accepting or rejecting the defective units. In this research, engineering is part of the rework loop that quality consults when components are not manufactured in accordance with the design specification. Refer to Figure 6.33. The structure and dynamic behaviour of this system dynamics model has been evaluated with the model variable, desired throughput, simulated as a step input.

The results depicted in Figure 6.36 for the model behaviour, clearly indicate a tipping point for the net process throughput and allocation to production confirming the simulation results from Morrison (2007). From these results the vicious and virtuous loops are demonstrated, indicating that managers could be caught up in self-attribution errors in the dynamics of process improvement. Process problems are typically not visible to managers but defects or defective units are. This dynamic behaviour is confirmed from the semi-structured interviews, archived data and direct observations determined from the case study data. Managers are challenged with decisions on allocation of labour hours to production which competes with labour hours required for improvements such as six sigma.

b) *How does the implementation of the quality improvement programme influence the dynamic behaviour of the manufacturing process?*

During the polar type case study design in this research, fieldwork data was gathered from archived data and semi-structured interviews for defective units per unit produced, which displayed exponential decay behaviour since the implementation of a six sigma quality improvement programme. Refer to Figure 6.4 for defective units per unit produced (DPU) time series plot. The exponential decay is typical for the structure and behaviour of a negative feedback loop with goal seeking behaviour. Exponential regression analysis done on the real system data in section 6.1.3 , indicated a half-life of 7.1 months while empirical studies done by Schneiderman (1988) indicate half-life of 7.6 months for a typical manufacturing process where DPU is calculated.

A dynamic hypothesis was formulated with the inclusion of an additional negative feedback loop with goal seeking behaviour into the system dynamics model previously proposed by Repenning and Sterman (2002). The dynamic hypothesis was grounded in theory through theory building from data gathered in interviews during the case studies. Refer to Figure 6.15 System dynamics model with a sustainability balancing feedback loop (B5), from a systems thinking perspective and paragraph 6.1.5 .

The system dynamics model as depicted in Figure 6.15 has been expanded into a simulation model, simulating the dynamic behaviour of the system with typical values selected for the model parameters and a desired defect level of 0.03. The system dynamics model included an information delay which described the typical measurement processes and analysis time in the measurement feedback loop. Refer to Figure 6.43 and Figure 6.45.

When the simulation was done with a desired throughput of 1400 units per week, the defective units per unit produced (DPU) followed exponential decay behaviour as depicted in Figure 6.48. The half life of the simulated DPU behaviour was not the same value as in the real system, but did replicate the same behaviour. A sensitivity analysis of the DPU behaviour indicated that the exponential decay of the DPU behaviour has been sensitive for the model parameter, unattended process problem level and time to correct problems.

The dynamic hypothesis, as simulated by the sustainability feedback loop in the complete quality improvement system dynamics model, did replicate the dynamic behaviour of the real system. Refer to Figure 6.48 for more detail. When a quality improvement programme such as six sigma, has been implemented successfully, the system dynamics model indicated that the quality improvement programme could be sustained over a long-term with the inclusion of the sustainability feedback loop. This behaviour is typical for sustainable performance as proposed by Zairi (2002) as one of the elements of sustainability.

c) *How do soft factors impact on the dynamic behaviour of the quality improvement programme?*

Management support of the quality improvement programme is one of the key elements to ensure sustainability (Besterfield et al 2003), (Buchanan et al 2005). This research demonstrated that management support is a function of management pressure and managerial effectiveness. Refer to paragraph 6.2.3 Soft factors - managerial effectiveness and management pressure . To demonstrate the impact of management pressure, managerial effectiveness and management support of the dynamic behaviour of the quality improvement programme, a novel analogy has been drawn between a capacitated delay structure and management support.

The stock of management time required to be allocated to the quality improvement programme has been compared to the stock of backlog orders in the capacitated delay structure. The analogy with management support was drawn with the shipments in a capacitated delay structure. Refer to Figure 6.17 for the Stock and flow diagram for the management support balancing loop (B7). In this research it was further demonstrated that the soft factor, managerial effectiveness is a function of another soft factor, management pressure. The relationship was derived from semi-structured interviews and field work during the case study research. Refer to Figure 6.19 that describes the Inverse relationship of the function managerial effectiveness as a function of management pressure.

Simulation results from the system dynamics program for a pulse input demonstrated that the manager experienced more management pressure when the manager's business unit did not met his targets for his quality improvement programme. When his business unit approached the target for the quality improvement programme, his management pressure reduced. Refer to Figure 6.25 depicting the simulation results for Management pressure and managerial effectiveness with DPU gap as a pulse input. The simulation results further demonstrated that management support is typically higher when the business unit approaches the quality improvement programme target and low when the business unit does not meet its quality improvement programme target. Refer to Figure 6.27 depicting the simulation results for Management support and allocated management time required with a DPU gap pulse input.

The simulation results further demonstrate that management support is sensitive to changes in the model parameter, delay in management support. When the delay in management support increases, management support typically reduces. Refer to Figure 6.29 for the Comparison of management support with different levels of delay in management support with a DPU gap pulse input. However, the simulation results for a varying delay in management support depicted in Figure 7.15, demonstrates that defective units per unit produced (DPU) are not sensitive to this variance.

Although management support is low due to the time it could take for managers to accept the new programme, managerial effectiveness is relatively high. Refer to Figure 7.16 for the dynamic behaviour of managerial effectiveness with a varying delay in management support. Due to the table function, managerial effectiveness (Figure 6.19), the sustainability feedback loop is maintained which ensures the usage of the tools of the quality improvement programme.

The dynamic behaviour of the output from the quality improvement programme measured in defective units per unit produced (DPU), was less sensitive to soft factors such as management support as long as the usage of the tools from the quality improvement programme was maintained.

d) *How can system dynamics be used to model sustainability, after the successful implementation of the quality improvement programme?*

Sustainability is typically recognised when working methods and performance levels persist (Buchanan et al 2005). Managerial behaviours and processual or implementation methods, are some factors used in this research to model sustainability through system dynamics. The theory for sustainability of quality improvement programmes in a heavy engineering manufacturing environment, developed in this research, is based on the dynamic hypothesis of the sustainability feedback loop. This loop takes into consideration information feedback driving the decision, based on the state of the system.

The measurement process creates this feedback loop which is depicted by the sustainability feedback loop depicted in Figure 6.15, describing the System dynamics model with a sustainability balancing feedback loop (B5), from a systems thinking perspective. This dynamic hypothesis is tested and validated in section 7.1.2 by comparing the model behaviour with real life behaviour as well as testing the model structure in comparison to the descriptive knowledge of the real system determined by case study one for the machine shop. During the testing and validation process, confidence in the model is achieved when model parameters are optimised by auto calibration. Refer to paragraph 7.1.1 Model tests and validation of the interaction of the first- and second-order improvement loops including the rework loop and paragraph 7.1.2 Model tests and validation of the complete quality improvement programme model including the sustainability feedback loop and management support loop.

The maintenance of the sustainability feedback loop is modelled with a switch in the system dynamics model where the input to the switch simulates the usage of the tools of the quality improvement programme as well as the measurement processes. The simulation results in

Figure 7.9 and Figure 7.10, successfully demonstrate that the model simulates the behaviour of the real system.

The impact of the gear strategy determined from case study one for the machine shop, when the focus of the machine shop shifted from a gear manufacturing shop to a general machine shop, is modelled through the switch function. After the implementation of the gear strategy, the feedback loop created by the quality improvement programme was broken, as modelled by the broken sustainability feedback loop. The model parameter defective units per unit produced (DPU) indicated a negative exponential decay behaviour since the implementation of the quality improvement programme and continued with the the improvement levels while the switch simulated the feedback loop being active. Refer to Figure 7.9 for more detail.

When the focus changed due to the implementation of the gear strategy, the DPU of the system returned to its original behaviour. Refer to Figure 7.9. The behaviour of the state of the system depicted by defective units, also demonstrated the same behaviour.

The system dynamics model of the complete quality improvement programme including the switch, Figure 7.7, satisfactorily modelled the impact of the sustainability feedback loop on the system performance, depicted by the model parameter DPU, by replicating the behaviour of the real system as determined by case study one for the machine shop.

e) *How can system dynamics be used to design new management policies for the sustainability of quality improvement programmes in a heavy engineering manufacturing environment?*

In this research, four decision points have been identified that could lead to new policies for sustainable quality improvement programmes. The four decision points, another novel contribution of this research, are described by management support, problem correction, defect correction and adjusting allocation. Figure 7.7 and Figure 6.45, takes reference. Management policies that could lead to sustainable quality improvement programmes in a heavy engineering manufacturing environment are determined by the decision rules at every decision point in the system. Decisions are the outcome from these decision rules which are applied to available information cues such as measurement and reporting processes.

A policy for management support has been based on information from the information delay, describing the number of measurement processes and analyses time. This information has also determined the amount of allocated management time required for improvements, which also has an impact on management pressure. The simulation results demonstrated that management pressure is sensitive for a variance in the analysis time but defective units per unit produced (DPU) is less sensitive for a varying analysis time. From these results it was concluded that the time taken to analyse the measurements from the quality improvement programme, should be kept as short as possible. Refer to Figure 7.11

A policy for management support has also been based on the delay in management support. The simulation results from the sensitivity analysis demonstrated that management support and therefore management pressure were sensitive to a varying delay in management support. Refer to Figure 7.13 and Figure 7.14 displaying the sensitivity of management support and management pressure respectively. The system dynamics simulation results further demonstrated that a varying delay in management support has little dynamic impact on defective units per unit produced (DPU).

The management support feedback loop is part of the sustainability balancing loop. The conclusion from the simulation results for a policy pertaining to management support is that long-term sustainability has been ensured with the maintenance of the sustainability balancing feedback providing the use of the tools of the quality improvement programme and measurements, as proposed by Zairi (2002) and Buchanan et al (2005).

The policy for defect correction is impacted by the productivity of the manufacturing system as well as the maximum allowable time for concession. The simulation results for the system dynamics model are displayed in Figure 7.18 and Figure 7.17 respectively for the dynamic impact on the model parameter, defective units per unit produced (DPU). The recommended policy for defect correction is to create the most productive manufacturing system possible and to have the concessions for defective units analysed and reported within 1.5 days. Refer to Figure 7.24.

The production manager through his planning system, allocates labour hours to production and the balance of the hours are allocated to the quality improvement programme for improvement. The throughput gap and time to adjust the allocation are the information used in this decision. The simulation results from the sensitivity analysis indicate that the defective parts per unit produced (DPU), are not sensitive to varying time to adjust allocation. Refer to Figure 7.21.

Problem correction is the average rate at which process problems are corrected. The information for this decision point is a function of time to correct problems, managerial effectiveness and problem correction effectiveness. The simulation results for the sensitivity of defective units per unit produced (DPU) with a varying time to correct problems, indicate that DPU is less sensitive to a variance in the time it takes to correct the process problems. Managerial effectiveness closes the feedback from the balancing sustainability loop. The simulation results indicate that if the quality improvement process is broken, the defective units and also DPU return to its previous level before the implementation of the quality improvement programme. Refer to Figure 7.9 and Figure 7.10.

The policy for long-term sustainability of quality improvement programmes in a heavy engineering manufacturing environment should be to maintain the quality improvement programme processualary and to keep the maximum allowable time for concession to 1.5 days.

8.3 Future research

The complete quality improvement system dynamics model developed in this research, assumes that the manufacturing system modelled during this research, manufactures homogeneous type products and that there is no complexity variation from product to product. Defect introduction of defective units is only a function of gross process throughput and process problems. Data gathered during the field work for the case study research, did indicate that complexity could exist from product to product that could have an impact on defect introduction. The time series data is displayed in Figure 7.2, Desired throughput and defective units per month. Data displayed per week, indicated randomness in the defective units data by a randomly changed level of defective units.

For future research, randomness could be introduced into process problems by introducing a model parameter into the model that has a dynamic impact on unattended process problem level. Sensitivity analysis during this research did indicate that unattended process problem level could have a dynamic impact on the level of process problems.

Buchanan et al (2005) identified eleven factors that could affect the sustainability of quality improvement programmes. Two of the factors identified in their research have been tested during this research to demonstrate in an original way its dynamic impact on the long-term sustainability of quality improvement programmes. For future research, the balance of the factors could be investigated further by expanding the model developed during this research.

The research done by Zairi (2002) proposed the creation of an organisational system that encourages co-operation, learning and innovation which could lead to continuous improvement. The dynamic impact of allocated management time required for improving learning could be investigated by expanding the model in this research.

The sensitivity analysis on defective units per unit produced (DPU) indicated that the model parameter, productivity of production time, has an important dynamic impact. Productivity of typical manufacturing systems could dynamically change depending on factors such as worker morale. During an intervention such as the gear strategy, process problems could change dynamically which could have a dynamic impact on defect introduction.

Worker morale could be one of the reasons for the dynamic change in process problems. For future research, the model in this research could be expanded to include the dynamic impact of worker morale or buy-in. It is recognised, that for the successful implementation and sustainability of quality improvement programmes that buy-in of employees into these programmes is important (Asif et al 2008).

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APPENDIX A

	Machine shop	**Final assembly**	**Tear down**	**Fabrication**
Work harder loop	Business unit manager " ... and our over time rate is actually pretty high. My over time is about 24% at the moment, which is related to the demand. We are working a lot of over time "	Business unit manager " ... I get the true shortage list, and then I start doing the expediting." " We did improve a little, the guys on the shop floor ... They say they did it from nobody. They worked hard to get it out."	Business unit manager "...having to work harder instead of worker smarter, they *[the workers*] did not know the difference" "... when people were achieving 10 days they were working excessive overtime, sometimes to 9 at night."	Team leader "...I had to work without breaks, I had to work long hard hours, we had to work around the clock.." Team leader " ...the main issue is the availability of the parts."
Rework loop	Business unit manager " The engineer comes once or twice a week ...if he says it is scrap, it goes into the scrap are. If he says it can be reworked, we will rework it. "	Business unit manager " ... If all the information and parts are not available to the people *[other departments in the value chain]*that is supposed to give me the finished product, I sit with the rework." " I have to rework it because if I have to send it back, I will never get the machine out." " ... we have to rework it...I have to modify the mainframe for all the conveyors have to fit..."		Team leader " I had to speak to *[business unit manager]* and tell him we need the parts to meet the target dates. I ask the machine operator when I will have the frame back...I do my set up for the next operations, only to find that once the frame arrives I do not have parts." Group quality manager " When that happens *[defects are created]* they *[operators]* ask if there are ways to rework it, and then you have to find a way to rework it "
Work smarter loop	Manufacturing Director "Quality programs that have been rolled out so far is the one that I am running with Moses Mudau the six sigma initiative to improve quality in machine shop..." "He came here *[Master Black Belt]*and he took some few people through six sigma basics and then the champion for *[the machine shop]* is *[the quality manager]* which is in the quality department". Opex manager "The wave in the machine shop has been more successful than in manufacturing and final assembly" Opex manager " A six sigma project was also rolled out, implemented by the quality manager...it was implemented to reduce defects." Business unit manager " Opex *[operational excellence]* is wide, we looked at the different aspects of all processes as well" " I have measurements ...from these reject reports ... we have a defect analysis ... That will tell us first of all the machine, it will tell us the type of defect..." " If there is something wrong on the machine ... therefore has to stop the machine. I will then do process experimentation or study ..." Technical supervisor " We took the complete workshop *[machine shop], ...* and did a training session which run for about 2 hours. " Quality inspector " We involved industrial engineering ... to modify the method in accordance to the operator's understanding. We also studied the geometry of the machine, we called maintenance to do this investigation"	Manufacturing Director "The other thing is the ongoing one to address the quality issues it is the what we call quality circles. So quality circles they currently running in ... and final assembly in *[assembly plant]*" "So in terms of quality circles, it was more from the shop floor, they themselves were eager to participate in this thing" Opex manager " ...we have also worked on final assembly, where layout changes have been done." Business unit manager " ...the only real improvement that we can see is that the housekeeping of the *[final assembly]* is much better..."	Opex manager " This is the second wave, we started at tear down where we changed the layout..." Business unit manager " ...Kaizen event...6S...process flow...what is required from the shop *[manufacturing and assembly]* and set it up for 80% of the work in the shop *[manufacturing and assembly].* "implementation...shadow boards, painting the area..." "One of the initiatives ...was to remove all the dirty operations from the factory...We also managed to reduce the travelling associated with waste."	Opex manager " ...part of the 2nd wave was the fabrication shop...The fabrication shop was one of the biggest focus areas for a long time." Business unit manager " ...I did not believe they had the right people on the team. I did not believe they have done what Opex could have achieved at that stage." " They *[improvement team members]* claimed that they could achieve certain results, but they never proofed it" " The complete process *[including supply chain]* was not improved, only the one step in the process."

Table A.1: Coding matrix for theory testing of theory developed by Repenning and Sterman (2000). Part one

	Machine shop	**Final assembly**	**Tear down**	**Fabrication**
Focus on throughput	Business unit manager " ...it is actually output related as well, if we put out more, the amount of defective parts increase as well" Technical supervisor " Our primary focus is to deliver against our orders at good quality and sometimes *[the quality improvement program suffers]* the methodology is suffering because of the work load. " Quality inspector " There *[management]* focus is only on production, ... but then the defect at the end is reducing the production."	Opex manager " I started a session with the team from the final assembly to draw up a value steam map, but we had to stop half way into the session. The team had been pulled back to their work stations due to machines that had to be build urgently..."	Business unit manager " He *[team leader]*needs to manage the capacity of the people, and has to move the people around to satisfy the demand. The department is measured against productivity, and when your people are working in other departments and working on jobs that can not be recovered, it shows negatively on your measurements..."	Business unit manager " ...top management had this firm believe, if you could reduce it *[cycle time of the fabricated frames]* to 25 days, you can bring in another 2 machines... " " This is now constrained by support like supply of materials" Group quality manager " The business unit manager is committed to achieve quality, but when the production pressure comes, they will push the production ... because they are being pushed " " It is very difficult to get a machine from production especially when the demand is high, ... it is very difficult to give the machine to investigate. "
Reinvestment loop	Business unit manager " This is the numbers for 2011, we exceeded 2010 in volumes and improved on the scrap rate" " ... We will zoom in on that *[defect analysis]* and found exactly what is the problem, machine or operator" " A lot of times the operator will say it is not them, it is the machine ... then we will investigate the machine" Technical supervisor " ... we sit and found out what went wrong ... then we will have a physical interview with the team leader and operator and ask what went wrong, ...you identify the problem and eliminate the problem going forward ..." " We value this quality improvement program quite important, but it does happen that there is a bit of production loss due to this " Quality inspector " At first the production was less due to the training and process experimentation done on the machine, but after the successful implementation of the program, the production start to increase with good quality " Quality manager " If you go there today, he [the operator] is one of the highest performers as a result of the intervention [quality improvement program]. "	Manufacturing Director "One of the few places we managed to do it is through the quality circles where they have these meetings every week and they are continuously driving for quality improvement through those quality circles" Business unit manager " The problem is now that the parts are sitting all over because we have already picked it" " I spend more time on the computer expediting parts that what I spend improving, methods and build processes on the shop floor"	Business unit manager " ...6S was just setting the foundation, now we need to look at better ways of improving the department, small changes...cycle time needs to be improved even further, remove bottle necks."	Team leader " ...the main issue is the availability of the parts."

Table A.2: Coding matrix for theory testing of theory developed by Repenning and Sterman (2000). Part two

		Machine shop	Final assembly	Tear down	Fabrications	Management
Management support	Vision	Business unit manager, machine shop " To improve all the time, give the customer an excellent service and a good quality product, obviously on time because that is part of quality "		Business unit manager, tear down " ... With the intent to increase the productivity and reduce the cycle time as well as increase the capacity with 25% on each of these initiatives" "... even today they see management committed to this process ..."		Manufacturing director " My role is initiator and also sponsor for the quality improvement programs like operational excellence" " ... they *[the team]* do a presentation to the VP and some *[board members]* "
	Management pressure	Business unit manager, machine shop " When we are not achieving our targets, it put me under pressure ... I get frustrated ... " " ... I have to get more and more involved again in their day to day activities ... It does some times happen that my own work starts to lag behind, then I have to put extra effort in to catch up with my own work ... " " It does put my time under pressure when I have to get involved in shop floor activities during the day "		Business unit manager " It is a battle to reduce the cycle time to 10 days and cut the over time" " if I meet my target, I go back to 30% focus, but when I do not meet my target I go to 70% focus on the improvement project " " I am under pressure ... I do feel pressure ... focussing on priority managerial activities first "		Business unit manager, machine shop " When the pressure is low I find my time management to be very well under control and have high focus levels on the quality improvement program" When we were bringing back work from the sub contractors to fill the capacity, ... the work complexity has changed ... this put pressure on my management time ... I can now only focus on this problem ... " " As the pressure increase, my focus is more detailed on certain activities, as the pressure decrease, my focus is broader on other management activities as well "
	Managerial effectiveness	Team leader, machine shop " *[Business unit manager]* and I discuss quality and quality improvement programs a few times per day and he will share his information " Business unit manager, machine shop " ... I spend about 20 % to 30% of my time on the shop floor ... I also have meetings ... we also discuss HR and IR issues ... discuss the machines that are not working ... make sure I get my recoveries " " The focus is not the same as it was two years ago " " ... I focussed 80% of my day on the improvement program and today I focus 40% on the program "		Business unit manager, tear down " Improvements unfortunately at the moment is taking a back seat, because of all the work I have to do in my department ..." " ... 30% of my time now is focussed in improvement and 70% on production, but previously I focussed 70% of my time on improvement and 30% of my time on production ... I had to make sure the program was successful and stable " " I prefer to have someone who could focus on improvements in the department ... " " It is also a function of my work load "		Quality manager, machine shop " We followed the methodology of sixsigma which is plan, do, check and act. Investigate the problem until we get to the root cause of the problem " Business unit manager, machine shop " It was my job to head up the consultations and hence all my management time went into this activity " " This brought a morale and motivation issue that also took a lot of my management time " " If we meet our targets, then I find it easy to manage my time and hence give attention to all my managerial activities. Other factors, such as the gear strategy, influence my management time in a negative way and then I have to increase my focus on certain detail activities. This cause a lack of attention to the quality improvement time "
	Managerial time management	Business unit manager, machine shop " I am 100% committed. I do regular audit walks on the floor and machine inspections" Team leader, machine shop " Every morning we have a board meeting where we discuss quality. The board meeting is at every cell where we have a visual performance board where quality issues, 6S results and work centre problems are displayed " " I have twice a week a formal meeting with my team leaders " " About 60% of my day realize the way I planned it "		Business unit manager " ... there is a lot of productivity and operational requirements that I have to take care of as well as IR and HR issues " " Whenever I walk the floor ... Things that needs to be improved. If we walk on the floor and discussing production requirements, we also look at things that need to be taken care of in terms of improvement " " Production is taking more of my time now " " I do work over time, I stay after 5 ... to get certain things done ... "		Business unit manager, tear down " Minimum 40% is MBWA and the other 60% is meetings and other operational requirements " " I get 60% done of what I have planned to do " Business unit manager, machine shop " About 60% of my day realize the way I planned it "
Continuous improvement	Incremental small changes	Manufacturing director " ... Setting time aside to focus on improvement ... through quality circles ... have these meetings every week ... continuously driving for quality improvement." Business unit manager, machine shop " I made small changes and then everybody accepted it as part of life" Team leader, machine shop " As you go along you identify more areas for improvement ... you keep on improving, a little bit every time "		Business unit manager " 6S was just setting the foundation, now we need to look at better ways of improving the department, small changes ... cycle time needs to be reduced even further" " ... It feels good when we meet our target ... Finding better ways to do the job better and faster ... "		Quality manager, machine shop " As soon as we are successful in fixing this problem, the next one becomes evident, and then we work on that one until that is solved. We are working at fixing the problems one at a time"

Table A.3: Coding matrix for theory development for sustainability. Part one

	Machine shop	Final assembly	Tear down	Fabrications	Management
Measurements	Business unit manager, machine shop " We try and track the defect at the origin of the defect ...we try to find the reject at that stage and not at the end of the process ... " Team leader, machine shop " The 6S part of Operational excellence is sustained fairly good. It is rolled out to the complete work shop " Quality inspector, machine shop " The process is still going very well. The reason is we keep on monitoring the product " " We are monitoring the defects per unit every month. *[Quality manager]* capture the information and do the graphs *[DPU graph]* and give it to management with root causes as well as cost " " Identify the root cause for the problem that occurred, which means some analysis ... From here follows some corrective actions like re-training etc. "	Business unit manager, final assembly " We still measure productivity, lead time and 6S "	Manufacturing director " ... If you look at *[business unit manager]* department in the tear down area, he is sending up his metric every month ..." " ... there is a departmental board ... With the target of the number of days he has to ship a machine. If he exceeds his date, the robot turns red and indicate he exceeds his TAT " " I investigate the reasons why it is deviating ... From these investigations I have to for example speak to maintenance to fix the crane " " If I do not meet my target, I focus on what needs to be done to meet my target. I do an analysis and then decide what needs to be done ... " " I have a dash board that I populate on a monthly basis to see where we are in terms of our target " " ... we are doing it once a month "	Manufacturing director " ... Target of 35 days for total turn around time for a frame, they achieved that. They had a metric ...[b*usiness unit manager] retired, ...* It collapsed. ... You need full owner ship, not only the manager..." Team leader, fabrications " It was only done then *[at the time of implementation],* and not maintained any more "	Operational excellence manager " ... We introduced process boards, visual performance boards ..." Quality manager, machine shop " We measure the process to make sure the defects per unit is not more than the target "
Meet goals	Business unit manager, machines hop " These are the targets we worked to and the actual number achieved *[DPU graph]*... the scrap rate was dropped in half "	Business unit manager, final assembly " ... I have to say the only real improvement we can see is that the house keeping of the shop is much better or 6S as it is called"	Business unit manager " The sustainability was questionable because of change in management. I managed to make quite a few changes and improvements, which helped to reduce the turn around time to 10 days again"	Business unit manager " There was this expectation that was created and frankly we could not achieve it. Even today I battle to achieve 35 days " Team leader, fabrications " The guys were trained on 6S ... after the paint the shop looked different ... the shop did not stay like that"	Operational excellence manager " The 6S measurements are send monthly to the US. The departments do an audit where the results are plotted on a graph and displayed on the board"
Use tools	Operational excellence manager " The processes that were installed are still being used today" Business unit manager, machine shop " ... then we will zoom in and find out exactly what is the problem, machine or operator " Team leader, machine shop " We use six sigma methodology "		Business unit manager, tear down " ... in both areas 6S check sheets have been implemented ... we also introduced performance measurements boards ..." "... all of this is still in place."	Business unit manager " ... there are tools like 6 S ... that you use to achieve 6S status" " That is achieved very well"	Operational excellence manager " All these measurements are in place" " ... 6S and value stream mapping are still being used" Quality manager, machine shop " The team looked at the root causes by using the Ishikawa diagram. We also used MSA analysis and pareto charts "
Positive trajectory of improvement	Operational excellence manager " If something goes wrong today in the machine shop then everybody knows it immediately" " ... what we measure there today is a huge improvement from what we had on we started with the program" Team leader, machine shop " There was a massive improvement and it was proven by the results pulled out of SAP "	Business unit manager, final assembly " We did improve on lead time and productivity from where we have been before, but we are still far from our targets"	Business unit manager " ... the cycle time was 30 days to 24 days and then we managed to bring it down to 10 days where it is currently running at"		

Table A.4: Coding matrix for theory development for sustainability. Part two

APPENDIX B

VENSIM® EQUATIONS

Appendix B.1 Figure 3.4 System dynamics simulation model of the interaction between first- and second-order improvement loops. Reconstructed and refined from Morrison (2007)

Adjusting allocation=(Indicated allocation to production-Allocation to production)/Time to adjust allocation
Units: hours/week/week
Allocation for maximum problem correction=4000
Units: hours/week

Allocation to improvement=Available time-Allocation to production
Units: hours/week

Allocation to production= INTEG (Adjusting allocation, 0)
Units: hours/week
The allocation to production is a stock that is increased or decreased by adjusting allocation

Available time=4000
Units: hours/week

Average Process erosion time=36
Units: weeks

Defect introduction=Gross process throughput*Process problems
Units: units/week

Desired allocation to production=Allocation to production+Resource gap
Units: hours/week

Desired throughput=STEP(1400, 10)
Units: units/week
The desired production is an exogenous goal of the process

Gross process throughput=Allocation to production*Productivity of production time

Units: units/week
Gross process throughput is the product of the amount of time
workers spend on production activities

Indicated allocation to production=MAX(0, MIN(Available time, Desired allocation to production))
Units: hours/week

Net process throughput=Gross process throughput-Defect introduction
Units: units/week
NPT is the difference between the Gross process throughput and
the amount of defects produced

Problem correction=Problem correction effectiveness*(Process problems/Time to correct problems)
Units: Dmnl/week

Problem correction effectiveness=Allocation to improvement/Allocation for maximum problem correction
Units: Dmnl

Problem introduction=(Unattended Process problem level-Process problems)/Average Process erosion time
Units: Dmnl/week

Process problems= INTEG (Problem introduction-Problem correction,0.4)
Units: Dmnl

Productivity of production time=1
Units: units/Hour

Resource gap=Throughput gap/Resources needed per unit
Units: hours/week

Resources needed per unit=Productivity of production time/(1-Process problems)
Units: units/Hour

Throughput gap=Desired throughput-Net process throughput
Units: units/week

Time to adjust allocation=1
Units: weeks

Time to correct problems=16
Units: weeks

Unattended Process problem level=0.9
Units: Dmnl

Appendix B.2 Figure 6.23: System dynamics structure of the complete management support model with the exogenous variable DPU gap

Adjusting allocated management time=(Normal management time-Allocated management time required for improvement)/Adjustment frequency
Units: hours/(Week*Week)
The input rate at which the allocated management time is adjusted at the adjustment frequency

Adjustment frequency=1
Units: Week
Time delay the manager take to reset his management time

Allocated management time required for improvement= INTEG (Adjusting allocated management time-Management support, INITIAL MANAGEMENT TIME)
Units: hours/Week
The integral of allocated management time with initial value

Delay in management support=1
Units: Week
This is the typical time it take for a manager to give support to the improvement programme

Desired allocated time for improvement gap=Target allocation to improvement-Allocated management time required for improvement
Units: hours/Week
The desired allocated time for improvement is therefore the difference between the amount of time already allocated to management time and the the time that is required by the process to be allocated to the improvement

DPU gap=PULSE(0, 1)
Units: Dmnl
Input function of DPU gap

Fraction of allocated time for improvement=Table fraction(DPU gap)
Units: Dmnl
The function Y=f(X) where the function is the lookup table Fraction and the input X is the DPU gap

INITIAL MANAGEMENT TIME=0

Units: hours/Week
Initial value of allocated management time

Management pressure=Desired allocated time for improvement gap/Total management time
Units: Dmnl
Managment pressure is the normalized input into the table
function Effectiveness to determine the managerial effectiveness

Management support=(Managerial effectiveness*Total management time)/Delay in management support
Units: hours/(Week*Week)
Management support is the fraction of the total management time
due to managerial effectiveness which happen after a certain
delay is overcome

Managerial effectiveness=Table effectiveness(Management pressure)
Units: Dmnl
Effect of management pressure on managerial effectiveness whith
the function Y=f(X). The Y is the managerial effectiveness and
the X is the management pressure

Normal management time=40
Units: hours/Week
This is the amount of time a manager has available per week
under normal circumstances for a normal week

Table effectiveness([(-1,0.2)-(1,0.8)],(-1,0.8),(-0.9,0.8),(-0.8,0.8),(-0.7,0.8),(-0.6,0.8),
(-0.5,0.8),(-0.4,0.8),(-0.3,0.8),(-0.2,0.79),(-0.1,0.78),(0,0.75),(0.1,0.7),
(0.2,0.6),(0.3,0.5),(0.4,0.4),(0.5,0.3),(0.6,0.25),(0.7,0.22),(0.8,0.21),
(0.9,0.2),(1,0.2))
Units: Dmnl
Effect of management pressure on managerial effectiveness

Table fraction([(-1,0)-(1,0.9)],(-1,0.8),(-0.5,0.8),(-0.1,0.8),(-0.09,0.8),(-0.08,0.78),
(-0.07,0.74),(-0.06,0.67),(-0.05,0.6),(-0.04,0.52),(-0.03,0.44),(-0.02,0.36)
,(-0.01,0.28),(0,0.2),(0.01,0.28),(0.02,0.36),(0.03,0.44),(0.04,0.52),(0.05,0.6),
(0.06,0.67),(0.07,0.74),(0.08,0.78),(0.09,0.8),(0.1,0.8),(0.5,0.8),(1,0.8))
Units: Dmnl
Effect of DPU gap on fraction allocated management time for
improvement

Target allocation to improvement=Fraction of allocated time for improvement*Normal management time
Units: hours/Week
The target allocation management time to improvement is a
function of the DPU gap and the target allocated management
time. This is a dynamic target

Total management time=48
Units: hours/Week
This is typical the amount of over time managers would work to
get through all their required managerial activities

Appendix B.3 Figure 6.33: System dynamics structure for the interaction between the first- and second-order improvement loops with the rework loop included

Adjusting allocation=(Indicated allocation to production-Allocation to production)/Time to adjust allocation
Units: hours/week/week

Allocate to production rework=Engineering concession/Productivity of production time
Units: hours/week

Allocation for maximum problem correction=4000
Units: hours/week

Allocation to improvement=Available time-Allocation to production
Units: hours/week

Allocation to production= INTEG (Adjusting allocation, 0)
Units: hours/week
The allocation to production is a stock that is increased or
decreased by adjusting allocation

Available time=4000
Units: hours/week

Average Process erosion time=36
Units: weeks

Defect correction=Rework production planning capacity*Productivity of production time
Units: units/week

Defect introduction=Process problems*Gross process throughput
Units: units/week

Defective units= INTEG (Defect introduction-Defect correction,0)
Units: units

Desired allocation to production=Allocation to production+Resource gap
Units: hours/week

Desired throughput=STEP(1100,10)

Units: units/week
The desired production is an exogenous goal of the process

Engineering concession=Defective units/Maximum allowable time for concession
Units: units/week

Gross process throughput=Allocation to production*Productivity of production time
Units: units/week
Gross process throughput is the product of the amount of time
workers spend on production activities

Indicated allocation to production=MAX(0, MIN(Available time, Desired allocation to production))
Units: hours/week

Maximum allowable time for concession=2
Units: week

Net process throughput=Gross process throughput-Defect introduction+Defect correction
Units: units/week
NPT is the difference between the Gross process throughput and
the amount of defects produced

Problem correction=Problem correction effectiveness*(Process problems/Time to correct problems)
Units: Dmnl/week

Problem correction effectiveness=Allocation to improvement/Allocation for maximum problem correction
Units: Dmnl

Problem introduction=(Unattended Process problem level-Process problems)/Average Process erosion time
Units: Dmnl/week

Process problems= INTEG (Problem introduction-Problem correction,0.4)
Units: Dmnl

Productivity of production time=1
Units: units/Hour

Resource gap=Throughput gap/Resources needed per unit

Units: hours/week

Resources needed per unit=Productivity of production time/(1-Process problems)
Units: units/Hour

Rework production planning capacity=MAX(0, MIN((Available time-Allocation to production), Allocate to production rework))
Units: hours/week

Throughput gap=Desired throughput-Net process throughput
Units: units/week

Time to adjust allocation=1
Units: weeks

Time to correct problems=16
Units: weeks

Unattended Process problem level=0.9
Units: Dmnl

Appendix B.4.1 Figure 6.43: System dynamics structure of the complete quality improvement programme with the sustainability feedback loop. Part one – system dynamics structure for the quality improvement programme including the re work loop

Adjusting allocation=(Indicated allocation to production-Allocation to production)/Time to adjust allocation
Units: hours/week/week

Allocate to production rework=Engineering concession/Productivity of production time
Units: hours/week

Allocation for maximum problem correction=4000
Units: hours/week

Allocation to improvement=Available time-Allocation to production
Units: hours/week

Allocation to production= INTEG (Adjusting allocation, 400)
Units: hours/week
The allocation to production is a stock that is increased or
decreased by adjusting allocation

Available time=4000
Units: hours/week

Average Process erosion time=36
Units: weeks

Defect correction=Rework production planning capacity*Productivity of production time
Units: units/week

Defect introduction=Process problems*Gross process throughput
Units: units/week

Defective units= INTEG (Defect introduction-Defect correction, 0)
Units: units

Desired allocation to production=Allocation to production+Resource gap
Units: hours/week

Desired throughput=STEP(1400, 0)
Units: units/week
The desired production is an exogenous goal of the process

DPU= (Defective units/Gross process throughput)/Measurement reporting delay
Units: Dmnl
Defective units per unit produced

Engineering concession=Defective units/Maximum allowable time for concession
Units: units/week

Gross process throughput=Allocation to production*Productivity of production time
Units: units/week
Gross process throughput is the product of the amount of time
workers spend on production activities

Indicated allocation to production=MAX(0, MIN(Available time, Desired allocation to production))
Units: hours/week

INITIAL PROCESS PROBLEMS=0.4
Units: Dmnl

Management pressure=Desired allocated time for improvement gap/Total management time
Units: Dmnl
Managment pressure is the normalized input into the table
function Effectiveness to determine the managerial effectiveness

Managerial effectiveness=Table effectiveness(Management pressure)
Units: Dmnl
Effect of management pressure on managerial effectiveness whith
the function Y=f(X). The Y is the managerial effectiveness and
the X is the management pressure

Maximum allowable time for concession=2
Units: week

Measurement reporting delay=1
Units: week
Measurement reporting delay is the delay in weeks between the
measurement being recorded and the next administration processes

Net process throughput=Gross process throughput-Defect introduction+Defect correction
Units: units/week
NPT is the difference between the Gross process throughput and
the amount of defects produced

Problem correction=(Problem correction effectiveness+Managerial effectiveness)*(Process problems/Time to correct problems)
Units: Dmnl/week

Problem correction effectiveness=Allocation to improvement/Allocation for maximum problem correction
Units: Dmnl

Problem introduction=(Unattended Process problem level-Process problems)/Average Process erosion time
Units: Dmnl/week

Process problems= INTEG (Problem introduction-Problem correction,INITIAL PROCESS PROBLEMS)
Units: Dmnl

Productivity of production time=1
Units: units/Hour

Resource gap=Throughput gap/Resources needed per unit
Units: hours/week

Resources needed per unit=Productivity of production time/(1-Process problems)
Units: units/Hour

Rework production planning capacity=MAX(0, MIN((Available time-Allocation to production), Allocate to production rework))
Units: hours/week

Table effectiveness([(-1,0.2)-(1,0.8)],(-1,0.8),(-0.9,0.8),(-0.8,0.8),(-0.7,0.8),(-0.6,0.8),
(-0.5,0.8),(-0.4,0.8),(-0.3,0.8),(-0.2,0.79),(-0.1,0.78),(0,0.75),(0.1,0.7),
(0.2,0.6),(0.3,0.5),(0.4,0.4),(0.5,0.3),(0.6,0.25),(0.7,0.22),(0.8,0.21),
(0.9,0.2),(1,0.2))
Units: Dmnl
Effect of management pressure on managerial effectiveness

Throughput gap=Desired throughput-Net process throughput
Units: units/week

Time to adjust allocation=1
Units: weeks

Time to correct problems=16
Units: weeks

Unattended Process problem level=0.9
Units: Dmnl

Appendix B.4.2 Figure 6.45: System dynamics structure of the complete quality improvement programme with the sustainability feedback loop. Part two - system dynamics structure for the management support loop with an information delay

Adjusting allocated management time=(Normal management time-Allocated management time required for improvement)/Adjustment frequency
Units: hours/(week*week)
The input rate at which the allocated management time is adjusted at the adjustment frequency

Adjustment frequency=1
Units: week
Time delay the manager take to reset his management time

Allocated management time required for improvement= INTEG (Adjusting allocated management time-Management support, INITIAL MANAGEMENT TIME)
Units: hours/week
The integral of allocated management time with initial value

Analysis time=4
Units: week
Time taken by the quality improvement team to measure and analyse the results

Delay in management support=1
Units: week
This is the typical time it take for a manager to give support to the improvement programme

Desired allocated time for improvement gap=Target allocation to improvement-Allocated management time required for improvement
Units: hours/week
The desired allocated time for improvement is therefore the difference between the amount of time already allocated to management time and the the time that is required by the process to be allocated to the improvement

Desired defect level=0.03
Units: Dmnl

DPU=(Defective units/Gross process throughput)/Measurement reporting delay
Units: Dmnl
Defective units per unit produced

DPU gap=Desired defect level-DPU
Units: Dmnl
Gap between the desired defect level and the actual defect level (DPU)

Fraction of allocated time for improvement=Table fraction(Information delay)
Units: Dmnl
The function Y=f(X) where the function is the lookup table
Fraction and the input X is the DPU gap

Information delay=SMOOTH N(DPU gap, Analysis time, 0, Measurement and reporting processes)
Units: Dmnl
Information delay to measure, analyse and report on the
defective units produced per unit produced

INITIAL MANAGEMENT TIME=0
Units: hours/week
Initial value of allocated management time

Management pressure=Desired allocated time for improvement gap/Total management time
Units: Dmnl
Managment pressure is the normalized input into the table
function Effectiveness to determine the managerial effectiveness

Management support=(Managerial effectiveness*Total management time)/Delay in management support
Units: hours/(week*week)
Management support is the fraction of the total management time
due to managerial effectiveness which happen after a certain
delay is overcome

Managerial effectiveness=Table effectiveness(Management pressure)
Units: Dmnl
Effect of management pressure on managerial effectiveness whith
the function Y=f(X). The Y is the managerial effectiveness and
the X is the management pressure

Measurement and reporting processes=4
Units: Dmnl
Number of measurement and reporting processes. Data is measured, analysed and reported

Normal management time=40
Units: hours/week
This is the amount of time a manager has available per week under normal circumstances for a normal week

Table effectiveness([(-1,0.2)-(1,0.8)],(-1,0.8),(-0.9,0.8),(-0.8,0.8),(-0.7,0.8),(-0.6,0.8),(-0.5,0.8),(-0.4,0.8),(-0.3,0.8),(-0.2,0.79),(-0.1,0.78),(0,0.75),(0.1,0.7),(0.2,0.6),(0.3,0.5),(0.4,0.4),(0.5,0.3),(0.6,0.25),(0.7,0.22),(0.8,0.21),(0.9,0.2),(1,0.2))
Units: Dmnl
Effect of management pressure on managerial effectiveness

Table fraction([(-1,0)-(1,0.9)],(-1,0.8),(-0.5,0.8),(-0.1,0.8),(-0.09,0.8),(-0.08,0.78),(-0.07,0.74),(-0.06,0.67),(-0.05,0.6),(-0.04,0.52),(-0.03,0.44),(-0.02,0.36),(-0.01,0.28),(0,0.2),(0.01,0.28),(0.02,0.36),(0.03,0.44),(0.04,0.52),(0.05,0.6),(0.06,0.67),(0.07,0.74),(0.08,0.78),(0.09,0.8),(0.1,0.8),(0.5,0.8),(1,0.8))
Units: Dmnl
Effect of DPU gap on fraction allocated management time for improvement

Target allocation to improvement=Fraction of allocated time for improvement*Normal management time
Units: hours/week
The target allocation management time to improvement is a function of the DPU gap and the target allocated management time. This is a dynamic target

Total management time=48
Units: hours/week
This is typical the amount of over time managers would work to get through all their required managerial activities

Appendix B.5 Figure 7.7: Structure of the system dynamics model for the complete quality improvement programme model with the introduction of a switch. Part one Adapted from Figure 6.43

Adjusting allocation=(Indicated allocation to production-Allocation to production)/Time to adjust allocation
Units: hours/week/week

Allocate to production rework=Engineering concession/Productivity of production time
Units: hours/week

Allocation for maximum problem correction=4000
Units: hours/week

Allocation to improvement=Available time-Allocation to production
Units: hours/week

Allocation to production= INTEG (Adjusting allocation, 400)
Units: hours/week
The allocation to production is a stock that is increased or
decreased by adjusting allocation

Available time=4000
Units: hours/week

Average Process erosion time=10.1
Units: weeks

Defect correction=Rework production planning capacity*Productivity of production time
Units: units/week

Defect introduction=Process problems*Gross process throughput
Units: units/week

Defective units= INTEG (Defect introduction-Defect correction, 0)
Units: units

Desired allocation to production=Allocation to production+Resource gap
Units: hours/week

Desired throughput:=GET XLS DATA('Book2 ver 2.xls', 'DES', 'B', 'C2')

Units: units/week
The desired production is an exogenous goal of the process

DPU= (Defective units/Gross process throughput)/Measurement reporting delay
Units: Dmnl
Defective units per unit produced

Engineering concession=Defective units/Maximum allowable time for concession
Units: units/week

Gross process throughput=Allocation to production*Productivity of production time
Units: units/week
Gross process throughput is the product of the amount of time workers spend on production activities

Indicated allocation to production=MAX(0, MIN(Available time, Desired allocation to production))
Units: hours/week

INITIAL PROCESS PROBLEMS=0.2
Units: Dmnl

Management pressure=Desired allocated time for improvement gap/Total management time
Units: Dmnl
Managment pressure is the normalized input into the table function Effectiveness to determine the managerial effectiveness

Managerial effectiveness=Table effectiveness(Management pressure)
Units: Dmnl
Effect of management pressure on managerial effectiveness whith the function Y=f(X). The Y is the managerial effectiveness and the X is the management pressure

Maximum allowable time for concession=0.35
Units: week

Measurement reporting delay=1
Units: week
Measurement reporting delay is the delay in weeks between the measurement being recorded and the next administration processes

Net process throughput=Gross process throughput-Defect introduction+Defect correction

Units: units/week
NPT is the difference between the Gross process throughput and
the amount of defects produced

Problem correction=(Problem correction effectiveness+Switch)*(Process problems/Time to correct problems
)
Units: Dmnl/week

Problem correction effectiveness=Allocation to improvement/Allocation for maximum problem correction
Units: Dmnl

Problem introduction=(Unattended Process problem level-Process problems)/Average Process erosion time
Units: Dmnl/week

Process problems= INTEG (Problem introduction-Problem correction,INITIAL PROCESS PROBLEMS)
Units: Dmnl

Productivity of production time=0.74
Units: units/Hour

Resource gap=Throughput gap/Resources needed per unit
Units: hours/week

Resources needed per unit=Productivity of production time/(1-Process problems)
Units: units/Hour

Rework production planning capacity=MAX(0, MIN((Available time-Allocation to production), Allocate to production rework))
Units: hours/week

Switch=
Switch input*Managerial effectiveness
Units: Dmnl

Switch input=PULSE(130, 100)
Units: Dmnl
This parameter is the switch that switch the effect of the
management feedback loop on at point in time of 134.695 weeks

Table effectiveness([(-1,0.2)-(1,0.8)],(-1,0.8),(-0.9,0.8),(-0.8,0.8),(-0.7,0.8),(-0.6,0.8),
(-0.5,0.8),(-0.4,0.8),(-0.3,0.8),(-0.2,0.79),(-0.1,0.78),(0,0.75),(0.1,0.7),
(0.2,0.6),(0.3,0.5),(0.4,0.4),(0.5,0.3),(0.6,0.25),(0.7,0.22),(0.8,0.21),
(0.9,0.2),(1,0.2))
Units: Dmnl
Effect of management pressure on managerial effectiveness

Throughput gap=Desired throughput-Net process throughput
Units: units/week

Time to adjust allocation=0.06
Units: weeks

Time to correct problems=30.5
Units: weeks

Unattended Process problem level=0.12
Units: Dmnl

Appendix C. Quantitative analysis of desired throughput and defective units per month.

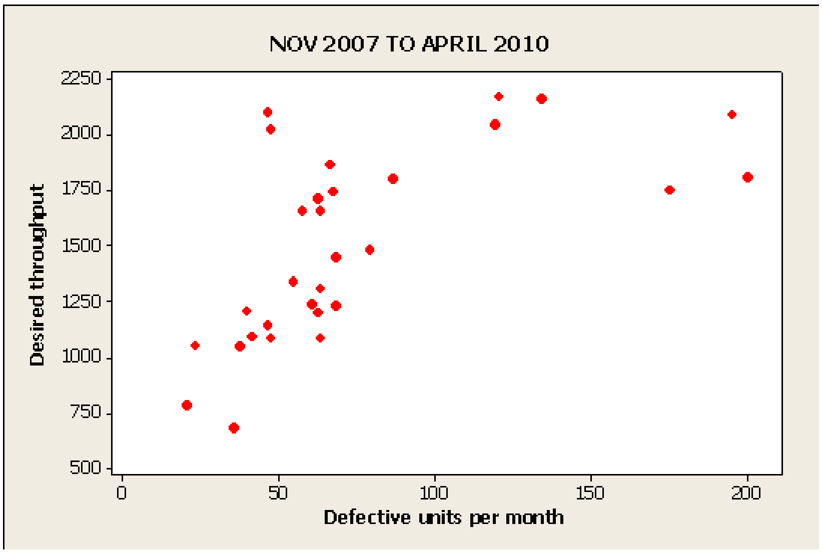

Figure C.1: Desired throughput versus defective units per month November 2007 to April 2010

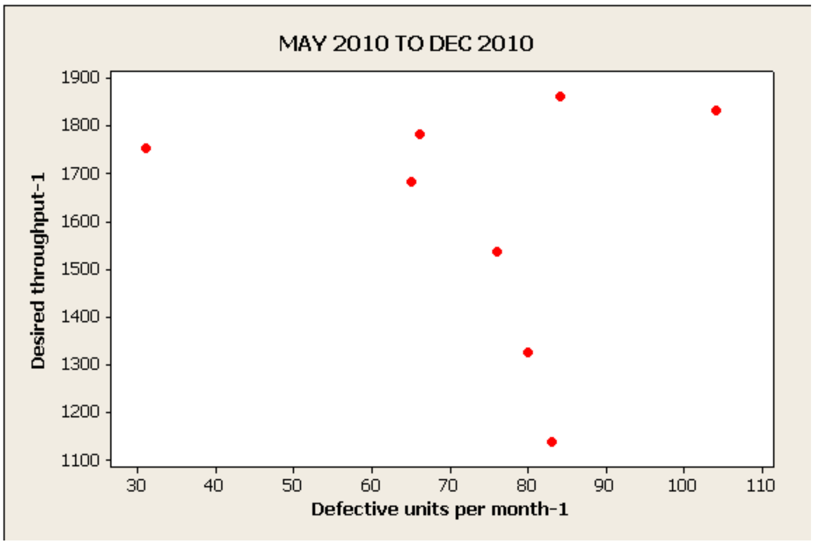

Figure C.2: Desired throughput versus defective units per month May 2010 to December 2010

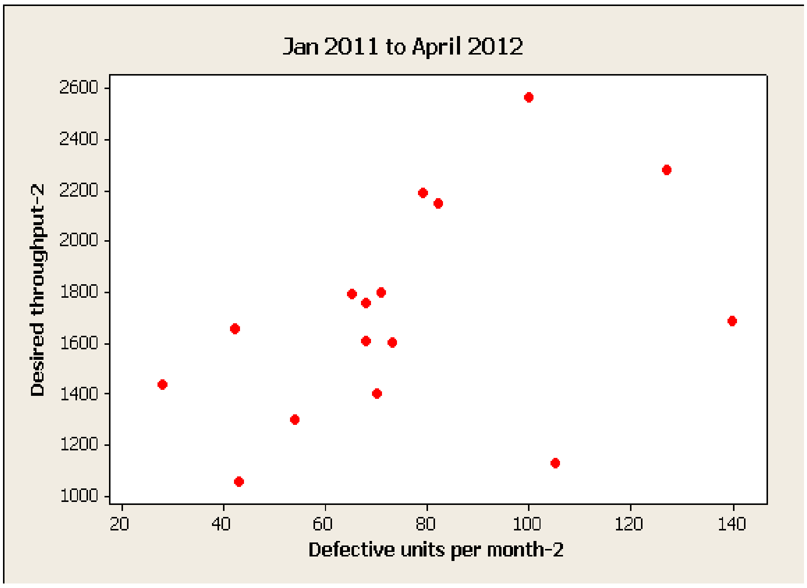

Figure C.3: Desired throughput versus defective units per month January 2011 to April 2012

Real-world problem	Statistical problem
Is there is statistical significant correlation between desired throughput and defective units per month with a confidence level of 95%?	Ho: There is no correlation between desired throughput and defective units per month. Ha: There is a correlation between desired throughput and defective units per month. For a statistical significance of 95% use p=0.05
Real-world answer	**Statistical answer**
Nov 2007 to April 2010 There is statistical evidence with a confidence level of 95% for a strong correlation between desired throughput and defective units per month.	**Nov 2007 to April 2010** Pearson correlation coefficient (r)=0.62, p=0.0 Accept the Ha: there is a correlation between desired throughput and defective units per month.
Nov 2007 to April 2010 There is no statistical evidence with a confidence level of 95% for a correlation between desired throughput and defective units per month.	**May 2010 to Dec 2010** Pearson correlation coefficient (r)=-0.13, p=0.759 Reject the Ha and accept the Ho: there is no correlation between desired throughput and defective units per month.
Jan 2011 to April 2012 Although the correlation is weak, there is no statistical evidence with a confidence level of 95% for a correlation between desired throughput and defective units per month.	**Jan 2011 to April 2012** Pearson correlation coefficient (r)=0.437, p=0.091 Reject the Ha and accept the Ho: there is no correlation between desired throughput and defective units per month.

Table C.1 Hypothesis test for correlation between desired throughput and defective units per month with a statistical significance level of 95%

Appendix D. Operational excellence and six sigma implementation time line

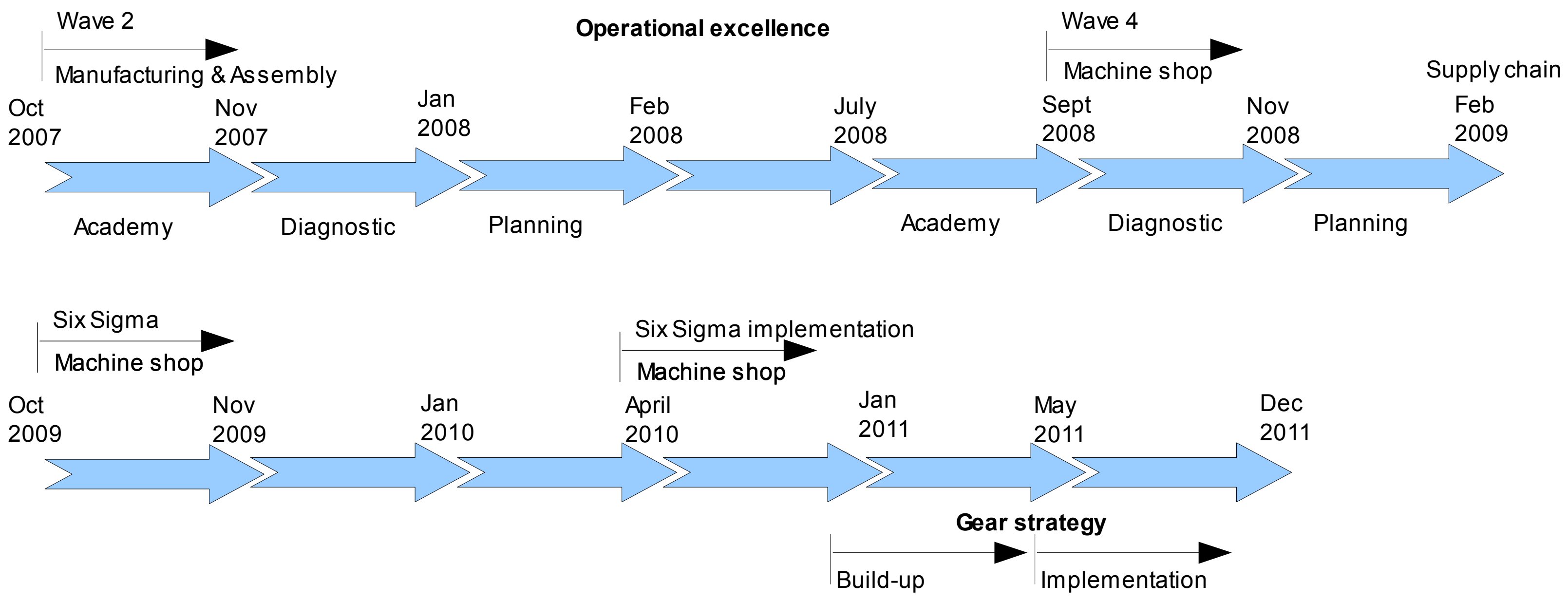

Figure D.1: Operational Excellence and Six Sigma implementation time line