Simulating Vicious Circles in New Product Introduction Systems

by

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Submitted in accordance with the requirements for the degree of

Doctor of Philosophy

The University of Leeds

School of Mechanical Engineering

June, 2014

Acknowledgements

I would like to express my sincere thanks to my supervisors Professor Alison McKay (The School of Mechanical Engineering) and Professor Chris W Clegg (Leeds University Business School), for supervision of my PhD study. I have learnt not only how to carry out an interest research but also how to manage my career development. The PhD study process is a privilege for both my academic development and personality building up. Thank you for generating a scholarship to support my PhD research. I appreciate China Agricultural University who approved my PhD study in the University of Leeds.

I am grateful to Shauna Coyle, who developed the case study new product introduction system when she worked at the Socio-Technical Centre in Leeds University Business School. The original data informing the conceptual model development was as well collected by her with the case study organisation. Her contribution to the research are primarily reported in Chapter 4 with respect. Thank you very much for the time put on discussing meeting reports, paper drafts, technical documents.

Many thanks to my colleagues at the Design System Group for their supports during my PhD study. Special thanks to Dr. Tarik Badi, Dr. Choong Chee Guan, Miss Issa Utami, Ms. Nina Mahbubah, and Dr. Saikat Kundu, with whom I often discussed the research.

I appreciate my parents for your love and suggestions, which is not regarding the research itself but on the most important philosophy of life.

Abstract

New product introduction systems are complex socio-technical systems that are used to design, develop, and deliver products and services to users. Lack of design information within such systems results in uncertainties that have an adverse effect on the performance of the whole system by creating a need for rework. Typical performance measurements for new product introduction systems are time, cost, and quality. Rework has a significant influence on time-related aspects of system performance because it consumes additional time resource that could otherwise be dedicated to other activities such as the development of new products. Rework reduces time resource available for information communication which in turn leads to more rework in the future. This results in vicious circles where limited time leads to more rework which further detracts from time to devote to other tasks in the future.

Vicious circles have previously been reported in societal systems. The goal of this research was to apply modelling and simulation techniques to understand time-related aspects of the vicious circles phenomenon in new product introduction systems and explore potential management interventions to mitigate the consequences of vicious circles. A case study from an international manufacturing organisation was used to inform the development of a simulation mapping between key elements of the new product introduction system and key concepts that underpin agent-based simulation methods. A simulation model was developed to represent vicious circles in the case study, based on the simulation mapping. The simulation model was verified and validated through a series of seven experiments.

Four further simulation experiments were then carried out. The first two experiments explored the impact of different prioritisations of responding to information requests on time-related aspects of the system performance. Results highlighted the importance of prioritising responses to information requests which significantly reduced rework volumes in the model. The final two experiments explored the balancing of time taken for individual product development activities and resources used. In simulations with low response rates, one means to avoid system collapse was to extend the time allowed for product development. Given the need to deliver products to market as quickly as possible, a final experiment explored ways to speed up product development to eliminate adverse effects on product development cycle time. By reducing the time taken to respond to requests, which in a real

world system could be achieved in a number of ways, e.g. improving team size or design capability, the product development cycle could be shortened.

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Chapter 1 Introduction

New product introduction systems are complex socio-technical systems that are used to design, develop, and deliver new products and services to users. Research and practice show that real challenges within such complex manufacturing systems do not come from technical aspects, but social-related issues. For example, Farrell and Hooker argue that a typical characteristic of design systems is that design process involves wicked problems that are associated with and caused by complexity of design systems (Farrell and Hooker, 2013). Design iteration within new product introduction systems is widely considered as a means to improve system performance (Ulrich and Eppinger, 2012). However design iteration across work teams, which was considered as a key sources of rework in this research, increases the system complexity and produces undesirable results (Wynn et al, 2007).

New product introduction system performance is influenced by various impacting factors and measured by distinctive standards with focus on different system operation environment and business goals. Typical performance measurements for new product introduction system are sometimes referred to as the iron triangle, i.e. time, cost, and quality. Time-related system performance is an outstanding concern considered by both academic community and industrial practice. Rework consumes additional design resources, like time resource of work teams, and therefore increases time pressure on the design system.

The vicious circles phenomenon and solutions to tackle them have been previously reported in societal systems (Masuch, 1985), but the vicious circles phenomenon in new product introduction systems is a novel research topic. Modelling and simulation techniques have been recognised as effective methods for operational system research (Axelrod, 2003). This research explored the application modelling and simulation techniques to understand time-related issues of vicious circles phenomenon in new product introduction systems.

1.1 Research Background

New product introduction system comprises a series of functional work teams that work on their design commissions independently but within an interactive engineering communication system. Engineering communication system, as a core part of the new product introduction systems, convey large volumes of design-related information collection, generation, and communication (Mckay et al, 2009), (Cho and Eppinger, 2001).

The performance of new product introduction systems are influenced by various impacting factors, considering different companies, countries, policies, and so forth. Technical aspects include product complexity, degree of innovation, design technology, manufacturing tools, product development method & procedure, and others (Krause and Kimura, 1997). Social aspects are considered as people, business goals, enterprise culture, environment, policies, and so forth (Challenger et al, 2009). Social aspects of new product introduction systems are widely acknowledged in academia and broadly considered in practice, in order to improve the performance of new product introduction systems (Challenger et al, 2010), (Clegg, 2000). It is recognised that social aspects, rather than technical perspectives, are real challenges faced by large manufacturing organisations (Garud and Kumaraswamy, 2005), (Shepherd et al, 2010).

Typical criteria used to measure the performance of new product introduction systems are referred to as traditional iron triangle, i.e. time, cost, and quality (Turner, 1993). Among the three measurements, time taken for product development is a primary criterion to assess the performance of a new product introduction system. (Kerzner, 2013). In the real world, the three dimensions are often considered together, and management interventions are usually employed for specific business strategies, e.g. time-cost trade-off (Roemer et al, 2000). This research considered social-related impacts on time-related performance in a case study new product introduction system, and management interventions in the real world operation were discussed in addition to focusing on results from four simulation experiments.

1.2 Case Study New Product Introduction System

This research used a case study new product introduction system employed by an international manufacturing organisation. This allowed the research to have a chance to gain insights of social-related impacting factors on the performance of the new product introduction system.

The case study new product introduction system comprises four functional work teams: preliminary design, detail design, manufacturing, and service.

The work teams complete specified design commissions and pass design results to the downstream work team by predetermined deadlines. In addition to the delivery of design definitions through the system, product design information is intensively communicated amongst different work teams. For example, the work team which undertakes the current design project often needs design information that is not available at current design phase, but might be available from other work teams. Therefore, the work team requests the information from downstream work teams, and the work team replies to information requests depending on conditions such as available timetable. In this way, the request-response information loops form amongst different work teams in the operational environment of the new product introduction system.

Responding to the information requests enhances product design quality (Wynn et al, 2007), given the responses are accurate enough and received in a timely manner. However, the downstream work teams are often busy working on their design commissions; this results in delays in responding to information requests. Under these circumstances, the information requests that are not responded to tend to produce design uncertainties within the system (Eckert and Clarkson, 2010), (Marujo, 2009). Design uncertainties tend to result in further design problems in later design stages (Eckert and Clarkson, 2010), which finally cause reworks necessitated in order to complete the design project (Cho and Eppinger, 2001).

Rework consumes a large volume of time resource within the new product introduction system, and significantly influences the system performance (Browning and Eppinger, 2002). For example, rework is identified at manufacturing stage and returned to detail design work team in this case study new product introduction system. The rework increases time pressure on detail design work team and further the whole design project (Coyle, 2012), (Terwiesch et al, 2002), especially under predetermined deadline development environment. When the impact of rework from a particular point is amplified through the whole design system, vicious circles are emerging within the system (Masuch, 1985).

Vicious circles influence not only a particular work team, but also the entire design project and even future design projects. Regarding complexity characteristic of such design systems, vicious circles produce significant unintended consequences within new product introduction systems (Garud and Kumaraswamy, 2005). Vicious circles drive the new product introduction system off its stable status and finally result in the system collapsing, therefore they are trying to be avoided in the real world (Masuch, 1985).

By using the case study, this research is to explore time-related impacting factors, e.g. the frequency of responding to information requests, on the performance of the whole new product introduction system. To this end, primary issues regarding how and why rework and vicious circles generate within such system were demonstrated based on the operational process within the case study new product introduction system. The final goal is to explore potential management interventions that could be used to mitigate the consequences of vicious circles and improve the performance of new product introduction systems. A challenge for the management of new product introduction system lies in identifying means of mitigating the effects of vicious circles.

1.3 Vicious Circles in New Product Introduction Systems

New product introduction system architecture has been well defined in both academia and practice (Cooper, 2008), (Ulrich and Eppinger, 2012), while social-related impact on the performance of complex organisations is an emerging issue (Challenger et al, 2010). This research demonstrated vicious circles phenomenon in a case study new product introduction system, where rework and vicious circles within the system are considered as outstanding performance impacting factors (Eckert and Clarkson, 2010), (Shepherd et al, 2010).

Rework in new product introduction systems and their influence on such systems were researched back to 1973 (Gowler and Legge, 1973). Rework is produced by design iteration, which was considered as a typical characteristic of design system (Ulrich and Eppinger, 2012), (Eckert and Clarkson, 2010), (Wynn et al, 2007). Design iteration happens either within particular work teams or across functional work teams depending on the degree of integration of a design system, therefore two types of rework are recognised as rework inside work team and rework across work teams. Practitioners and researchers found that the rework across different work teams produces a significant impact on the performance of the new product introduction system. Such rework is associated with uncertainties involved in the design system, which are resulted by incomplete design information within the system (Marujo, 2009), (Bao et al, 2011), (Wynn et al, 2011). Issues related to rework were discussed in literature, but there is no systematic research found regarding how and why rework arises from new product introduction systems, i.e. how incomplete information generates within the systems, and how the incomplete information further results in rework.

Vicious circles phenomenon and the solutions to tackle them have been previously reported in societal research (Perry, 2006). Vicious circles problems are referring to as deviation-amplifying feedback loops in literature (Masuch, 1985). Vicious circles are caused by unintended change that is generated at a particular point within the system but its influence is amplified through the entire system (Masuch, 1985), (Garud and Kumaraswamy, 2005). Vicious circles problems and their impact on the new product introduction system significantly influence the system performance (Coyle, 2012) (Shepherd et al, 2010), while there is no literature found discussing how to manage vicious circles and mitigate their consequence on the performance of new product introduction systems.

Two challenges ahead of such research areas are: 1) The management of new product introduction system involves wicked problems, especially in such complex interactive design systems, (Farrell and Hooker, 2013). Within a complex design system, interactions between different functional work teams produce feed forward and feedback loops, which involve far-reaching consequences across the whole system that further increase the degree of the system complexity. In addition, the new product introduction system is typically characterised by long development duration and large volume of budget. For these reasons, the vicious circles phenomenon in new product introduction system is difficult to be observed and researched in the real world. 2) Socio-technical research on new product introduction system is an emerging subject (Challenger et al, 2010), which currently provides limited research procedures and methods.

Modelling and simulation techniques are been widely applied in complex social-related research, which are currently focused on societal areas. Application of modelling and simulation methods to understand performance of organisational systems becomes a promising research area (Hughes et al, 2012), (Axelrod, 2003). This research examined an application of modelling and simulation techniques to gain insights of time-related influence on vicious circles problems in the case study new product introduction system.

1.4 Research Aim and Objectives

The aim of this research was to apply modelling and simulation techniques to understand time-related aspects of vicious circles that arise from the case study new product introduction system, and to explore potential management interventions that might be used to mitigate vicious circles and their consequences on time-related aspects of new product introduction system performance. The following objectives were pursued.

1) To characterise the vicious circles phenomenon in new product introduction systems based on literature review and practitioners' experience.

2) To define a case study new product introduction system, demonstrating the vicious circles phenomenon and its influence on time-related system performance.

3) To develop a simulation model to represent time-related aspects of the vicious circles and provide insights into how and why vicious circles arise in the new product introduction system.

4) To verify and validate the simulation model by applying verification and validation strategies and methods.

5) To apply the simulation model to the case study new product introduction system, and recommend interventions for managers to mitigate time-related aspects of vicious circles and their consequences on the system performance.

1.5 Thesis Structure

The thesis structure is outlined in Figure 1.1.

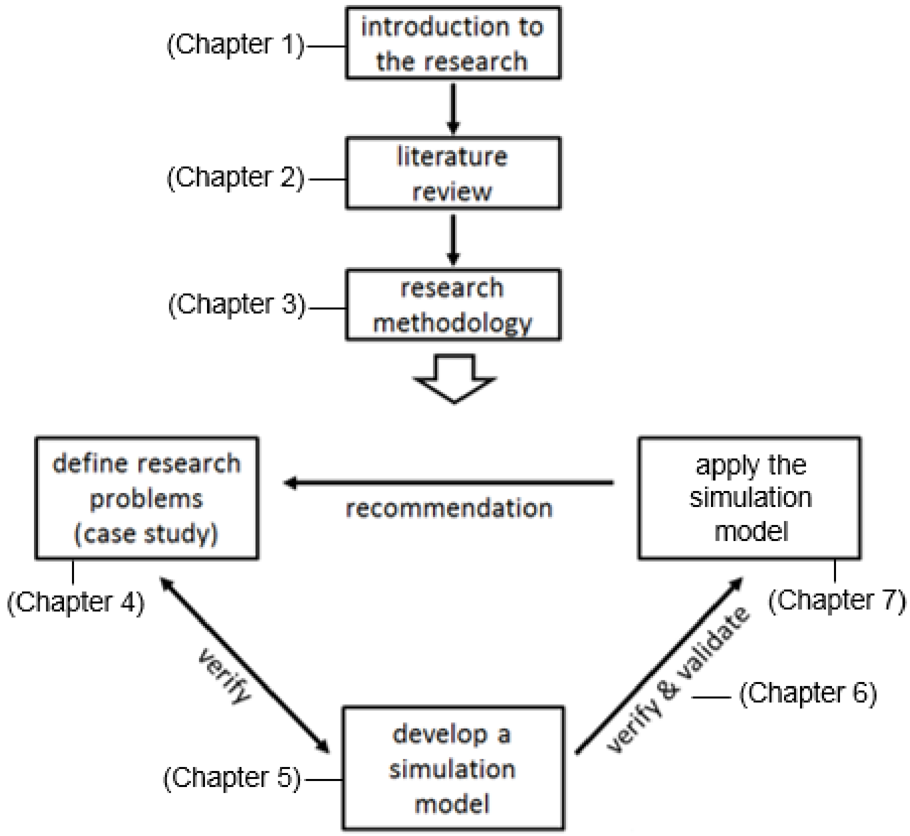


Figure 1.1 Thesis outlines

Four key knowledge domains are reviewed in Chapter 2: new product introduction systems, the phenomenon of vicious circles, modelling and simulation techniques, and model verification and validation methods. Chapter 3 introduces the research methodology and a thirteen-step research procedure that was used in this research. Chapter 4 defines a case study new product introduction system vicious circles problems, with focus on time-related impact on new product introduction system. Chapter 5 developed a simulation mapping between key characteristics of new product introduction systems and key concepts that underpin agent-based simulation methods. Applying the simulation mapping, a simulation model was developed to represent the case study new product introduction system. The verification and validation activities and results of the simulation model is reported in Chapter 6. Chapter 7 presents results from application the simulation model to the case study with a view to addressing the four research questions identified in Chapter 4. Recommendations for managers on how to best manage time-related issues of vicious circles problems are proposed. Chapter 8 concludes research results, outlines research contributions, declares limitations of the research, and recommends further work.

Chapter 2 Literature Review

The research intent was to apply modelling and simulation techniques to understanding vicious circles phenomenon arisen in the case study new product introduction system, and to explore potential management strategies that might be used to mitigate vicious circles and their consequences. In order to understand the cutting edge knowledge in this area, literature in four knowledge domains were reviewed: new product introduction systems, vicious circles, modelling & simulation techniques, and model verification & validation methods. This chapter is discussing the following issues.

New product introduction systems are comprised of a series of functional work teams who develop and deliver new products to market. Different manufacturing organisations define different new product introduction system structure, in order to implement specified business goals. Therefore, new product introduction systems have different focuses due to various considerations and impacting factors. This chapter reviewed distinct such systems from different perspectives of both technical aspects and organisational considerations.

Engineering communication system is a core part of new product introduction system, conveying large volume of product related information and data. Due to social nature of the system, the efficiency of information communication within such systems varies. Low performance of information communication produces design uncertainties within new product introduction system. The design uncertainties usually cause design problems, which further result in rework tasks are necessitated within the manufacturing system.

Reworks consume additional time resources within the systems and increase the time pressure on the product development (Terwiesch et al, 2002). The influence of reworks is impacting on not only the current product package but also the future projects. The extreme condition is that the new product introduction system breaks down because it is not able to complete excessive reworks within satisfactory time frame. This kind of organisational phenomenon occurred within new product introduction system was defined as vicious circles in this research. This chapter is exploring how the reworks and related issues are demonstrated in literature and practice.

Vicious circles are a kind of social phenomenon that significantly influences system performance. Vicious circles phenomenon and potential solution to tackle their influence have been previously reported in societal research areas. Vicious circles within new product introduction systems are dangerous and probably associated with additional reworks within the systems. Therefore, this chapter introduced and explored how and why vicious circles arise within such complex manufacturing systems. Different types and characteristics of vicious circles were analysed. The management strategies about how to mitigate such kind vicious circles and their consequence were analysed in this chapter.

Modelling and simulation approach is an alternative method to understand social related phenomenon. Application modelling and simulation method to understand vicious circles within new product introduction system is a novelty. In this chapter, different simulation methods and tools are introduced, advantage and disadvantage of distinct simulation methods are analysed, and potential simulation method and tool for this research are suggested.

Model verification and validation activities are to make sure a simulation model possesses sufficient accuracy to represent a research problem or interest. Model validation could no guarantee a model is 100% correct, but could approve the model is reasonable with respect to specified research focuses. In this chapter, different model verification and validation strategies and methods are introduced. Potential application the strategies and methods are suggested, with focus on specific research purpose.

Potential contributions of the four knowledge domains to this research project are summarized up at end of each subsection.

2.1 New Product Introduction Systems (NPISs)

The systems used to design and develop new products and then support them over the whole life spans are referred to in a number of ways: for example, product development process (Ulrich and Eppinger, 2012) (Browning et al, 2006), (Smith and Morrow 1999), new product development (Griffin, 1997b), new product processes (Cooper, 1994), new product introduction process (Ruffles, 2000), product service system (Cho and Eppinger, 2001), enterprise engineering system (Terwiesch et al, 2002), product life cycle (Grieves, 2006), design iteration process (Wynn, 2007), stage-gate systems (Cooper, 2008), product launch system, phased review process, and others. In this research, the terminology of new product introduction system (NPIS) is used to represent such kind of processes or systems.

A new product introduction system includes a series of product development stages, i.e. design, manufacturing, distribution, after-sale service, and others (Ulrich and Eppinger, 2012). Functional work teams at each stage carry on distinct product development commissions and deliver product design package to the next stage. New product introduction system is an extreme complex process system, considering both technical aspects and organizational perspectives. This kind of complexity is further exaggerated by low efficiency of information communication within the system, which therefore often results in unintended results of the new product introduction systems.

On the other hand, new product introduction system takes long time to develop a new product. A fact is that few products can be developed in less than one year, many require three to five years, and some take as long as ten years (Ulrich and Eppinger, 2012). Therefore, companies try to keep the product development system high performance and efficiency, in order to shorten product research and development cycle and time-to-market (Cooper and Kleinschmidt, 2011). Therefore, time related issue is primary consideration from both business goals and shareholders' interest.

New product introduction systems performance and design capability are valuable to many impacting factors, e.g. enterprise culture, employee education, policy, market and finance, geography, and others (Krause and Kimura, 1997). And traditional system performance measurements are often referring to the iron triangle, i.e. time, cost, and quality.

In this section, the author reviewed and introduced distinct new product introduction system models with distinct focuses on either technical perspectives or organisational views. In general, the new product introduction system structure and characteristics were summarized. Regarding the system performance, potential influencing factors on the new product introduction system were discussed. With respect to the case study new product introduction system vicious circles, the rework arisen in the systems and the reasons behind it are analysed.

2.1.1 Different NPIS models

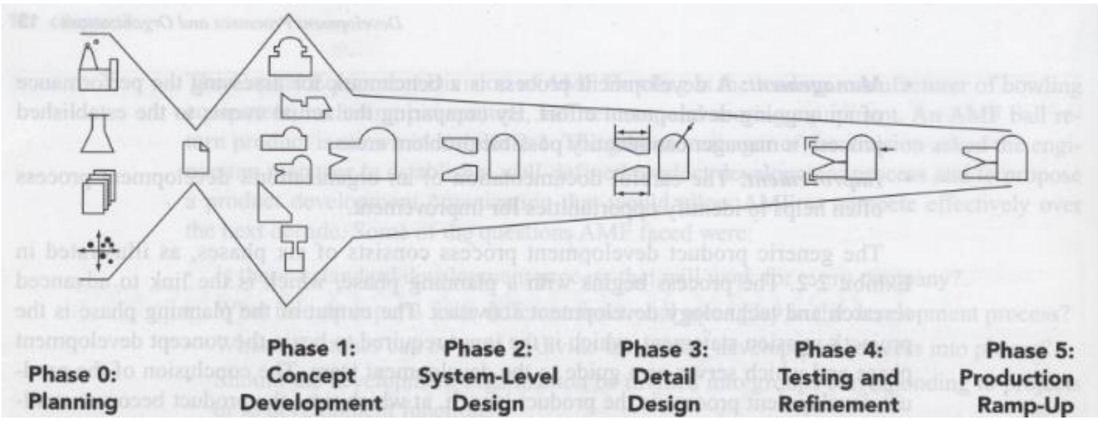
New product introduction system is the initial creation of a wide set of alternative product concepts and then the subsequent narrowing of alternatives and increasing specification of the product until the product can be reliably and repeatedly produced by the production system (Ulrich and Eppinger, 2012).

New product introduction systems are designed with focus on efficiency and specified purpose, in order to keep products' competition and business sustainable development. New product introduction systems also contribute to other aspects like, assessing organisational performance, training new employees, making report to stakeholders, introducing new products to market, and so forth. Therefore, new product introduction system models employed by different organisations perform distinct architectures and specifications.

Both technical and organisational perspectives are reviewed and highlighted in the following new product introduction system models, in order to insight social related aspect impact on the system performance. In addition, product development strategies used to improving system performance are reviewed and discussed.

2.1.1.1 The generic product development process

Figure 2.1 illustrates a generic product development process, which contains six work stages: planning, concept development, system-level design, detail design, testing and refinement, and product ramp-up stage. The intent of introduction to generic product development process is to understand technical perspectives of a new product introduction system.



The figure is adapted from (Ulrich and Eppinger, 2012)

Figure 2.1 The generic product development process

The development process begins with the initial creation of a wide set of alternative product concepts and then the subsequent narrowing of alternatives and increasing specification of the product until the product can be reliably and repeatedly produced by this production system.

2.1.1.1.1 Definition of the generic product development process

Each work stage associates different functional work teams that work in a collaborative and interactive way to complete the specified design commissions. For instance, when product design package proceeds to the concept development stage, the marketing team collects customers' needs, the design team conducts prototype experiments, the manufacturing team estimates the production feasibility, the financial team analyses the economic aspects, and so forth. Therefore, the generic product development process is a complex interactive organisation. Table 2.1 displays detailed specifications for the work stages and work teams.

Table 2.1 Work stage specifications

This table is adapted from (Ulrich and Eppinger, 2012)

phase 0: planning	**phase 1: concept development**	**phase 2: system-level design**	**phase 3: detail design**	**phase 4: testing and refinement**	**phase 5: production ramp-Up**
marketing					
• articulate market opportunity • define market segments	• collect customer needs • identify lead users • identify competitive products	• develop plan for product options and extended product family	• develop marketing plan	• develop promotion and launch materials • facilitate field testing	• place early production with key customers
design					
• consider product platform and architecture • assess new technologies	• investigate feasibility of product concepts • develop industrial design concepts • build and test experimental prototypes	• develop product architecture • define major sub-systems and interfaces • refine industrial design • preliminary component engineering	• define part geometry • choose materials • assign tolerances • complete industrial design control documentation	• test overall performance, reliability, and durability • obtain regulatory approvals • assess environmental impact • implement design changes	• evaluate early production output
manufacturing					
• identify production constraints • set supply chain strategy	• estimate manufacturing cost • assess production feasibility	• identify suppliers for key components • perform make-buy analysis • define final assembly scheme	• define piece-part production processes • design tooling • define quality assurance processes • begin procurement of long-lead tooling	• facilitate supplier ramp-up • refine fabrication and assembly processes • train work force • refine quality assurance processes	• begin full operation of production system

other functions					
• research: demonstrate available technologies • finance: Provide planning goals • general managemen t: allocate project resources	• finance: facilitate economic analysis • legal: Investigate patent issues	• finance: Facilitate make-buy analysis • service: Identify service issues		• sales: develop sales plan	• general managemen t: conduct post-project review

2.1.1.1.2 Characteristics of the generic product development process

In order to assess whether the work completed by each stage is acceptable or not, the checking points are set following each stage to measure work quality against design specifications and requirements. According to assessment results, the checking points decide whether the project proceeds to next stage, stops, or returns to previous stages for rework. Considering complexity of collaboration within many functional work teams, seldom products can luckily proceed throughout all each stages without any rework produced. Therefore, the generic product development process is not a sequentially linear process but a complicated interactive organizational system. It was described in Ulrich's book like this:

> *"Rarely dose the entire process proceed in purely sequential fashion, completing each activity before beginning the next."*
> *(Ulrich and Eppinger, 2012)*

The generic product development process is also an intensive information-communication system. Huge volume product design and manufacturing data & information created, communicated, and delivered among different work stages and work teams. For example, data & information collected at the planning stage contains: company objectives, strategic opportunities, available technologies, and others. This kind of information created in one work team will be requested and then reused by other work teams. Before design package proceeds to next work stage on deadline due, both design results and design data & information are measured against specified specifications. Therefore, intensive engineering information communication amongst different work teams is another characteristic with new product introduction systems.

The third characteristic is that the generic product development process is a risk management system. At early stage of product development, various risks are emerging due to many reasons, e.g. low efficiency of information communication within the work teams. As the product package progresses through the process, risks and uncertainties are gradually eliminated, and the product functions are validated step by step. When the process is completed, the product is well defined and successfully produced.

2.1.1.1.3 Summary

This section introduced a generic product development process with focus on technical perspective. It includes a series of product design stages and a set of checking points following each stage. Majority of design activities are carried out at work stages by functional work teams in a collaborative environment. The checking points measure design outputs against specified design commissions. According to assessment results, the checking points decide whether the project proceeds to next stage, stops, or rework.

The generic product development process is a complicated interactive organisational system, within which design iterative is necessary. The generic product development process is also an intensive information-communication system, which aims to enhance design quality. the system defines three decision results from the checking points, i.e. go, kill, or rework.

The generic product development process model does not demonstrate how and why the reworks arise from the product design system. The influence of rework on the current project and the whole design system is not involved in the model.

2.1.1.2 The stage-gate system

The stage-gate system model was developed by Robert G. Cooper. And continuous improvement on the system model was since 1970’s until now (Cooper, 1979), (Cooper and Kleinschmidt, 1986), (Cooper, 1994), (Cooper, 2008), (Cooper and Kleinschmidt, 2011). The stage-gate system is being employed by many international companies (Arleth and Cooper, 2012).

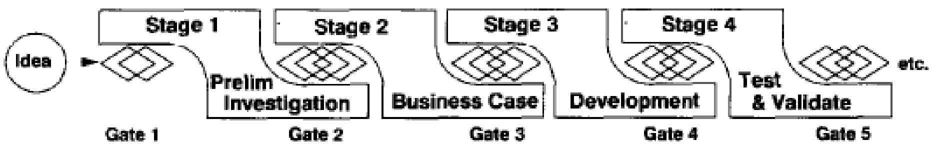
The intent of introduction to the stage-gate system model is to understand organisational aspects of the new product introduction system. In doing so, the following content introduced the stage-gate system design architecture, operation principles, and system characteristics.

2.1.1.2.1 Introduction to the stage-gate system

The stage-gate system was developed and gradually matured as an evolutionary process. The first generation of stage-gate system was named phased project planning, which was developed in 1960's by the National Aeronautics and Space Administration (Cooper, 1994). This version of stage-gate system breaks product development process into discrete phases, and review points are set after each phase. This version of the stage-gate system mostly focuses on technical perspectives rather than systematic risks. The first generation stage-gate system focuses too much on engineering process and ignored organizational nature of product development process.

The second generation stage-gate system is a very much cross-functional system, where marketing and manufacturing are integral parts of the product development process (Cooper, 1994). While, one of benchmarks of this version of stage-gate system is that projects must wait at each gate until all tasks have been completed, which makes some new product processes tend to be bureaucratic. Comments said that the stage-gate system created some time-consuming steps. Although there are many shortcomings with both the first and second generations of the stage-gate system, they are still great product development systems at that time (Cooper, 1994).

Addressing problems of the second version, the third generation stage-gate system focuses on efficiency, which aims to speed up the already effective second generation stage-gate system and effectively allocate development resources. The third generation stage-gate system model is displayed in Figure 2.2.



This figure is adapted from (Cooper 1994)

Figure 2.2 The third generation stage-gate system

2.1.1.2.2 Characteristics of the stage-gate system

Two primary components involved in the stage-gate system are stages and gates. The third generation stage-gate system contains four cross-functional stages, e.g. preliminary investigation, business case, development, and test & validate. A project is gradually developed by the stages, and checked by each gate to decide whether the current project proceeds to next stage, stop or carry out rework in previous stage given necessary.

Each stage completes their part of work at the end of agreed deadline, and delivers it to be checked at decision gates. Each gate is consists of three primary elements (Cooper, 2008):

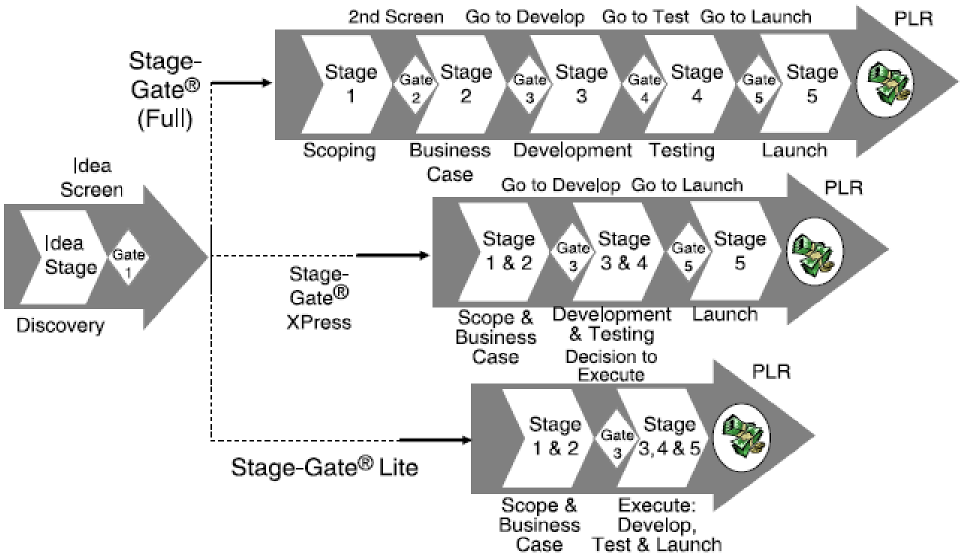
- Deliverables: what the work team completes on the design package at this stage.
- Criteria: against which the project is judged. The criteria include must-meet criteria, knock-out barriers, and should-meet principles.
- Outputs: a decision, e.g. go, kill, hold, or recycle.

The third generation stage-gate system is not a linear and bureaucratic system, but an iterative product development process, enabling the system more flexible and adaptive. It possessed some characteristics of the iterative design process, which was achieved by employing fuzzy gates into the system.

The fuzzy gate means the gate decision may not a rigid conditions, like either go or kill. The gate could make a conditional decision, since some information is missing at the moment, but the project is a promising one. At this situation, the decision maker has right and responsibility to save the project. While, the decision must consider the balance between time, cost, and project risk. Fuzzy gate introduces probability of reworks on a particular project.

2.1.1.2.3 The next generation of stage-gate system

The next generation stage-gate system has been developed into a more flexible and adaptive product development platform containing three distinct versions. They are full scale stage-gate system, express stage-gate system, and elite stage-gate system. Figure 2.3 displays the next generation stage-gate system.



This figure is adapted from (Cooper, 2008)

- Stage-Gate® (Full): Major new product projects go through the full five-stage process.
- Stage-Gate® XPress: Moderate risk projects use this process.
- Stage-Gate® Lite: Sales-force and marketing requests use the this process.

Figure 2.3 Next generation stage gate system

The upgraded next generation stage-gate system is a flexible industrial product service and service product innovation platform. It is able to suit all kinds of firms, from small and medium-sized enterprises to international organisations (Cooper, 2008).

2.1.1.2.4 Summary

The stage-gate system introduced social natural of the new product introduction systems. The stage-gate system comprises a series of functional work stages and gates followed each stage. The work teams at each stages complete the product development commissions and deliver them to the decision point. The decision maker determines whether the project is satisfactory or not, against a series of measurements and policy.

The decision point at stage-gate system applies fuzzy gate. The fuzzy gate does not make a rigid decision, like green means go or red means kill, but a conditional decision. The conditional decision provides opportunity for the projects that is not complete but promising in the future. The fuzzy decision is considering the balance between time, cost, and project risk. And rework is unavoidable within the stage-gate system for those projects under conditional decisions.

The fuzzy gate provides alternative management solution, which saves product development time and budget in the real world, and introduces reworks into the system. The stage-gate system model explores strategy to solve the problem for one particular project. While, it does not demonstrate the influence of rework produced in the current project on the future projects.

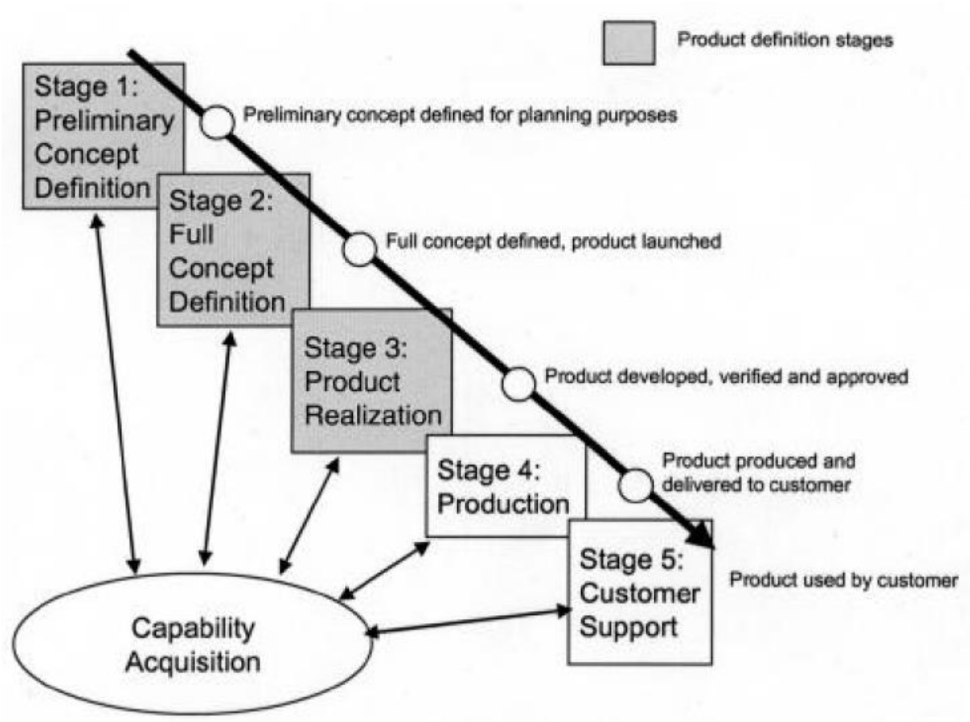
2.1.1.3 The new product introduction process

New product introduction process model demonstrated by Philip Charles Ruffles (Ruffles, 2000) reported a best practice in enterprise-wide business architecture. The new product introduction process model focused on a series of time-based activities, with intent to improve design system capability. The model considered three aspects of product development performance measures, i.e. product quality, time, and cost.

The purpose of introduction to the new product introduction process model have three considerations. Firstly, the new product introduction process model introduced a best practice in the real world. Secondly, the model discussed strategies about how to improve the design system capability and performance. And finally, application information technology to improving manufacturing system performance was analysed.

2.1.1.3.1 New product introduction process definition

In Figure 2.4, the new product introduction process comprises five stages: preliminary concept definition, full concept definition, product realization, production, and customer support. Distinct requirements and commissions are specified for each work stage to develop a new product. The first three stages, as a whole, were considered as product definition period in this research.



This figure is adapted from (Ruffles, 2000)

Figure 2.4 New product introduction process

The new product introduction process was represented as a collection of time-based design stages and activities. At end of each stage, capabilities necessary for carrying out all activities are acquired, e.g. appropriate time, sufficient budget, available resource, mature market opportunity, reliable domestic facilities & supply chain, and others. The Figure 2.4 demonstrated an ideal process for a business organization developing a new product. Actually, new product development is an extreme complex iterative process in nowadays competitive business environment.

The new product introduction process model includes both work stages and review points like other product development models. In this model, each stage considered capabilities necessitated for product development from operational practice perspective. In the following paragraphs, each stage's functions and commissions were introduced.

During preliminary concept definition stage, one or more product concepts which potentially meet a market opportunity are evaluated to determine a preferred solution. Functional, physical, schedule, and cost targets are established. Capability needed for carrying out current and further development activities are acquired.

The full conceptual definition stage commences when the market opportunity is mature and the necessary capabilities have been acquired. At this stage, a product specification is developed, where functional and physical whole-system, subsystem and component requirements are defined. In addition, a comprehensive risk assessment is conducted towards the end of this stage, where the preliminary concept is evolved into a complete conceptual definition or specifications.

The production realisation stage is normally the most expensive and time consuming phase for a business. During this stage, the finished conceptual definition is fully designed and verified, delivering a set of instructions to manufacturing and service sections. Furthermore, schedule and cost are to be managed and manufacture and support issues are addressed to prevent expensive downstream rework activities. The output of this phase is a complete product specification with instructions for manufacturing and serves sections. The instructions include, but not limited to, drawings, specifications, maintenance and operating documents. The first three phases absorb large amount of product development time and determine large proportion of product development budgets, so it is important that it is performed as possible to minimize the cost to the business.

The fourth stage is production, where factories are being operated to produce the product, according to the definitions, specifications, instructions, and manufacturing methods defined in previous stages. The final stage is customer support, which include all the services necessary to support a product. Technical support group should be performed by the team who are also responsible for it during the product definition phases, which idea is further considered in Chapter 3.

2.1.1.3.2 The model’s contribution to this research

Integrated project work teams are defined in this model. When a new product design project allocates at one work stage, the work team at this stage work interactively with other work teams, in order to improve design efficiency and produce a qualified output. Therefore, the new product introduction process is a complex interactive and iterative process.

Design work teams’ capability is increasingly enhanced across the new product introduction process. the system capability is acquired from three aspects in this model, i.e. product development process technology, investment on facilities and machines, and skilled people and employee education. The model demonstrated how to carry out appropriate activities to improve the new product introduction process design capability.

Application information technology into the new product introduction process was discussed in this model. Emerging information technology must be integrated with the work practice which, as a whole, results in the product development process and product a potentiality of added value. The final goal of application information technology is to reduce time scale and cost, and increase system capability and product quality.

Risk management and rework are highlighted at product definition period. The integrated project work teams should first identify all the areas of risks and assess them in terms of likelihood and consequence. A ranking is then established for each likelihood and consequence, enabling the higher areas of risk to be highlighted and addressed first. Reworks in the model are considered to be mitigated by managing schedule and cost within the project plan and manufacturing and support issues.

2.1.1.3.3 Summary

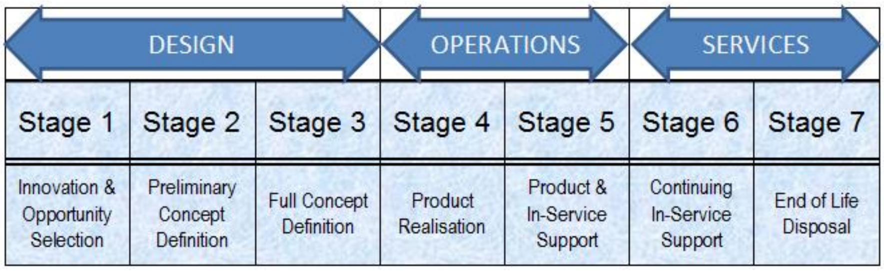
New product introduction process model introduced a best practice of product development in an international manufacturing organization. Besides typical product development process characteristics demonstrated in other models, e.g. work stages and checking points, this model highlighted capability necessitated for each stage to appropriately carry out specified product development activities.

Integrated project work teams are defined in the model, in order to improve design system efficiency and performance. Work teams' capability is acquired through the system process, with respect to three impacting factors, i.e. process technology, facilities, and people skills. Information technology must be considered with working practice together, which results in the product development process. Risk management was discussed. Rework should be reduced by managing time and cost issues within the project management.

Although the rework issues were discussed in the model, the influence of them on the system performance was not discussed. In addition, how and why the rework arises in the new product introduction process was not discussed.

2.1.1.4 Other NPIS models

Lloyd (2006) illustrated another product development process (in Figure 2.5), which includes three main categories: design, operations, and services. The product development process was further divided into seven production stages: innovation & opportunity selection, preliminary concept definition, full concept definition, product realisation, product & in-service support, continuing in-service support, and disposal phase (Lloyd, 2006).

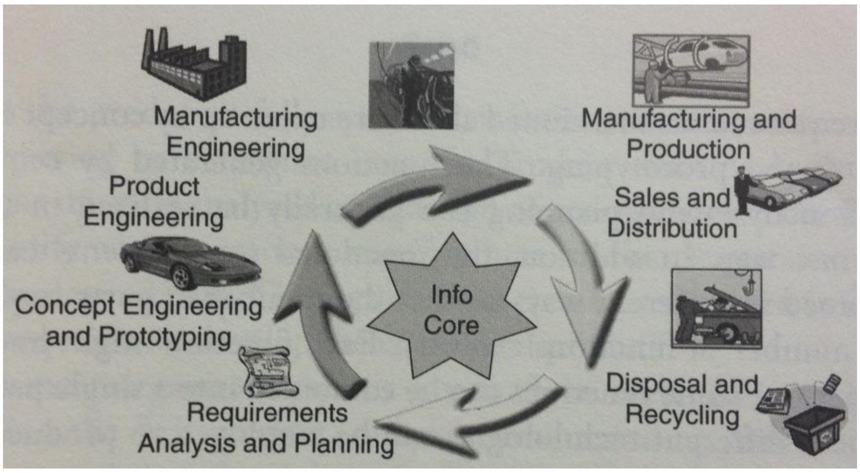


This figure is adapted from (Lloyd, 2006)

Figure 2.5 Product development process

Following each product development stage, a series of review points are set, evaluating capability for manufacturing, supply chain, schedule, budget, and so forth. Considering the review results, a decision is made whether the project proceeds to next stage, stops, or reworks on it. (Jinks, 2010), (Lloyd, 2006). Design information and data mainly generated at early stages of the process, and serves for the whole product development process. Within the process, design iteration and further rework are also necessitated to make sure a qualified design.

Grieves (2006) described a product lifecycle management (PLM) model in Figure 2.6. The product lifecycle management model comprises seven stages to serve a product’s whole life cycle. They are requirements analysis and planning, concept engineering and prototyping, product engineering, manufacturing engineering, manufacturing and production, sales and distribution, and disposal & recycling. Product lifecycle management is a ‘from cradle to grave’ product and service system (Grieves, 2006).



This figure is adapted from (Grieves, 2006)

Figure 2.6 Product lifecycle management model

The centre of product lifecycle management is information core, which represents all the product data and information over the product's life. The information core is separate from the functions or stages that use it. And the product information does not belong to any functional area, but is available to all functional areas. Considering the volume of product information generated and communicated within the system, the product lifecycle management system operates as an information-rich and communication-intensive process.

In addition, other definitions and demonstrations of product lifecycle management are available in literatures. For example, the product lifecycle management is a business strategic approach for the effective management and use of corporate intellectual capital (Sudarsan et al, 2005). Product lifecycle management is a systematic, controlled concept for managing and developing products and product related information. It is a concept and set of systematic methods that attempts to control the product information previously described." (Saaksvuori, 2008)

From product lifecycle management definitions introduced above, the characteristics of PLM could be concluded from three perspectives. Product lifecycle management could be understood as:

- A complex social related system to manage a product's whole life cycle;
- Comprised by a series of cross-functional work teams; and

- An information-rich and communication-intensive process.

2.1.2 Summary

Different new product introduction system models were introduced with focuses both technical aspects and organisational perspectives. Characteristics of new product introduction systems were reviewed.

New product introduction systems are comprised of a series of product development stages where functional work teams conceive, design, manufacture, and finally commercialise a new product (Ulrich and Eppinger, 2012). Each work team independently carries on specific design commissions, but in an interactive environment. Following each work stage, checking points are allocated assessing design output by against design requirements.

Social related characteristics of new product introduction system models are considered. Design iteration is inevitable for large scale of design projects, due to the fact that engineering information that is needed at current stage dependents on the later design results (Wynn et al, 2007). Rework, as a type of design iteration, is caused by low efficiency of engineering information communication within new product introduction system (Marujo, 2009). Rework consumes a large quantity of time resources and human resource, which has a significant influence on the system performance (Terwiesch et al, 2002).

The new product introduction systems were well defined in literatures. The performance and capability of new product introduction systems were broadly discussed as well. The strategy about how to improve new product introduction system performance has been suggested. For example, the fuzzy gate was allocated at the third generation of the stage-gate system, where a conditional decision may be made (Cooper, 2008). By doing so, the company could save product development time and budget. While, this further enhances the possibility of rework within the systems. Loch argued that improved communication could reduce the negative effect of rework at the expense of product development leading time (Loch and Terwiesch, 1998).

The rework issues in new product introduction systems are discussed in many literatures as mentioned above, but how and why the rework arises in new product introduction systems was not found in literature. And, the rework impact on the performance of new product introduction systems, from the social aspects, was not systematically introduced in literature.

2.2 Vicious Circles Phenomenon

Vicious circles problems, as a typical social phenomenon, are broadly existing in nature systems, biology systems, social systems, and organizational systems. The definitions and characteristics of both processes and systems are introduced in early part of this section. The nature of complex systems results in vicious circles phenomenon in many natural and man-made systems. The focus of this research is performance of new product introduction systems; vicious circles phenomenon within the system and impacting factors associated with vicious circles are discussed in the rest of context. General strategies to mitigate vicious circles in social systems and specified solutions to new product introduction systems are discussed.

The author reviewed definitions of both systems and processes, demonstrated two types of feedback loops using two examples, analysed vicious circles e.g. deviation-amplifying feedback loops and their consequence. This section employed some definitions from dictionaries, books, and articles. The original intent was to help understanding characteristics of process and systems where vicious circles arise as an unexpected result.

Regarding the introduction to nature and characteristics of processes and systems, there are two considerations. The first was to further approve that both new product introduction systems and new product development processes involve the same key concepts. Therefore, this section starts with studying both systems and processes in a general way. Secondly and the most important, the author was to pave a way to a conclusion that new product introduction systems have the same architecture as agent-based simulation methods have. The second issue is further discussed in Chapter 5.

2.2.1 What are systems?

In this subsection, the definitions of a system were studied firstly, a model of system was developed to represent typical systems, and the system nature was concluded.

2.2.1.1 Definition of systems

Let us begin with some definitions from literatures and dictionaries. A system is defined as a set of individuals working together as parts of a mechanism or an interconnecting network; a complex whole (Oxford, 2003). From on engineering perspective, The international council on systems engineering defines system as an integrated set of elements that accomplish a defined objective (INCOSE, 2000). The Heritage dictionary gives a definition of system as a group of interacting, interrelated, or interdependent elements forming a complex whole (Heritage, 2009). From the view of organizational behaviour, a system is an interrelated set of elements that perform as a whole (Moorhead and Griffin, 2012).

2.2.1.2 A model of system

According to above system definitions, a system usually contains a series of nodes or elements. The individuals interact with each other with specific intent or not. The communication occurs among different individuals. Therefore, a model of system is demonstrated as Figure 2.7.

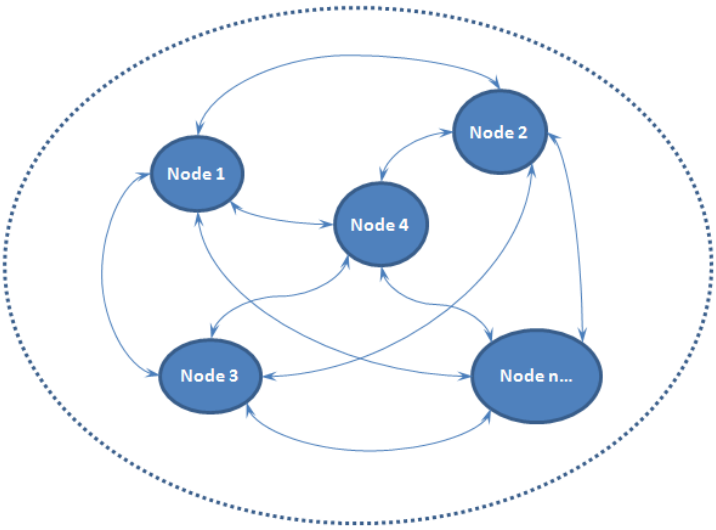


Figure 2.7 A model of system

In Figure 2.7, the individual nodes independently carry on different activities, but in an interactive environment. And the information is generated from each node, and exchanged and communicated through dual-arrow lines within the entire system. Each node uses information from and provides necessary information to other nodes (Abdelsalam and Bao, 2006), (Mountney et al, 2007), (Wynn et al, 2007), (Kumar et al, 2009). The reason why a system model boundary in Figure 2.7 uses dotted line, rather than solid line, is that the system is vulnerable to influence from inside or outside of the system.

2.2.1.3 Characteristics of systems

In summary, a system comprises two primary components: a series of individual nodes or elements, and a complicated information network linking them. Systems are extreme complicated, considering the increased information exchange channels with the increasing of individual nodes involved. Therefore, the characteristics of a system is concluded as follows:

- Comprises of a series of functional individuals;
- Communication occurs regarding information generated and used in the system;
- Communication complexity is greatly increasing with the individuals involved.

2.2.2 What are processes?

In this section, the concepts of processes were studied, a model of process was developed to represent a typical process, and nature of process was concluded.

2.2.2.1 Definitions of processes

A process is illustrated as an organized group of related activities that work together to create a result of value (Hammer, 2001), (Browning et al, 2006). The definition of a process from the Oxford Dictionary is a series of actions or steps taken in order to achieve a particular end (Oxford, 2003). The Longman Dictionary defines a process as a series of actions that someone takes in order to achieve a particular result.(Longman, 2002).

The basic elements involved in a process are activities or actions, which are designed and conducted by people with particular purpose. Among different specific activities, communication in terms of information and data are necessary with focus on completing the process commission. The process designer is keen to get an expected result from the process. Therefore, a process usually begins with available resource collections and input, and finally producing results.

2.2.2.2 A model of processes

According to above process definitions of processes, a model of process is demonstrated in Figure 2.8.

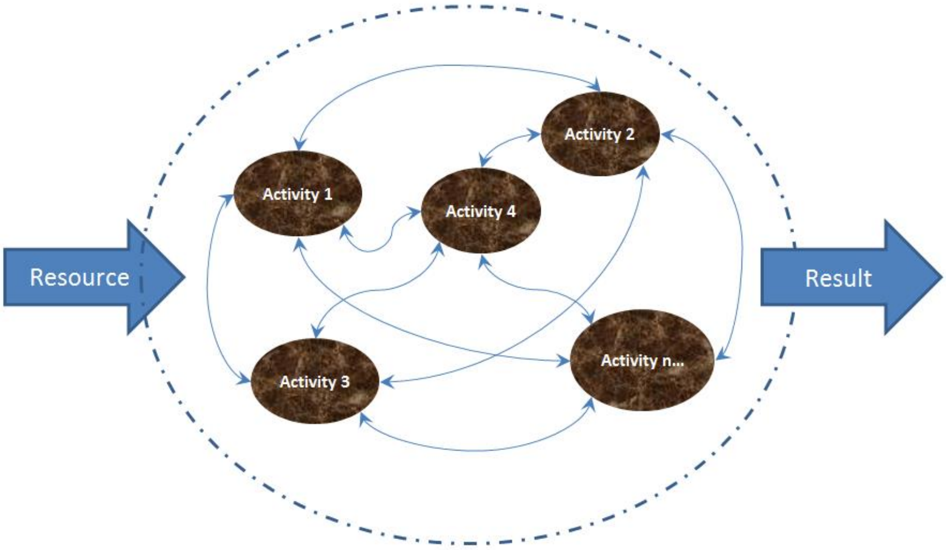


Figure 2.8 A model of process

A process is comprised of a series of activities or stages that are designed towards an expected output. Communication system links different activities and supports the process producing satisfactory outcomes. The process is also vulnerable to impact from either inside or outside environment changes, so the process model boundary is also a dotted-line circle.

Both systems and processes have the same structure and functional elements, therefore they are considered as a same terminology and without differences in this research.

2.2.2.3 Characteristics of processes

A process contains a series of activities that are interacted within communication networking, with respect to producing expected outcomes. The characteristics of processes were concluded as follows:

- Comprised of a series of individual activities or work teams;

- Communication networks are necessary with respect to producing an intended outcomes;

- Information loops form within a process to support decision making and complete specific commissions; and

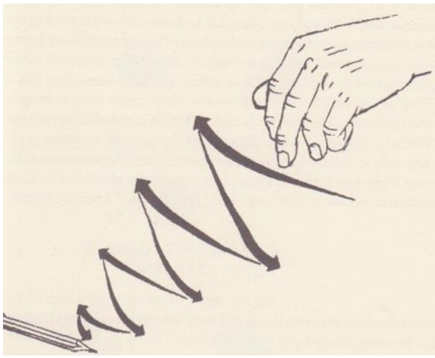
- The information loop could influence the process and its erformances.

2.2.3 Communication within systems

The systems are comprised of a series of activities or stages linked within a complex communication network. Systems are vulnerable to any change caused by either inside or outside impacting factors. When a change occurs within a system, another counter-change is automatically generated by the system attempting to neutralize the change impact on the system (Morgan 2006). Both change and counter-change form communication feedback loops.

2.2.3.1 An example of change and counter-change

A familiar example in our daily practices, but usually omitted by us is the process when a person tries to pick an object with his or her hand in Figure 2.9. This story explains both change and counter-change within a system. This example further demonstrates both activities’ impact on a system.



This figure is adapted from (Morgan 2006)

Figure 2.9 Change and counter-change

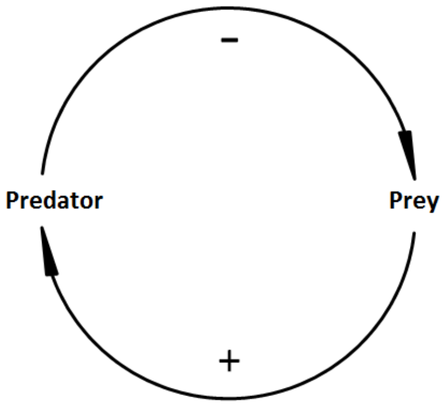
The curve of a hand going to pick a pencil is not a straight line, although majority of us might assume it is. While, the guarantee to make sure the pencil is finally to be picked is that when the hand is off the direction onto the pencil, our brain will control the hand produce a counter-change, making the hand back to its right way. This kind of counter-changes or feedbacks occur very frequently, until the gap between the fingers and the pencil becomes zero. By doing so, the system achieves its original objective, e.g. the hand picks the pencil.

In above story, the function of counter-change is positive to eliminate the effect of an unintended change. Finally, the system achieved the particular purpose. Both change and counter-change form a communication feedback loop. Communication feedback loops are not always positive to keep the system stable and achieving the system goal. Sometimes, communication feedback loops make the system accelerating off its balance status till out of control.

Change and counter-change often happen within a dynamic system. Both activities form communication feedback loops within a system. Some communication feedback loops are positive to keep a system stable, however some communication feedback loops are negative and destroy the system.

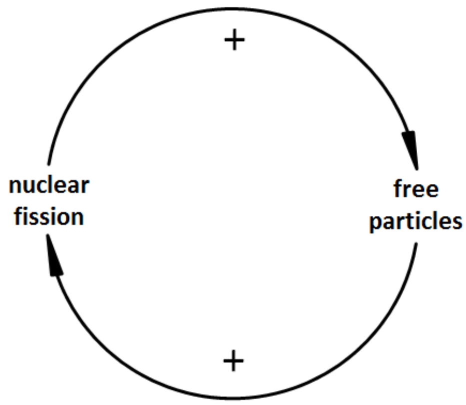
2.2.3.2 Two types of feedback loops

There are two types of communication feedback loops within a system: negative feedback loops and positive feedback loops (Richardson, 1983), (Masuch, 1985). They are demonstrated in Figure 2.10 and Figure 2.11.



This figure is adapted from (Masuch, 1985)

Figure 2.10 Negative feedback loop



This figure is adapted from (Masuch, 1985)

Figure 2.11 Positive feedback loop

In Figure 2.10, the predator and prey game is a negative feedback loop. When the number of predator increases, the number of prey will decrease on reverse direction. And when the number of prey goes down, the number of predator will go down too because of food reduction. This kind of feedback loops could direct the system back to its original status, so it is also defined as self-correcting feedback loops. Negative feedback loops enable the system being in a balance status.

The Figure 2.11 displays a positive feedback loop of nuclear fission. When the nuclear atoms are split and produce huge energy, the quantity of free particles increase, which further accelerates the nuclear fission. Positive feedback loops make the system accelerating off its balance status along the change direction and finally out of control, so the positive feedback loops are also defined as self-reinforcing feedback loops. Positive feedback loops make system off its balance status and eventually collapse.

2.2.4 Vicious circles

In this section, vicious circles are referring to positive feedback loops, i.e. deviation amplifying feedback loops. Regarding the case study new product introduction system, vicious circles phenomenon and their impacting factors are demonstrated in this subsection.

2.2.4.1 Rework in new product introduction systems

Reworks are often necessary within new product introduction system due to the social nature of the design system. The rework is assumed as an intended change within the system, and the counter-change under this situation is that particular work team spends additional design resources, like the work teams’ time resource to complete these rework tasks.

The counter-change in new product introduction system ensures that the product project could be completed within satisfactory time frame and with satisfactory product quality. However, from the full view of performance of the new product introduction system, both rework and additional activities increase the time pressure on new product introduction system. Therefore, the communication feedback loops considered in this way, i.e. rework and additional activities, have a negative impact on the system performance.

2.2.4.2 Vicious circles in new product introduction systems

As discussed in Section 2.2.4.1, two primary elements involved in the new product introduction system are rework and time pressure of the design system. The case study new product introduction system research problems, i.e. vicious circles, are demonstrated in Figure 2.12.

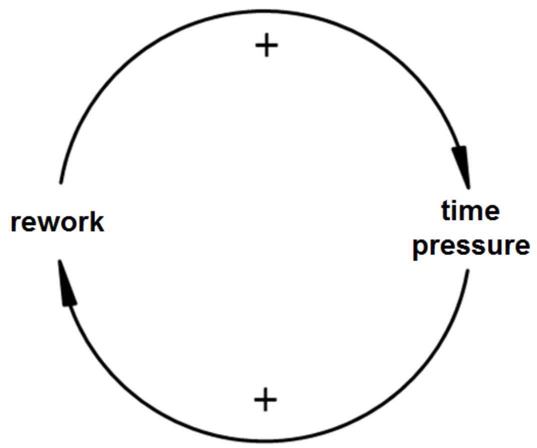


Figure 2.12 Vicious circles in NPISs

In the new product introduction system vicious circles, rework occurs as an unintended activities within the system. Because of these rework tasks, particular work teams have to carry on additional activities, in order to complete the reworks and make sure the product is developed. By doing this, the new product introduction system increases time pressure based on a predetermined time frame. Enhanced time pressure on the system influence the daily work of each work team, which means more reworks would be necessitated in the future. This kind of phenomenon is defined as vicious circles in the case study new product introduction system.

Vicious circles phenomenon in new product introduction systems significantly influence system performance. At its extreme condition, the new product introduction system breaks down because the system is not able to complete excessive rework tasks. Therefore, the vicious circles are dangerous and must be mitigated.

2.2.5 Strategies to avoid vicious circles in NPISs

Vicious circles are dangerous in societal research areas, the strategies how to mitigate vicious circles or turn them to virtuous circles were discussed in literatures. For example, Perry argue increased investment in poverty area could achieve sustainable economic growth (Perry, 2006). In his/her research, an additional change was added into the original system, in order to tackle the influences of vicious circles. When managing knowledge system, Garud and Kumaraswamy (2005) argue decoupling original system processes or introducing a deviation counteracting feedback loop within the original system (Garud and Kumaraswamy, 2005).

In the case study new product introduction system, vicious circles are defined as positive feedback loops. Within the communication feedback loops between rework and system time pressure, they are self-reinforced with each other. In order to break down this kind of deviation-amplifying feedback loops, a deviation counteracting feedback loop is introduced into the new product introduction system. By doing so, a management strategy to mitigate vicious circles in new product introduction systems was developed in Figure 2.13.

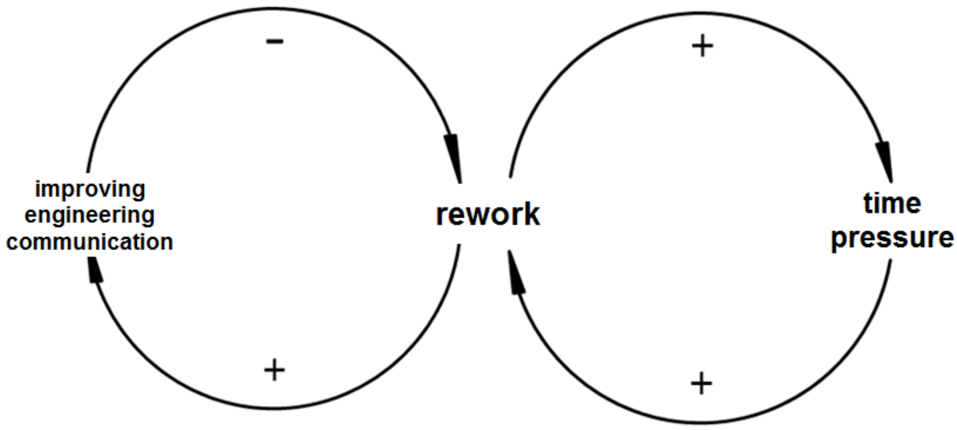


Figure 2.13 Strategy to manage vicious circles in NPIS

Employing a negative feedback loop in the vicious circles (left part of Figure 2.13), the impact of vicious circles on the system performance is effectively reduced, therefore the vicious circles could be mitigated considering different application situations.

Focusing on vicious circles in new product introduction systems, the rework is an indicator of the system time pressure. And within new product introduction systems, the rework are closely associated with and influenced by the efficiency of engineering communication. The management strategy is to improve efficiency of engineering communication, and reduce rework volume within new product introduction systems, and the time pressure on each work team are finally released. By using this method, the vicious circles could be mitigated in new product introduction systems.

2.2.6 Summary

Both systems and processes are comprised of a series of elements or activities linked within a complex information communication network. Social systems are vulnerable to impacts from either inside or outside influencing factors. When a change occurs within the system due to either inner factors or outer factors, a counter-change will be automatically generated by the system, attempting to eliminate the change's influence. Both change and counter-change produces positive or negative impacts on the system performance.

There are two types feedback loops: negative feedback loops and positive feedback loops (vicious circles), which were demonstrated by two examples. Negative feedback loops enable the system goes back to its reference status when a change occurs within the system, so negative feedback loops are positive to keep the system stable. Positive feedback loops (vicious circles) push the system going off its balance status, so positive feedback loops are negative.

Rework generated in new product introduction system increases time on particular work teams and the whole system, which further produces a possibility of more reworks arise in the system in the future. This kind of social phenomenon was defined as vicious circles problems in this research.

Potential management strategy to mitigate influences of vicious circles was developed in this research. Improved engineering communication is an potential strategy to reduce rework tasks necessitated within new product introduction systems. By doing so, the time pressure on the new product introduction system could be released. Therefore, the impact of vicious circles on new product introduction systems are expected to be mitigated in new product introduction systems.

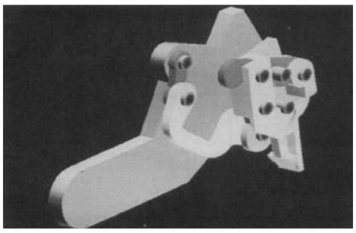
2.3 Modelling and Simulation Methods

In this section, modelling and simulation techniques and methods were reviewed, including modelling and simulation applications, modelling and simulation development, simulation processes, agent-based simulation method, discrete-event simulation method, and NetLogo simulation tool introduction.

2.3.1 Two distinct modelling and simulation fields

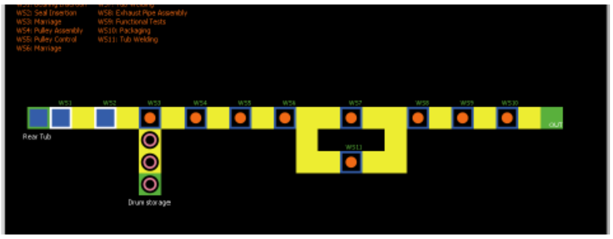
Modelling and simulation techniques are widely applied in two distinct areas: mechanism simulation and process & system simulation. Mechanism simulation relates to the simulation of physical mechanical system, through which movement and velocity of mechanical components can be simulated and analysed for whole machine optimization, for example, kinematic simulation of 3D CAD models (Kimura et al, 1998). An example was shown in Figure 2.14.

Whereas, process and system simulation relates to the simulation of the performance of the systems, including both industrial production process and business service process (Axelrod, 1997) including, manufacturing systems (Barbosa and Leitao, 2011), organisations (Nicolae and Wagner, 2011), human systems (Bonabeau, 2002), complex problems process (Pereda and Zamarreno 2011), automotive assembly line (Kibira and McLean, 2007). One example was displayed in Figure 2.15.



This figure is adapted from (Leigh et al, 1989)

Figure 2.14 Mechanism simulation



This figure is adapted from (Barbosa and Leitao, 2011)

Figure 2.15 Process system simulation

In this research, without special specification, simulation is referring to process and system simulation.

2.3.2 Simulation techniques

Let us begin with two definitions of simulation. Simulation was defined as driving a model of a system with suitable inputs and observing the correspondingly outputs (Bratley et al, 1987). Another was demonstrated as the process of designing a model of a real system (or a system-to-be), then conducting experiments with this model for the purpose of either understanding the performance of the system and/or evaluating various management strategies and decision-making through simulation results (Shannon, 1983), (Shannon, 1992).

The purpose of simulation includes prediction, performance assessing, training, entertainment, education, proof, discovery, and so forth (Axelrod, 1997). The application of simulation techniques to various research areas, including computer systems, manufacturing processes, business organizations, government systems, ecology environment system, social systems, and other systems (Shannon, 1983), (Shannon, 1992). Modelling and simulation approaches were also applied into interdisciplinary research fields, for example, product development process decision making (Abdelsalam and Bao, 2006), (Pesonen et al, 2008), integrated product teams management (Sim et al, 2009), new product introduction systems (Bhuiyan et al, 2004), (Garcia, 2005), (Wynn et al, 2007), organisational management (Hughes et al, 2012), and others.

To some extent, the simulation technology is being considered as the third science research methodology, in addition to the traditional deductive and inductive reasoning (Axelrod, 1997), (Macal and North, 2007).

2.3.3 Simulation processes

The specific simulation process used to conduct identified research problems may vary for a range of reasons including differences in the problem being addressed, purpose of the simulation experiments, experimenters' preferences, limitation of simulation technologies, and so forth.

Contributions to modelling and simulation process models include, but not limited to: (Shannon, 1983), (Pegden, 1995), (Seila, 1995), (Banks, 1999). For example, Shannon's simulation process (Shannon, 1983) includes the following steps:

- system definition
- model formulation
- data preparation
- model translation
- validation
- strategic planning
- tactical planning
- experimentation
- interpretation
- implementation
- documentation

In the next decade, Seila (1995) developed another simulation process procedure, which includes thirteen steps as follows:

- problem statement and objectives
- systems analysis

- analysis of input distribution
- model building
- design and coding of the simulation program
- verification of the simulation program
- output data analysis design
- validation of the model
- experimental design
- making production runs
- statistical analysis of data
- implementation
- final documentation

Modelling and simulation process models include a series of activities that serve to build up a simulation model, and validate the simulation model with the real world, applying appropriate validation strategies. Accommodating simulation processes formulas found in literatures into case study problems, an research procedure was developed for this research. Details are demonstrated in Chapter 3.

2.3.4 Simulation methods

Two simulation methods applied in operational research communities are discrete-event simulation (DES) (Cho and Eppinger, 2001) and agent-based simulation (ABS) (Siebers et al, 2010), in addition to other simulation methods, like Monte Carlo simulation, mathematical simulation, pilot simulation, and so forth.

2.3.4.1 Discrete-event simulation

Discrete-event simulation method is a matured and credible simulation method (Siebers et al, 2010). Discrete-event simulation is one way of building up models to observe the time-based behaviour within a system. Formal methods were developed to build simulation models and ensure the models are credible (Siebers et al, 2010). Arena and Witness are two examples of discrete-event simulation tools (Klingstam and Gullander, 1999), (Kelton et al, 2002).

2.3.4.2 Agent-based simulation

Agent-based simulation is a relatively new simulation method (Macal and North, 2007), (Macal and North, 2010), (Garro and Russo, 2010). Agent-based simulation method builds up system model as a bottom-up infrastructure (Macal and North, 2007), (Macal and North, 2010). Within agent-based simulation environment, individual agents interact with each other under specified simulation rules. Through this kind of interaction among different agents, macro level system performance is observed by the operator and then analysed (Macal and North, 2010).

Agent-based simulation model comprises three primary components, which are (Macal and North, 2010), (Garcia, 2005):

- A set of agents with their characteristics and independent behaviours;
- A set of simulation specification rules defining how and with whom agents interact; and
- The simulation world where agents interact with each other.

Agent-based simulation tools include, but not limited to: NetLogo (Sklar, 2007), Spread sheet (Yin and Ma, 2012), Repast, Starlogo, Swarm, Matlab, Mathematica, Anylogic (Siebers et al, 2010), (Robinson and Ding, 2010), (Macal and North, 2010), (Hughes et al, 2012) and others.

2.3.5 Summary

Modelling and simulation techniques are broadly applied in operational system research. Two simulation methods used in process system simulation are discrete-event simulation and agent-based simulation. Agent-based simulation builds up system models as a bottom-up infrastructure, which involves three primary components:

- A set of agents with their characteristics and independent behaviours,
- A set of simulation specification rules defining how and with whom agents interact, and
- The simulation world where the agents interact with each other.

Agent-based simulation method was employed in this research, because agent-based simulation method builds up simulation models as a bottom-up infrastructure, which is the same way as a new product introduction system performs in the real world, given the research focus is on system performance evaluation. This issue is further discussed with details in Chapter 5.

Simulation processes are comprised of a series of activities that build up a simulation model and then verify & validate the model with the real world. Simulation processes introduced in this section have been developed into an research procedure in Chapter 3. Details about simulation model development activities are illustrated in Chapter 5. Simulation model validation activities are demonstrated in Chapter 6.

2.4 Model Verification and Validation

The reasons why model verification and validation are issued as an independent section are: firstly, simulation model verification and validation is an important part of model development process, and secondly relevant issues to be addressed in this research are a large volume content that is suitable for a separate subsection.

Simulation models are increasingly being used to solve complex organisational system problems and to support management decision-making. However how to ensure that simulation models being applied possess sufficient accuracy become highlighted topics. To start this issue, the author made a general introduction to model verification and validation firstly, and then explained why model verification and validation is not a panacea, but is extreme important and necessary for simulation model development.

Model verification and validation process is a series of validation activities carried out along with the simulation model development process. In this section, both simplified model verification and validation process models and detailed model verification and validation process model are reviewed and analysed. Four model verification and validation strategies and a series of model verification and validation methods are introduced and explained, with respect to case study used in this research.

Simulation model verification and validation enhances both modellers' confidence and users' trust when using the model (Sargent, 2005), (Van Horn, 1971). Model verification and validation is a critical and time-consuming evaluation process as well. Contributions to model verification and validation knowledge include, but not limited to: (Schlesinger, 1979), (Law, 2007), (Sargent, 2005), (Robinson, 1997) (Balci, 1998), (Macal, 2005), (Xiang et al, 2005), (Thacker et al, 2004), (Tocher, 1967).

2.4.1 Introduction to model verification and validation

Model verification is determining that a simulation computer program performs as intended, e.g. debugging the computer program. One of early researchers, A.M. Law described model validation as determining whether the conceptual model is an accurate representation of the real world (Law, 2007). Conceptual model is the description of the real world systems, in terms of mathematical, logical, verbal representation of the problem entity developed for a particular study (Sargent, 2005). (Jagdev et al, 1995).

Model verification process is to determine that a conceptual model implementation accurately represents the conceptual model description and its solution (Thacker et al, 2004). Verification is concerning with identifying and removing errors in the model by comparing simulation results from the simulation model to analytical solutions from the reality. So, the verification process is dealing with the mathematics relationship and simulation rule specifications associated with the model (Macal, 2005), (Thacker et al, 2004). In other words, model verification process is trying to build a model right (Balci, 1997) and address a mathematics issue (Riha et al, 2006).

Model validation process is to determine the degree to which a model is an accurate representation of the real world system with respect to specific model use. (Macal, 2005), (Thacker et al, 2004). The final goal of simulation model validation is to make the model useful in the sense that the model addresses the right problems, provides accurate information about the system being modelled, and to make the simulation model actually used (Macal, 2005). Therefore, simulation model validation process is concerning with quantifying the accuracy of the model by comparing simulation results to experimental or operational outcomes (Thacker et al, 2004). The intent of simulation model validation is to build a right model (Balci, 1997) and address operational concerns (Riha et al, 2006).

Model verification activities keep carrying on until a simulation model is built up to represent the conceptual model with sufficient confidence. In contract, model validation needs to be discussed with simulation project owner until the simulation model is accurate enough to represent the case study new product introduction system with focus on the research purpose.

Table 2.2 listed primary contributions to model verification and validation knowledge. Literatures marked with stars are important contributions to this research.

Table 2.2 Contributions to model verification and validation

researchers and affiliation(s)	**model verification determines whether or not**	**model validation determines whether or not**	**literatures that support the issues**	**contribution to knowledge**
Stewart Schlesinger The Aerospace Corporation, California, U.S.A. the Society for Computer Simulation	a simulation model represents a conceptual model within specified limits of accuracy.	a simulation model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model.	(Schlesinger, 1981), (Schlesinger, 1979)*, etc.	Terminology, definitions of model verification and validation.
Robert G. Sargent Syracuse University, NY, U.S.A.	The simulation model programing and implementation of the conceptual model is correct.	The simulation model's output behaviour has sufficient accuracy with the simulation model application.	(Sargent, 2013), (Sargent, 2009), (Sargent, 2005)*, (Sargent, 1996), (Sargent, 1985), (Sargent, 1979), etc.	The Sargent Circle, 4 primary model verification and validation strategies, 15 model verification and validation methods.
Charles M. Macal The University of Chicago and Argonne	The model performs as intended.	The model represents and correctly reproduces the behaviours of	(Macal, 2005)*, (Macal and North, 2005), etc.	Model verification and validation depends on intended use of

National Laboratory, Chicago		the real world system.		the simulation model.
Osman Balci Department of Computer Science, Virginia Tech., Virginia, U.S.A.	Building a model right.	Building a right model.	(Balci, 2010)*, (Balci, 1998), (Balci, 1998), (Balci, 1997), etc.	20 model verification and validation rules, model development and validation should be conducted together.
Nigel Gilbert University of Surrey, Surrey, UK.	This model is right. Getting rid of bugs.	This is the right model. Checking whether the model is a good model of a real world interest.	(Gilbert, 2010) *, (Gilbert, 2008), (Gilbert and Troitzsch, 2005), etc.	Model verification and validation depends on the modeller's objectives. Sensitivity verification method.
Stewart Robinson Loughborough University, Loughborough, Leicestershire, UK	The conceptual model has been transformed into a simulation model with sufficient accuracy.	The simulation model is sufficiently accurate for the intended research purpose.	(Robinson and Brooks, 2010), (Robinson, 1999), (Robinson, 1997)*, etc.	Specified model validation methods depend on the stage the model has been reached. Model verification and validation is to build up confidence.

2.4.2 Challenges of model verification and validation

Model verification and validation is a method to check whether a simulation model is accurate enough to represent a real world interest. However, model verification and validation technique is not a panacea. It is necessary to make a brief discussion about the characteristics of model verification and validation before further activities are carried out.

Model verification and validation techniques are being developed as an evolution way. One evidence is that model verification and validation procedures and validation-related terminologies are still not standardized (Kleijnen, 1995). Sometimes, especially at early stage of literature review, the author often got confused by various definitions and terminologies relevant to model verification and validation. For example, Sargent defined the conceptual model as the mathematical, logical, or verbal representation of the problem entity developed for a particular study (Sargent, 2005). In this definition, the conceptual model is represented by mathematical, logical, or verbal descriptive means. The followers include, but not limited to: (Xiang et al, 2005), (Balci, 1998), (Robinson, 1997), and others. However, in the research from Schlesinger and Thacker, the mathematical model is comprised of conceptual model, mathematical equations, and modelling data needed to describe the reality (Thacker et al, 2004), (Schlesinger, 1979). By this definition, the mathematical model was defined as a higher hierarchy level than conceptual model.

Model verification and validation applies appropriate strategies, because there is no model verification and validation methods could guarantee a model is 100% accurately representing a real world system (Kleijnen, 1995). Therefore, model verification and validation considers satisfactory accuracy of a simulation model (Carson, 2002), (Robinson, 1997), and depends on the purpose of the simulation and the model intended use (Macal, 2005). More evidences could be found in literature. For example, model verification and validation process means a series of activities that have are carried out to verify and validate the simulation model to the necessary degree for specific modelling purpose (Carson, 2002). Balci (1998) defined model verification as model transformed from one form to another, as intended, with sufficient accuracy (Balci, 1998). He defined model validation as the model performs with satisfactory consistent accuracy within applicability domains (Balci, 1998).

All definitions of model verification and validation introduced above contain keywords like, satisfactory accuracy, intended use, simulation purpose, necessary accurate degree, sufficient accuracy, and so forth. Therefore, what the model verification and validation could guarantee is that a simulation model meets its intended requirements, regarding simulation methodology and simulation purpose (Macal, 2005).

Regarding the case study new product introduction system, application modelling and simulation techniques to understand performance of such manufacturing system, e.g. vicious circles in in this research, is more challengeable. The reasons behind this concern are:

- The simulation model not only handles complex information communication but also considers organisational perspectives of the system (Jagdev et al, 1995);
- The input and output data are mostly social-related, which means that the input data is difficult to collect, and output data is difficult to be validated;
- Standard model validation procedures, like established in physical simulation system, do not exist in social-related system validation (Macal, 2005); and
- The model verification and validation process usually involves code programing and debugging activities, which is a challenge for some researchers in operational engineering area.

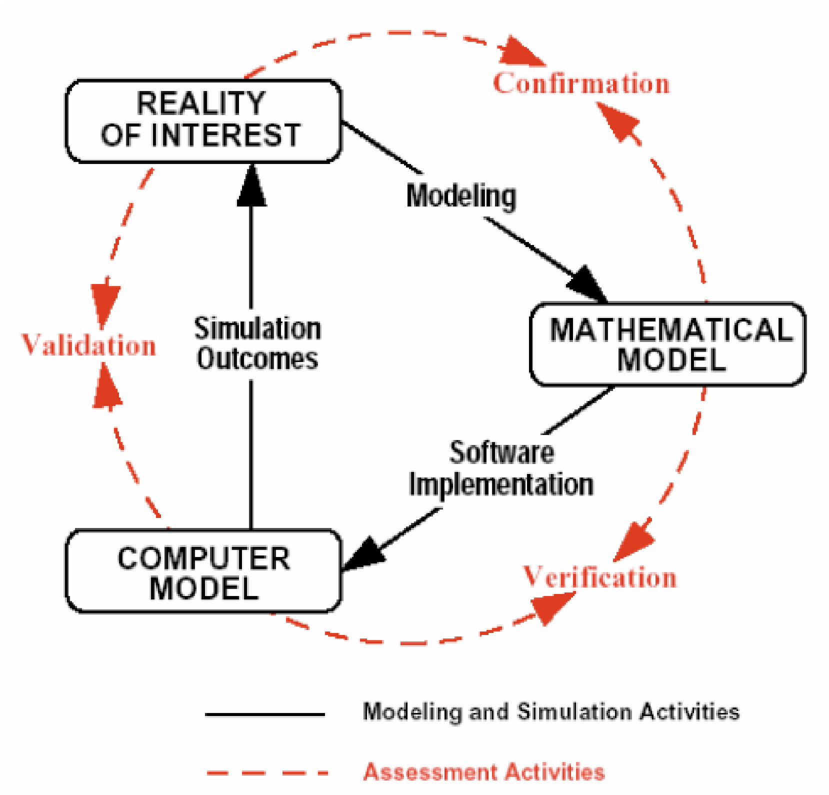
In summary, model verification and validation is not to prove that a simulation model is correct and accurate for all possible condition and applications (Chapurlat et al, 2003), (Carson, 2002),(Robinson, 1997), (Kleijnen, 1995). But, model verification and validation process can provide evidence that a simulation model is sufficiently accurate to represent and understand the specified real-world system. The model verification and validation process completes when the sufficiency is reached (Sargent, 2005), (Thacker et al, 2004), (Carson, 2002), (Robinson, 1997).

2.4.3 Model verification and validation processes

Model verification and validation is actually a part of simulation model development process (Xiang et al, 2005), so model verification and validation activities are usually integrated within the process of simulation model development. In this subsection, different model verification and validation process models found in literature are introduced in an independent way. There are two ways to demonstrate a model verification and validation process, either in a simplified pattern or a detailed style.

2.4.3.1 Model verification and validation process (Schlesinger)

Figure 2.16 illustrates a model verification and validation process to represent a real world research interest (Schlesinger, 1979). The verification and validation process diagram was reported at Los Alamos national Laboratory by (Thacker et al, 2004), which was developed by one of early researchers in this field (Schlesinger, 1979).



This figure is adapted from (Schlesinger, 1979)

Figure 2.16 Model verification and validation process (Schlesinger)

In Figure 2.16, the reality of interest represents the physical system from which the model development information and data is being collected. The reality of interest could be a component problem, subsystem, or the complete system. It is the project owners their selves that check whether the definition of reality of interest is accurate enough.

The mathematical model comprises conceptual model, mathematical equations, and modelling data needed to describe the reality of interest. The process of selecting important features and mathematical methods to represent the reality of interest is modelling process. Evaluating the correctness of the modelling process and its result with the reality of interest identification is a series of confirmation activities.

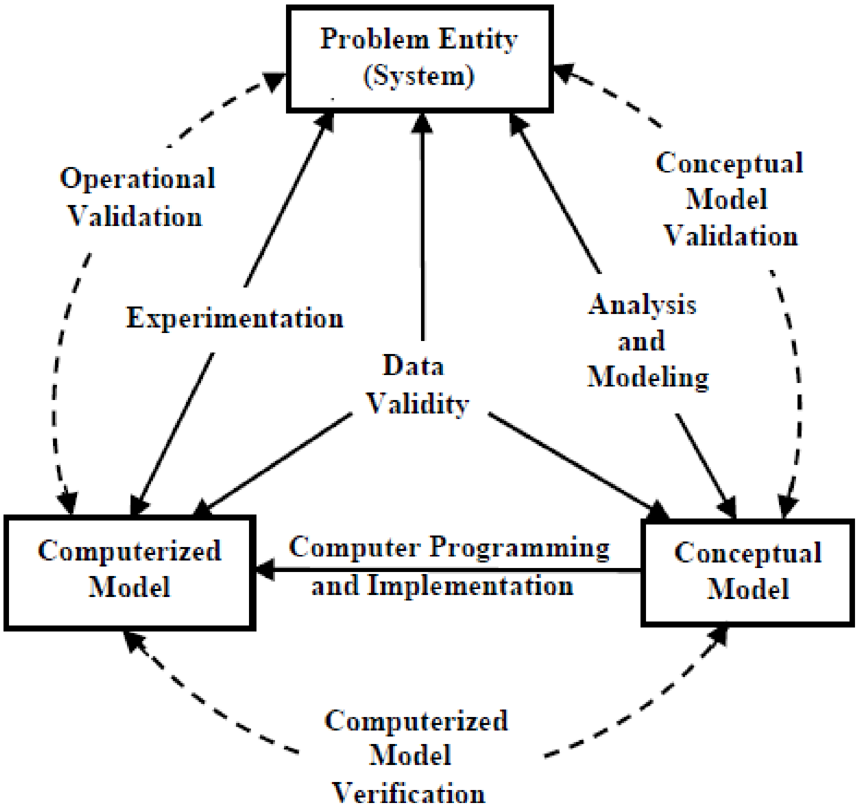
The computer model represents implementation of the mathematical model. The computer model comprises computer programs, conceptual and mathematical modelling assumptions, data inputs, solution options, simulation outputs, and so forth. The verification activities focus on identifying and removing errors occurred at the software Implementation process.

As the last stage, validation activities are focusing on evaluating the accuracy of the simulation model by comparisons of simulation outcomes from the computer model with the data from the real world (the reality of interest). Model validation is an on-going activity as experiments are improved and/or parameter ranges are extended.

In summary, Schlesinger’s model verification and validation process is an important contribution to the knowledge domain. Primary model verification and validation architecture developed in his work is broadly being considered in model validation community today. This model contains three primary validation stages: the reality of interest is approved by the project owners, the mathematical model is confirmed by comparing with the original definition of the reality of interest, and the computer model is translated from the mathematical model, and validated with the reality of interest.

2.4.3.2 **Model verification and validation process (Sargent)**

Figure 2.17 (Sargent, 2005) demonstrates another model verification and validation process model, which original version was published at the Winter Simulation Conference in 1979 (Sargent, 1979). The model verification and validation process was gradually improved and is being broadly employed in today’s model verification and validation community (Sargent, 1985), (Sargent, 1996), (Sargent, 2009), and (Sargent, 2013). In order to memorize his contribution, the model verification and validation process diagram is referred to as the Sargent Circle in literature (Thacker et al, 2004).



This figure is adapted from (Sargent, 2011)

Figure 2.17 Model verification and validation process (Sargent)

In Figure 2.17, the problem entity (system) is a system, idea, situation, or phenomena to be modelled. The conceptual model is developed for a particular study on the problem entity (system) by using mathematical, logical, or verbal approaches. The computerised model is an implementation of the conceptual model upon a computer simulation platform.

Conceptual model is developed by analysing and modelling of the identified problem entity (system) and computerised model is developed through computer programing and implementation of the developed conceptual model. The implementation of computerised model on the identified problem entity is obtained by carrying out experimental activities.

Conceptual model validation is defined as determining that the theories and assumptions underlying the conceptual model definition are correct and that the model representation of the problem entity is reasonable for intended model use. Computerised model verification is defined as assuring that the computer programming and implementation process and results are correct, with respect to the definition of a conceptual model. Operational validation is defined as determining that the computerised model output behaviour has sufficient accuracy for the model's intended purpose in the model applicability domain. Data validity is defined as ensuring that the data necessary for model building, model verification and validation, and application simulation model experiments to solve real world problems are adequate and correct.

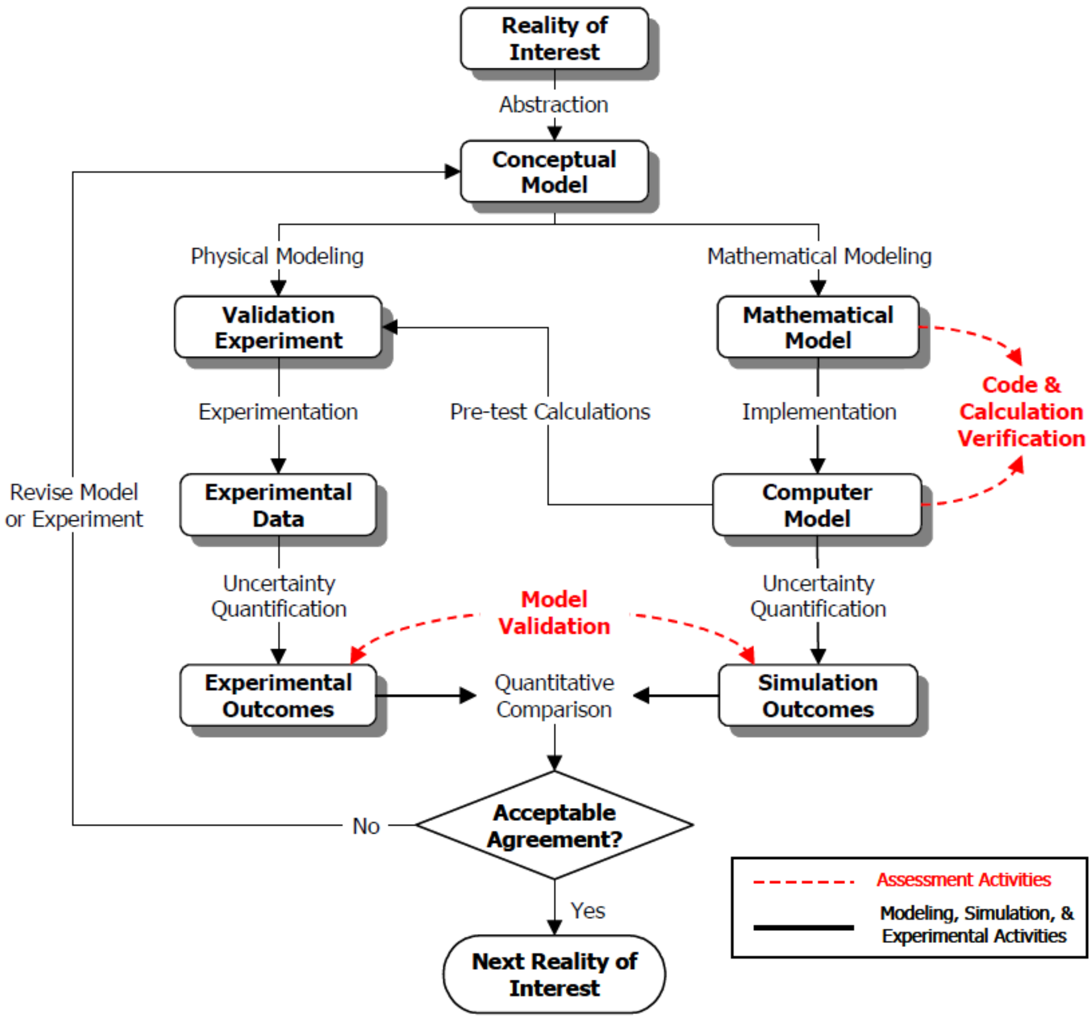
In summary, Sargent developed a model verification and validation process model, which comprises three primary stages: problem entity definition, conceptual model development, and computerised model implementation (verification with the conceptual model and validation with identified research problems). Data validity activities are an extreme important part within the model verification and validation process, in order to keep each step of the validation process and all activities are valid. Appropriate validation strategies and methods are selected and applied to each stage of simulation model development process.

Figure 2.16 and Figure 2.17 introduced two examples of simplified model verification and validation process models. Detailed model verification and validation processes include more activities, with broader model validation vision.

2.4.3.3 Detailed model verification and validation process (Thacker)

In order to demonstrate the model verification and validation process in a comprehensive and detailed style, researchers upgraded and developed model verification and validation processes into detailed model verification and validation models. Contributions to this knowledge domain include, but not limited to: (Sargent, 2005), (Chapurlat et al, 2003), (Balci,1998), (Thacker et al, 2004), and others.

Figure 2.18 introduced one detailed model verification and validation process model, which was released at the Los Alamos National Laboratory (Thacker et al, 2004).



This figure is adapted from (Thacker et al, 2004)

Figure 2.18 Detailed model verification and validation process

At beginning of the process, a conceptual model is defined to represent the reality of interest. When the conceptual model is specified and complete, it is then described by two distinct ways using different approaches: mathematical modelling and physical modelling.

At the right branch, a computer model is developed to implement the conceptual model. At left branch, validation experiment is conducted to obtain relevant and qualified experimental data. The purpose of validation experiment was to provide sufficient evidence needed to verify, validate, and implement the computer model.

The mathematical modelling team develops a computer model upon a selected computer platform, with respect to the mathematical model translated from the conceptual model. When the computer model get verified through code and calculation verification activities, it produces simulation outcomes. Simultaneously, the physical modelling team defines and conducts a series of validation experiments, collecting experimental data, and finally producing experimental outcomes. By quantitative comparison between simulation outcomes and experimental outcomes, a final decision of whether the computer model is validated or not is drawn. If the assessment result is no, the whole process of model verification and validation including both computer model and validation experiments need to be revised.

This detailed model verification and validation process model provides a potential validation methods to verification and validation of new product introduction systems. That is to apply results from a pilot simulation to validate a simulation model, through comparing results from both experiments.

2.4.3.4 Summary

Model verification and validation process is an important part of simulation model development. Distinct validation activities are carried out to verify and validate each stage of simulation model development, with respect to the intended model use.

Both simplified model verification and validation process models and detailed model verification and validation process model were introduced. When applying simplified model verification and validation method, model validation process is defined as an interactive process along with the simulation model development. Detailed model verification and validation process model considers that both simulation model development and model validation process are two separate processes which would be conducted in a parallel way. Considering specified research aim and objectives for this research, simplified model verification and validation process model was employed. Further details could be found in Chapter 3.

Within simplified model verification and validation framework, model verification and validation activities are carried on following three primary simulation model development stages: research problem identification, conceptual model definition, and simulation model development. At each stage, various verification and validation methods are specified and associated activities are carried out to ensure sufficient accuracy is maintained by the simulation model.

2.4.4 Model verification and validation strategies and methods

In this subsection, model verification and validation strategies and methods were reviewed and analysed. As discussed in literatures, primary model validation principle used in this research is to apply distinct model verification and validation strategies and methods to different simulation model development stages.

2.4.4.1 Model verification and validation strategies

Researchers developed distinct model verification and validation strategies with their experience either in academia or industry practice. Contributions to this knowledge domain include, but not limited to: (Sargent, 2005), (Balci, 1994), (Robinson, 1997), (Carson, 2002), (Banks et al, 2010), (Thacker et al, 2004). There are four primary strategies used to determine whether a model is valid or not (Sargent, 2009):

- Self-validation: The simulation model development team itself makes the decision as to whether a simulation model is valid or not;
- Co-validation: The simulation team involves the model user within the simulation model development process; the model validation process is integrated with the model development process.
- Independent validation: Applying an independent third party to decide whether a simulation model is valid or not; and
- Scoring validation: Using a scoring model to determine whether a simulation model is valid or not.

Each strategy possesses distinct characteristics which results in that different strategies may be suitable for different validation situations. Detailed introduction to validation strategies selection and their applications on the case study new product introduction system are demonstrated in Chapter 3.

2.4.4.2 Model verification and validation methods

Contributions to model verification and validation methods development include, but not limited to: (Carson, 2002), (Sargent, 2011), (Macal and North, 2005), (Robinson, 1997), (Xiang et al, 2005), (Gilbert, 2010), (Balci, 2010), (Balci, 2012) and others. Distinct validation methods are introduced in the rest of this section. Followed each validation method are examples regarding how this method could be applied to this research. More model verification and validation methods could be found in above literatures and others.

Animation: Simulation model operational behaviour is graphically displayed as the model runs over time. For example, the movements of components or the whole product through the new product introduction system are graphically displayed in a simulation world.

Model to model validation: Outcomes of a simulation model being validated are compared to outcomes of another valid model, regarding the same research problem. For example, simulation results from an agent-based simulation model (to be validated) are compared to outcomes of a (valid) discrete-event simulation model.

Event validity: The events occurrences of the simulation model are compared to those of the real system to determine if they are similar with sufficient accuracy. For example, comparison of the occurrence of assumptions at preliminary design stage in the simulation model with its occurrence in the real world of the case study new production introduction system.

Extreme condition tests: The simulation model structure and outputs should be reasonable for any extreme and unlikely combinations in the real world. For example, if frequency of responses to the information requests from preliminary design team becomes zero, the new product introduction system is definitely collapsed.

Face validity: Asking knowledgeable individuals about the system whether the simulation model and its behaviour are reasonable and acceptable. For example, requiring the case study organisation managers whether the simulation model and its behaviour are reasonable, focusing on specified research interests.

Historical data validation: If historical data exists (or data collected on a system specifically for building and testing a model), part of the data could be used to build simulation model and the remaining data are used to determine whether the model performs as the system does. For example, part of data collected from the case study new product introduction system is used to inform the simulation model development, and relevant data regarding system performance is used to evaluate whether the simulation model performs as system operation in the real world.

Operational graphics: Values of various performance impacting factors, for example, the number of requests issued by preliminary design team, the number of responding issued by detail design team, and the assumptions produced at preliminary design stage, are graphically and dynamically demonstrated in output area of the simulation model. Therefore, the behaviours of the system performance are visually displayed to ensure the simulation model are correct and reasonable.

Sensitivity analysis: This method consists of changing the values of the input data and parameters of a simulation model to determine the effect upon the performance of the model and its output. The same relationship should occur in the simulation model as in the real world system. For example, when detail design team increases the frequency to respond to preliminary design team requests, the assumptions produced at the preliminary design stage should be decreasing accordingly.

Predictive validation: The simulation model is used to predict the system performance, and comparisons are made between the performance produced from the system and the forecast from the model, in order to determine if they are the same or similar enough. The systems input data may come from a real operational system or be obtained by conducting experiments of the system.

Traces: The behaviour of different types of specific entities in the simulation model is traced through the simulation model operation to determine if the model's logic is correct and if the necessary accuracy is obtained. For example, a product design is traced through a simulation model to check if the simulation model is sufficiently accurate to mimic the real world new product introduction system.

Turing tests: Individuals who are knowledgeable about the operations of the system being modelled are asked if they can discriminate outputs between real world system and the simulation model.

2.4.5 Summary

Model verification and validation is an essential part of simulation model development process. Verification process is to determine whether a simulation model accurately represents the conceptual model description and its solution (Thacker et al, 2004). Validation process is to determine which degree a simulation model is an accurate representation of the real world system with respect to simulation purpose (Macal, 2005), (Thacker et al, 2004).

Model verification and validation procedures and validation activity terminologies are still not matured and standardized (Kleijnen, 1995). Another finding is that model verification and validation cannot prove that a simulation model is correct and accurate for all possible applications areas (Chapurlat et al, 2003), (Carson, 2002),(Robinson, 1997), (Kleijnen, 1995). Therefore, simulation model usually focuses on one or few view(s) of a research problem, considering identified simulation purpose. What model verification and validation could guarantee is that the simulation model represents interested view of the reality with sufficient accuracy (Macal, 2005).

Model verification and validation process is a series of validation activities carried out along with the simulation model development process. In this section, both simplified model verification and validation process models and detailed model verification and validation process model were reviewed. Simplified model verification and validation process models were selected for this research, which are further discussed in Chapter 3.

Four model verification and validation strategies were introduced. They are self-validation, co-validation, independent validation, and scoring validation. A series of model verification and validation methods were reviewed and analysed. Model verification and validation strategies and applications in this research are further discussed in Chapter 3. Potential applications of distinct model verification and validation methods to this research were discussed at each end of validation methods.

2.5 Conclusion for Literature Review

Literature review was carried out in four key knowledge domains: new product introduction systems, vicious circles, modelling and simulation techniques, and model verification and validation. The results of reviewing literature and potential contributions to this research are concluded as follows.

New product introduction systems are a series of product development stages a company employs to conceive, design, manufacture, and deliver a new products and services to users (Ulrich and Eppinger, 2012). The functional work teams at each work stage are linked within a complex engineering information communication network. Another characteristic is that new product introduction system is not a sequentially linear system but a complex interactive organizational system, where design iteration is necessitated for the system implementing its design work. In addition, either design iteration (Wynn et al, 2007) or fuzzy gates (Cooper, 2008) inevitably involve rework into the new product introduction systems (Ulrich and Eppinger, 2012). Rework consumes a large amount of design resources, like work team’s time, that might result in more consequences, e.g. vicious circles.

Vicious circles are a kind of social phenomenon that broadly exists in complex organisational processes and systems (Morgan, 2006), (Masuch, 1985), (Gowler and Legge, 1973). Both processes and systems comprises of a series of individuals activities linked within a complex communication network. Information feedback loops are a means of communication within such systems, which is formed by changes occurred within the system and the counter-change automatically generated within the system. Two types of information loops are negative information loops and positive information loops. Negative information loops enable the system goes back to its balance status, while positive information loops amplify the effect of an unintended change within the system, resulting in unintended consequence.

Vicious circles are referring to deviation amplifying feedback loops in the case study new product introduction system. Vicious circles in such large organisational systems consume huge volume of time and cost budget and, at its extreme condition, destroy the entire design system. Therefore, vicious circles and their consequence are dangerous and need to be mitigated, in order to keep the system a stable operational environment. Vicious circles problems and solutions to tackle them are reported in societal systems, but how and why vicious circles arise in new product introduction system is not found in literature.

Modelling and simulation techniques are widely applied in understanding complex organisational systems (Axelrod, 2003). Two modelling and simulation methods used to mimic process systems are discrete-event simulation and agent-based simulation (Siebers et al, 2010). Agent-based simulation method builds a simulation model as bottom-up architecture, which is the same way as a new product introduction system performs in the real world. This is the primary reason why agent-based simulation method was considered in this research. Agent-based simulation method characteristics (Macal and North, 2010), (Garcia, 2005) were concluded as three items:

- A set of agents, with their own characteristics and independent behaviours;
- A set of simulation rule specifications to define how and with whom agents interact; and
- A simulation world, where the agents interact with each other.

A simulation model is built up and validated to represent a real world system, in order to help understanding the reality (Browning, 2009). Simulation model usually focuses on one or few view(s) of the research problem, with respect to specific research purpose. Simulation process is comprised of a series of experimental activities that are carried out to implement the simulation model on the research problems. The simulation process models studied in this chapter have been developed into a research procedure in Chapter 3.

Model verification and validation is an essential part of simulation model development, which is often conducted along with model development process in a parallel way. Model verification and validation cannot guarantee that a model is correct and accurate for all possible applications (Chapurlat et al, 2003), (Carson, 2002),(Robinson, 1997), (Kleijnen, 1995). However, model verification and validation process can provide evidence that a model is sufficiently accurate to represent and understand specific research problems. The model verification and validation process is complete when the sufficiency is reached (Sargent, 2005), (Thacker et al, 2004), (Carson, 2002), (Robinson, 1997). Sargent’s simplified model verification and validation process model (Sargent, 2011) was employed and developed into a part of research methodology in this research.

Four model verification and validation strategies are self-validation, co-validation, independent validation, and scoring validation. Potential applications of distinct model verification and validation strategies to this research are further discussed in Chapter 3. A series of model verification and validation methods were introduced and analysed. Potential applications of distinct model verification and validation methods to the case study new product introduction system simulation model were discussed and suggested. The primary principle of model validation is to apply distinct model validation strategies and methods to different mode development stages.

Chapter 3 Methodology

Research methodology is a plan, structure, and strategy about how to introduce and then address a research problem (Kerlinger and Lee, 1999), (Kumar, 2011). In this chapter, the research architecture is introduced. The research architecture involves two processes i.e. research design process and research validation process, and three research stages i.e. research problem definition, conceptual model building, and simulation model development. A thirteen-step research procedure was developed to carry out research activities associated within the research architecture. Along the research design process, distinct design methods are discussed and applied to different stages involved in the research procedure. A key aspect is the research validation process where different validation strategies are discussed and employed to distinct validation situations in the research procedure. And a series of validation methods are analysed and specified for different validation phases, with implementing the validation strategies selected.

3.1 Research Architecture

The research explored the application of modelling and simulation techniques to build understanding of the vicious circles phenomenon in a case study new product introduction system. Insights gained were used to explore potential management strategies that might mitigate the vicious circles and their consequences.

The overall research architecture is shown in Figure 3.1. Two primary processes involved in the research are research design process and research validation process. In order to achieve identified research objectives, a series of research activities were conducted to explore the research problem and potential solutions. A series of validation activities were then carried out to check the accuracy and efficiency of the simulation models and simulation results, with respect to the real world case study.

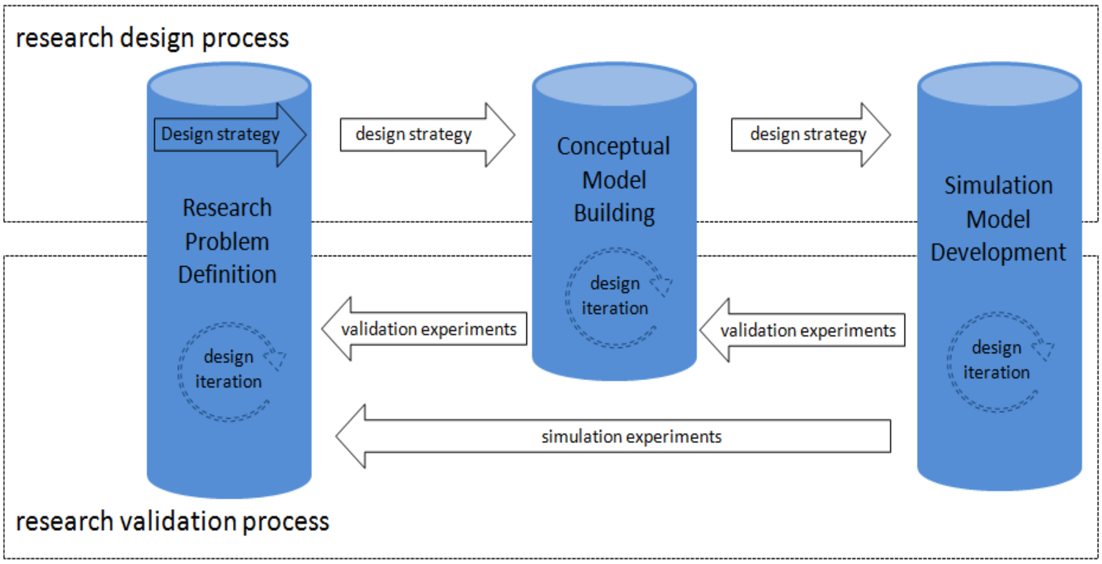


Figure 3.1 Research architecture

Three research stages involved in the research architecture and associated within the two research processes are research problem definition, conceptual model building, and simulation model development. At each research stage, a series of research activities are carried out to design and address the research problem.

- In the research problem definition phase, a case study new product introduction system was analysed, with focus on understanding of the vicious circles phenomenon arisen in the system. By doing so, the research problems was identified to activate the following research activities, with respect to specified research aim and objectives.

- In the conceptual model building phase, a conceptual model flow chart was built up to represent the identified research problem and illustrate logical relationships amongst each elements involved in the systems. In order to make sure the conceptual model represents the research problem with sufficient accuracy, validation strategies and methods were employed and implemented.

- In the simulation model development phase, a simulation model was developed to demonstrate and visualize the conceptual model and explore potential solutions to tackle the real world vicious circles problems. In order to achieve this, a series of validation experiments and simulation experiments are designed and conducted. Finally, potential management solutions were suggested to inform the real world new product introduction system, tackling the impact of vicious circles on the system.

3.2 Research Procedure

Incorporating experiment research method (Adèr and Mellenbergh, 1999), (Neuman, 2007) with simulation research method (Banks, 2000), (Banks et al, 2010), the author developed a research procedure to implement the research activities involved in the research architecture. The research procedure is demonstrated in Figure 3.2.

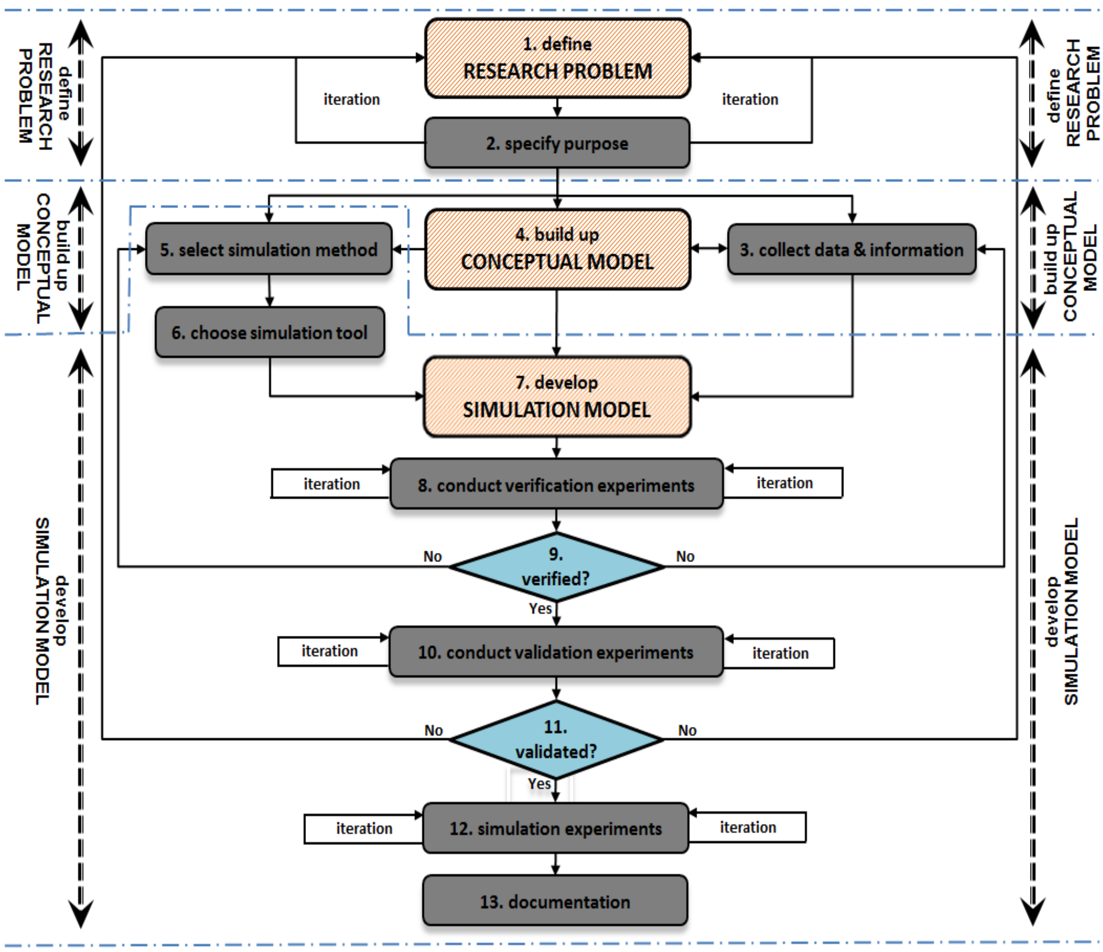


Figure 3.2 Research procedure

The research procedure integrates with two research processes, i.e. research design process and research validation process, and involves three research stages, i.e. research problem definition, conceptual model building, and simulation model development. They were further divided into the following thirteen separate research activities:

1. **Define research problem:** research interest from case study owner part is generated, the real world problem is identified, and expectations from the research results are issued.
2. **Specify purpose:** the research purpose, in the forms of research aim & objectives, is specified.
3. **Collect data & information:** the data and information needed to inform the definition of both conceptual model and simulation model is identified and collected. Data as input to the simulation model is defined and collected.
4. **Build up conceptual model:** a conceptual model is defined and built up with respect to specified research purpose using data and information collected, in order to appropriately represent relationships within the research problem.
5. **Select simulation method:** one modelling and simulation method is specified to represent defined research problem, considering both suitability and feasibility.
6. **Choose simulation tool:** the software tool upon which the simulation model will be built up and conducted is selected, considering both availability and adaptability.
7. **Develop simulation model:** a computer-based simulation model is developed with respect to the defined conceptual model, applying selected simulation method and tool.
8. **Conduct verification experiments:** verification experiments are conducted upon the simulation model, with focus on checking whether the simulation model is a right, reasonable, and reliable model to represent the conceptual model.
9. **Verify the simulation model:** simulation results from verification experiments are reviewed; the simulation model and results are verified

against specified verification methods and measurements. If necessary, steps 3, 4, 5, 6, 7 and 8 may be revisited. By addressing comments, feedbacks, and suggestions from different perspectives, the simulation model is improved and upgraded to conduct next stage of validation experiments.

10. **Conduct validation experiments:** validation experiments are conducted upon revised simulation model. Validation experiments are to check whether the simulation model possesses sufficient accuracy to represent and then address the research problem, with respect to specified research purpose.
11. **Validate the simulation model:** simulation model and results produced by validation experiments are validated against specified validation methods and measurements. If necessary, steps from the beginning may be revisited and redesigned as a result.
12. **Simulation experiments:** simulation experiments are conducted to simulate real world operational scenarios. Simulation results are analysed and discussed. Potential management solutions are issued to address the specified research problems.
13. **Documentation:** instructions and documents supporting the simulation model and simulation experiments are developed, e.g. how to operate the simulation model, how to set input data values, and hot to analyse model results, and so forth. This part of work is necessary for other users or clients to properly understand, modify, or further improve the simulation model if necessary. It also enhances confidence for users applying it to solve the real world problems. A simulation model user manual for operating the simulation model was developed.

Results from these research steps are introduced in Chapter 4, Chapter 5, Chapter 6, and Chapter 7 separately.

3.3 Research Design Process

It could be seen from the research architecture in Figure 3.1 that three design stages are research problem definition, conceptual model building, and simulation model development. On the other hand, different research design strategies possess distinct characteristics and procedures.

Applications of different design strategies to the three research stages are discussed in this section.

3.3.1 Distinct research design strategies

Five research design strategies normally used in social science research are: experiment, survey, archival analysis, history, and case study (Yin, 2009), (McKenzie et al, 1997). Each strategy possesses distinct characteristics to introduce different types of research problems. Table 3.1 provides some suggestions regarding how to specify appropriate research design strategies for different research problems or research activities.

Table 3.1 Research design strategies

This figure is adapted from (Yin, 2009)

#	research methods	forms of research questions	requires control over behavioural events?	focuses on contemporary events?	potential application in the research
1	**experiment**	how, why	yes	yes	simulation model development
2	**survey**	who, what, where, how many, how much	no	yes	
3	**archival analysis**	who, what, where, how many, how much	no	yes /no	
4	**history**	how, why	no	no	conceptual model building
5	**case Study**	how, why	no	yes	research problem definition

3.3.2 Application of design strategies

Three primary design stages involved in Figure 3.1 are research problem definition, conceptual model building, and simulation model development. Research problem was defined by the case study owners. Conceptual model was built up by involving both case study owners and the author, to represent the defined research problem. Simulation model was developed by the author to implement the conceptual model. The instructions of how to apply the design strategies to these research stages are demonstrated in the following subsections, with respect to case study used in this research.

3.3.2.1 Case study method for research problem definition

The research problem definition stage applies a case study method (row 5 in Table 3.1), telling a story about vicious circles in a new product introduction system employed by an international manufacturing organization. A single-case study is identified and defined by the case study owners.

The research problem is about an operational phenomenon in the new product introduction system, i.e. vicious circles. Vicious circles heavily influenced performance and efficiency of the new product introduction system. The gap between current system performance and research expectations was identified, in a form of research aim & objectives. Finally, the research problem is formally stated. Applying case study design strategy, the vicious circles was introduced in a descriptive way. Research problem definition process and discussion are reported in Chapter 4.

3.3.2.2 History method for conceptual model building

Conceptual model building stage uses a history design strategy (row 4 in Table 3.1). Both case study owners and the author are involved in the conceptual model construction, using historical data and information collected from the case study new product introduction system. The focus of this stage is on building up a reasonable conceptual model representing the identified research problem, with respect to case study owner’s interest. The conceptual model is reported and demonstrated in Chapter 5.

The conceptual model is primarily designed by the case study owners. The reasons include: it is the case study owners that identified the research problem; the case study owners possesses better understanding of specifications of the case study new product introduction system; the case study owners finally determines whether the conceptual model is correct or not.

The author is also involved into the conceptual model building stage, which is based on two considerations. The first is that the author should understand the conceptual model definition process, which is necessary for the next stage task of developing a simulation model to implement the conceptual model. And second, co-operation process provides potential opportunities, e.g. communicating the conceptual model relationship specifications with the case study owners. Actually, the author has started to conceive the simulation model development from this stage.

3.3.2.3 Experiment method for simulation model development

Experiment design strategy (row 1 in Table 3.1) is applied to simulation model development stage. The simulation model was developed by the author upon a computer based simulation platform, implementing the conceptual model. At this stage, the author is solely responsible for selecting simulation methods, choosing simulation tools, programming simulation procedure, and testing the simulation model. The simulation model development process and results are reported in Chapter 5.

The reasons why experiment method was selected include two points. First, new product introduction system life cycle is quite long, even more than ten years (Ulrich and Eppinger, 2012), while the PhD program was not able to provide sufficient time resource to carry out field research activities. Modelling and simulation is an alternative technique that has been used for understanding social research problems. By applying simulation experiments, research cycle could be greatly shortened.

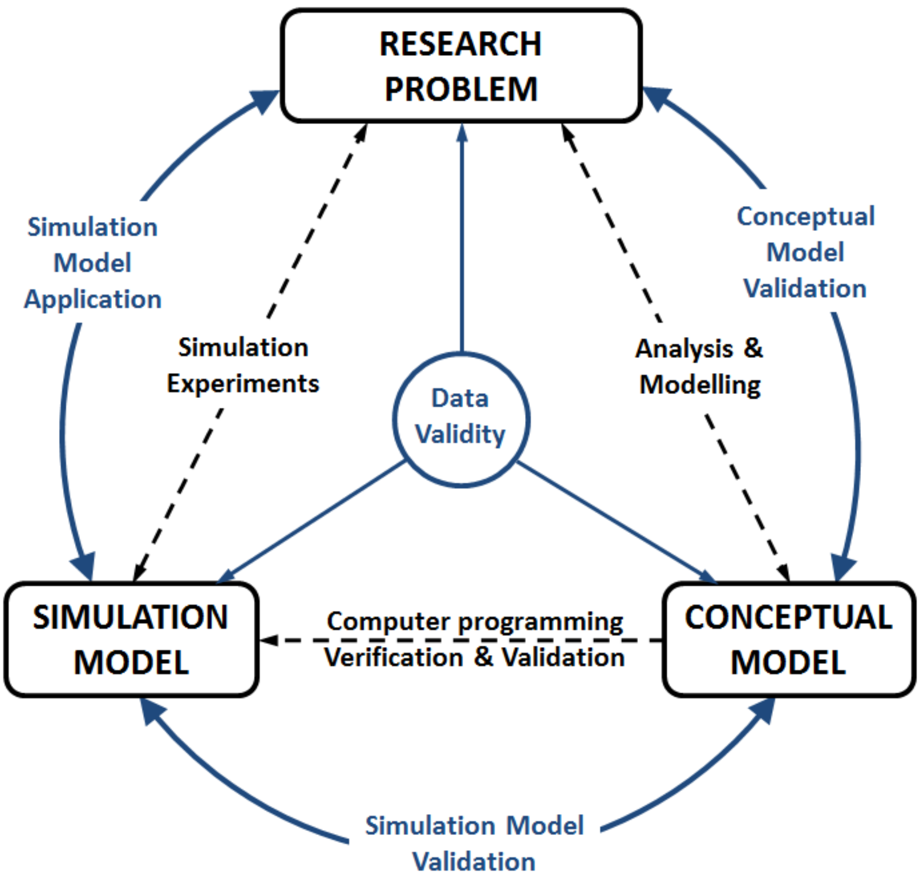
Second, this kind of single-case study research needs repeating the operation system many times, with intent to explore how and why vicious circles arise from the system. It is hard to imagine what a huge cost will be if repeating a real world new product introduction system. While, simulation experiment model enables the same or different operational scenarios repeat again nearly without any additional cost. Therefore, saving cost is the second consideration.

3.3.3 Summary

In the research design process, three design stages are research problem definition, conceptual model building, and simulation model development. As a design principle used in this research, distinct design strategies were applied to different stage of research process. As a result, case study method was applied for the research problem definition, which was carried out by the case study owners. History method was employed for conceptual model building, which was co-conducted by both case study owners and the author. And experiment method was selected for simulation model development, which was solely design and conducted by the author.

3.4 Research Validation Process

Model validation guarantees the model is accurate enough to represent and address the identified research problem, with respect to research purpose and the model application situations. According to research architecture in Figure 3.1, three validation stages involved in the research were: conceptual model validation with the research problem, simulation model validation with the conceptual model, simulation model application on the case study research problem. Model validation diagram developed for and applied in the research is demonstrated in Figure 3.3.



This figure is developed from (Sargent, 2011)

Figure 3.3 Model validation diagram

Conceptual model validation is to ensure the conceptual model is a sufficiently accurate representation of the identified research problem. Simulation model validation makes sure that the simulation model is exactly the right model to represent the conceptual model and address the identified research problem. Simulation model application is to apply the simulation model on the real world research problem solving. Data validity is integrated within the three validation activities, ensuring the data necessitated for the simulation model development is adequate and correct (Sargent, 2011).

Validation principle used in this research is applying appropriate validation strategies to different validation stages, considering characteristics of both validation situations and validation strategies.

3.4.1 Validation strategies

In this section, validation strategies and their distinct characteristics are introduced, and then applications of these strategies at different stages of the research are discussed.

3.4.1.1 Four model validation strategies

Four common simulation model validation strategies are self-validation, co-validation, independent validation, and scoring validation (Sargent, 2011). Model validation strategies application considers research purpose and the model use (Gass, 1993), (Robinson and Brooks, 2010), (Sargent, 2011). The four validation strategies were introduced and analysed in Table 3.2.

Table 3.2 Model validation strategies

This table is developed form (Sargent, 2011)

	self-validation	co-validation	independent validation	scoring validation
conductor	model development team	model development team and project owner	an independent third party	model development team
evaluator	model developer itself	model user	an independent third party	model development team itself
description	The model development team itself makes the decision that	The model user are heavily incorporated with the model	A third party (independent from both model development team and model	Scores are determined considering various aspects of the

	whether the model is valid or not.	development process.	users) decides whether the model is valid.	validation process.
comments	This is a subjective decision. While, it has its own advantages. The model development team itself possesses best understanding of the model.	The validation activity is conducted by both model development team and the model users. This method shortens model development cycles.	Independent assessment is conducted by an independent third party. Model development time and budget greatly increases.	The validation result may be influenced by subjective nature of the method. Over-confidence for a higher score may mislead the model users.

Each validation strategy possesses distinct characteristics, and may be suitable for, and eventually was specified for different applicability situations.

3.4.1.2 Distinct characteristics of validation strategies

One frequently used model validation strategy is self-validation, where the modeller him/herself decides whether the simulation model is valid or not, based on a series of simulation results from various considerations. One advantage applying the strategy is that the model builder possesses better understanding in terms of the model quality and limitations than others. On the other hand, the disadvantage is that the model validation result is vulnerable to modeller’s subjective judgment. Therefore, self-validation may produce a subjective decision (Sargent, 2011). However, it is still broadly used in practice.

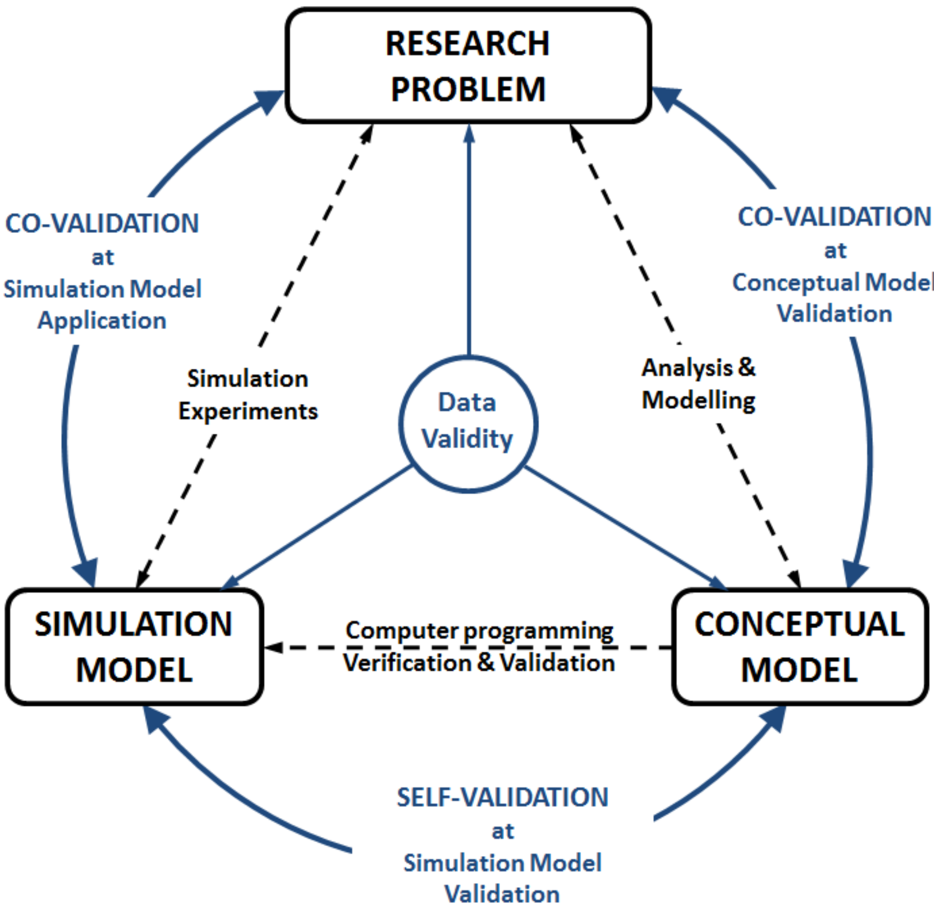
Co-validation strategy involves the model sponsor within model validation process. By doing so, the simulation model sponsor was associated within the model validation process and each decision making. This strategy enables both model development and model validation proceeds in a parallel pattern, which results in a potential advantage to reduce model development cycle. In addition, the responsibility of determining whether a simulation model is valid or not is moved to the model sponsor party by using this strategy. Co-validation strategy could shorten model development time, save cost, and increase model reliability as a result (Sargent, 2011).

Independent validation strategy performs as a total different scenario, which is conducted by an independent third party. The independent validation strategy ensures high credibility of model validation process and validation results. While, the third party is necessary to understand modelling purpose and consider modelling process firstly, and then design and carry out model validation activities. So, independent validation activities could not commence till the model development process entirely completes. As a result, this validation strategy consumes large volume of additional time and budget. Independent validation strategy is suitable for large-scale, long-term, high-budget, and high-credibility model validation projects (Robinson and Brooks, 2010).

Scoring validation method considers different perspectives when users conduct the simulation model (Balci, 1989). While, scoring model is designed, conducted, and analysed by model development team itself. Given no model users were involved in, the scoring validation method is still vulnerable to a subjective validation judgment, which is not often used in practice (Sargent, 2011).

3.4.2 Application of validation strategies

Model validation principle used in the research is to apply different validation strategies onto different validation situations, considering characteristics of both validation activities and validation strategies. In order to clearly demonstrate model validation process, the Figure 3.3 is reproduced in Figure 3.4 and overlaid with validation strategies used at specific stages. Instructions about how to carry out these strategies in different validation stages are introduced in the following subsections.



This figure is developed from (Sargent, 2011)

Figure 3.4 Model validation strategy application

3.4.2.1 Co-validation strategy at conceptual model validation

A conceptual model was built up by the case study owners and the author, by analysing and modelling the identified research problem. Co-validation strategy is applied to check whether the conceptual model is a satisfied representation of the research problem. Two parties involved in conceptual model validation are the case study owners and the author. The reasons why co-validation strategy was employed come from two considerations.

Firstly, the research problem was originally identified by the case study owners, who is acknowledgeable about the research problem very well. And he understood conceptual model specifications that are needed to exactly represent the research problem. Therefore, it is reasonable for the case study owners to be primarily responsible for the conceptual model validation activity.

Secondly, the modeller/author could acquire sufficient model design information for simulation model development, by involving in conceptual model validation. Simultaneously, the author/modeller could make an initial decision whether the conceptual model could be translated into a simulation model based on a computer simulation platform. Therefore, the author/modeller played a supporting role in the conceptual model validation stage.

3.4.2.2 Self-validation strategy at simulation model validation

A simulation model was developed by the author from the validated conceptual model. The purpose of simulation model validation is to make sure the simulation model is an accurate enough representation of the valid conceptual model. As a matter of fact, the simulation model was developed by the author, so it is beneficial for the author to validate it at this stage. Therefore, self-validation strategy was employed at simulation model validation.

The simulation model validation stage includes two validation activities, i.e. simulation model verification and simulation model validation. Simulation model verification is making sure the simulation model is logically correct in terms of model procedures programming. Simulation model validation ensures the simulation model is accurate enough to represent the conceptual model. Both model verification and model validation activities were conducted by the author. Simulation model verification and validation results are introduced in Chapter 6.

3.4.2.3 Co-validation strategy at simulation model application

Simulation model application used co-validation strategy, which involves two parties of the case study owners and the author. Simulation model application is an implementation and test of the simulation model to real world research questions.

Research questions were designed by the case study owners. Simulation experiments were then designed and conducted by the author to address the questions. Simulation results were discussed between the case study owners and the author. As a result, potential management solutions are approved to inform the reality. Simulation model application results are introduced in Chapter 7.

3.4.3 Summary

The three model validation stages involved in the research are: conceptual model validation, simulation model validation (including two activities of simulation model verification and simulation model validation), and simulation model application. Four model validation strategies are self-validation, co-validation, independent validation, and scoring validation. The overall validation principle used in this research is applying distinct validation strategies at distinct validation stages.

As a result, co-validation strategy was applied at the conceptual model validation stage, which was primarily conducted by the case study owners. Self-validation strategy was selected for simulation model validation stage (including two activities of simulation model verification and simulation model validation), which was solely conducted by the author. And co-validation strategy was applied for simulation model application stage, which was co-conducted by the case study owners and the author.

Simulation model verification and simulation model validation results are reported in Chapter 6. And simulation model application and results are reported in Chapter 7.

3.5 Model Validation Methods

In this section, various model validation methods were introduced. Potential applications of the validation methods to different validation activities in this research were discussed.

3.5.1 Validation methods

Contributions to simulation model verification and validation knowledge domain include (Carson, 2002), (Sargent, 2011), (Macal and North, 2005), (Robinson, 1997), (Xiang et al, 2005), (Gilbert, 2010), (Balci, 2010), (Balci, 2012), and others. Simulation model verification and validation methods that were found in literatures and showed potential relevance to the research are:

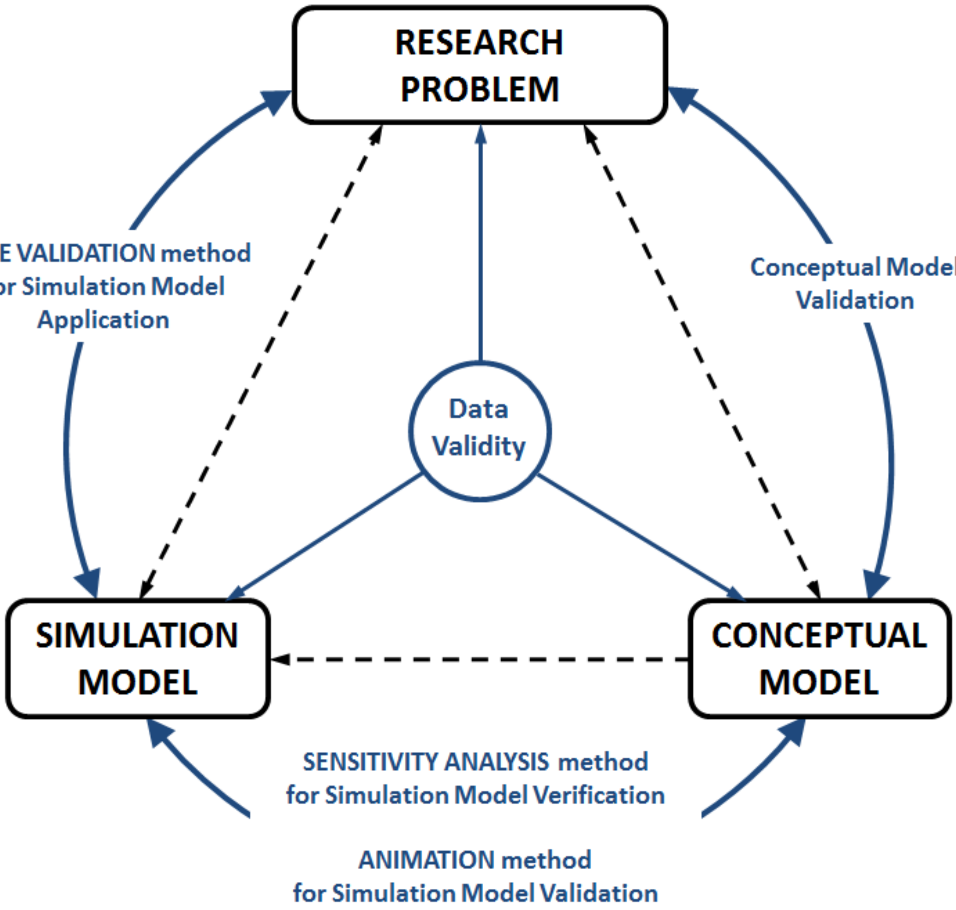
- Animation validation
- Model to Model validation
- Event validation
- Extreme Condition test
- Face Validation

- Historical Data validation
- Operational Graphics validation
- Sensitivity Analysis validity
- Predictive validation
- Traces validation
- Turing test
- Game validation
- And others

Simulation model validation methods have been discussed and explained in Chapter 2 with details. And potential applications of the methods to the case study new product introduction system vicious circles simulation model validation were demonstrated as well. Therefore, there was no more explanation in this section.

3.5.2 Application of validation methods

Three validation activities primarily conducted by the author were: simulation model verification, simulation model validation, and simulation model application. Applications of distinct validation methods to the three validation activities were specified and demonstrated in Figure 3.5.



This figure is developed from (Sargent, 2011)

Figure 3.5 Model validation method application

Figure 3.5 was further developed from Figure 3.4, overlaying with distinct validation methods used for specific model validation activities. Instructions about how to implement validation methods onto the three validation activities are introduced in the following subsections.

3.5.2.1 Sensitivity analysis for simulation model verification

Sensitivity analysis method contains a series of verification experiments, changing the values of input data and parameters of the simulation model to determine the effect upon the model's output. In doing so, a series of verification experiments were designed and conducted by the author.

The simulation model verification process includes three levels of verification analysis, i.e. quantitative analysis, qualitative analysis, and sensitivity analysis. Simulation model verification ensures that the simulation model is logical correct, reasonable, and reliable to represent the vicious circles conceptual model.

Quantitative analysis was used to check whether the logical relationship of impacting factors within the simulation model is right. These impacting factors include requests generated in each work team, responses issued by the work teams, and requests-awaiting-responses in the system. The relationship amongst different impacting factors should perform the same as the simulation specifications. In addition, when the values of input data change as a linear pattern, the simulation model output would be keeping around the same change trend.

Qualitative analysis was used to check whether simulation model agents' operational performance is reasonable, considering the value change of impacting factors. For one example, when the frequency of (detail design team) responses to the requests (generated in preliminary design team) decreases, the requests-awaiting-responses in the system will increase, and the rework volume will increase as well, which further results in low performance of the detail design team as a consequence. In this case, detail design team operational performance, e.g. low performance, was well explained by the impacting factor value change, e.g. responses frequency decreasing.

Sensitivity analysis was used to check whether the simulation model and simulation results are reliable to represent the vicious circles conceptual model. In the way to conduct sensitivity analysis experiment and analysing simulation results, potential solutions to tackle the vicious circles problem were discussed.

In summary, by conducting simulation model verification activities, i.e. quantitative analysis, qualitative analysis, and sensitivity analysis, the simulation model was verified as logically correct, reasonable, and reliable to represent the vicious circles conceptual model. Simulation model verification analysis results are reported in Chapter 6.

3.5.2.2 Animation method for simulation model validation

NetLogo was selected as simulation tool for this research. NetLogo interface provides a simulation world where individual agents interact with each other in a real time pattern under defined simulation specifications, representing different elements in the case study new product introduction system. This type of NetLogo function provides one opportunity of applying animation validation method to test the simulation model (Chan et al, 2010). Simulation model validation activities were designed and conducted by the author.

When the simulation model operates, the information generated and communicated within the new product introduction system was graphically displayed in the simulation world. That is, the requests generated at each work stage and responses issued by the work teams are demonstrated at a real time fashion. The most important, the product's movement through the system is graphically displayed when the simulation model runs. In addition, the rework process could also be demonstrated in the simulation world. All key actions of elements involved in the system could be mimicked in NetLogo simulation world, so animation validation method was selected for simulation model validation activity.

Animation validation process is to observe the simulation model operational behaviours and compare with the verified simulation model operational performance plots. Simulation model validation is further discussed in Chapter 6.

3.5.2.3 Face validation method for simulation model application

Face validation method is employed for simulation model application. Simulation application experiments are to check the efficiency when applying the simulation model to real world research problem solving. The simulation model application process is described as follows.

Firstly, the research questions are identified by the case study owners, with intent to understand and explore the specified vicious circles research problem. Then, the author designs and conducts simulation experiments, providing potential solutions to these questions. The experiment results are analysed and discussed between the author and the case study owners. Finally, potential management solutions according to the experimental results are suggested. Simulation experiments and results are reported in Chapter 7.

3.5.3 Summary

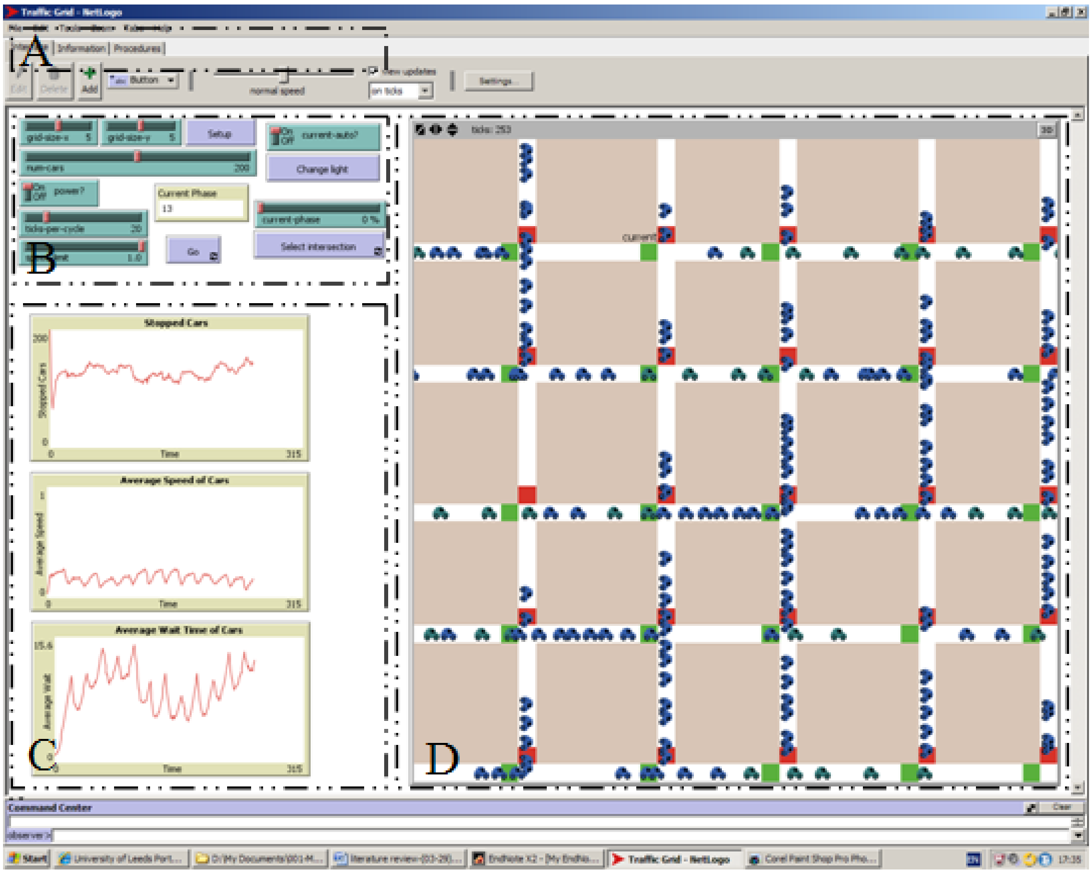
In this section, three model validation activities primarily conducted by the author/model were introduced, i.e. simulation model verification, simulation model validation, and simulation model application. Various model validation methods were introduced and specified for different validation activities, considering different characteristics of validation methods and activities. As a result, Sensitivity analysis was employed for simulation model verification, which was conducted by the author. Animation method was applied for simulation model validation, which was conducted by the author. And face validation method was selected for simulation model application, which was co-conducted by both case study owners and the author together.

3.6 Introduction to NetLogo

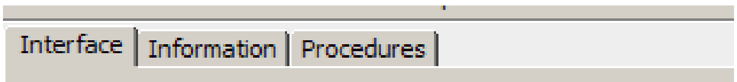
Different simulation methods and tools were introduced in Section 2.3. Both agent-based simulation and discrete-event simulation are dynamic simulation methods that are well-suited to understanding the operational performance of complex systems such as the new product introduction system used in this research. The agent-based simulation method was selected in this research, rather than discrete-event simulation. The primary reason for this selection was that new product introduction systems are driven, in the real world, in a bottom-up architecture where the behaviour of individuals in the system influences overall system performance. That is similar to an agent-based simulation model structure and characteristics. Further details can be found in Sections 5.1 and 5.2 where details of development of the simulation model used in this research are provided.

NetLogo tool was chosen as simulation program for use in this research. NetLogo is a programmable modelling environment for simulating natural or social phenomena (Wilensky, 2009). Another advantage is that NetLogo website provides sufficient self-learning information including, tutorials, model library, user manual, and so forth. Comprehensive information enables both experienced practisers and new users make good use of the tool. Details can be found at URL: http://ccl.northwestern.edu/netlogo/docs/ (Wilensky, 2009).

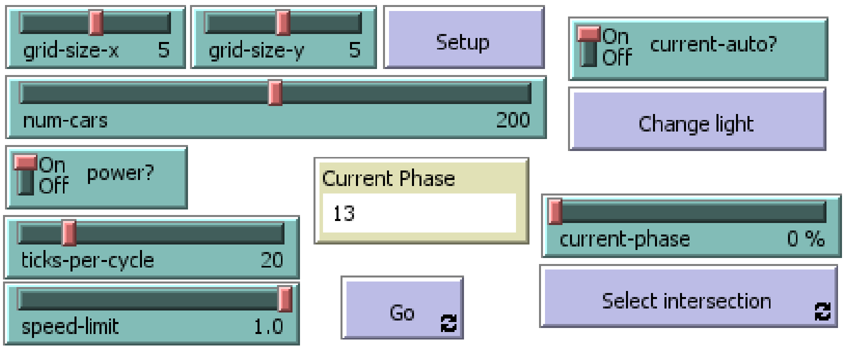
Figure 3.6 illustrates a typical NetLogo simulation model environment (Wilensky 2009). NetLogo simulation program contains three tags: interface, information, and procedures (A). Simulation interface further includes three sections: input and operation area (B), output area (C), and simulation world (D).


A
B
C
D
Stopped Cars
Average Speed of Cars
Average Wait Time of Cars
Command Center

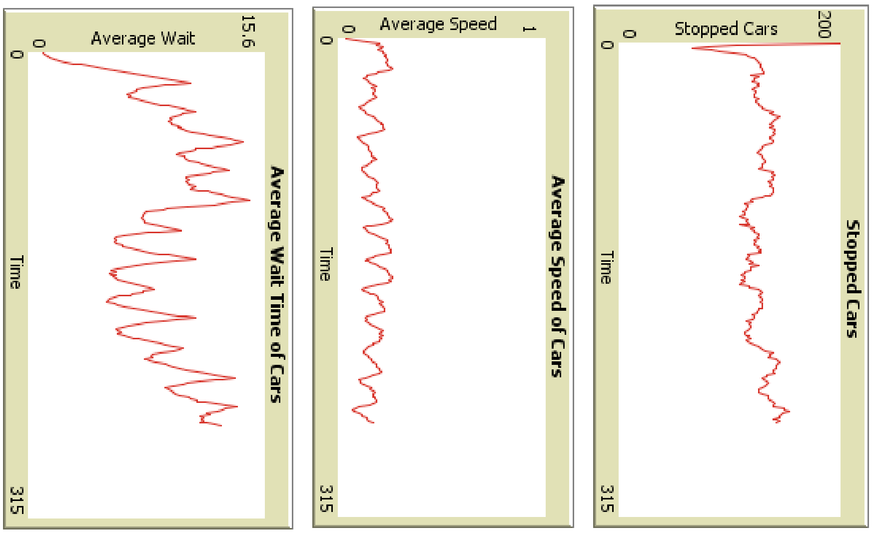
Z


Interface
Information
Procedures

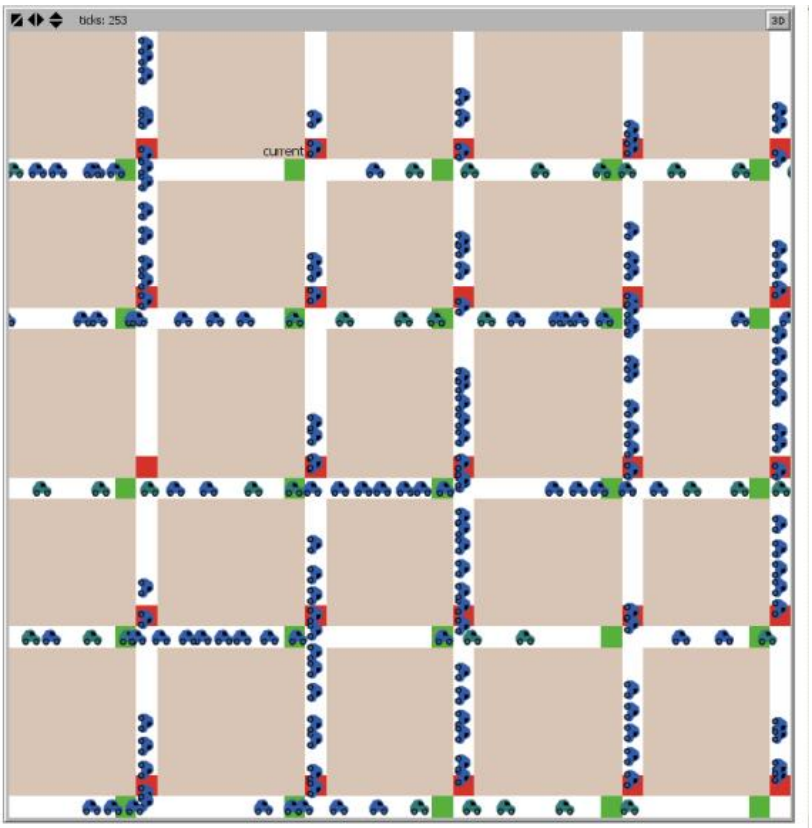
A


grid-size-x 5
grid-size-y 5
Setup
On Off current-auto?
num-cars 200
Change light
On Off power?
Current Phase
13
current-phase 0 %
ticks-per-cycle 20
Select intersection
speed-limit 1.0
Go

B



C



D

This figure is adapted from (Wilensky, 2009) Z: simulation interface
A: interface tags B: input and operation section C: output section D: simulation world

Figure 3.6 Introduction to NetLogo

Within input and operation area, necessary data and information is imported into the simulation model by using various accesses, e.g. sliders, choosers, and input boxes, which further displayed in picture B. Each value could be changed at any time, even when the program runs.

Once the go button is clicked, the simulation model starts running. The independent agents, controlled by simulation rules, interact with each other and exchange information simultaneously. As a result, macro-level system performance is influenced and determined by the micro-level of agent activities is displayed in simulation world D. Simulation results are displayed in output area C in a real-time pattern, in the means of plots box or output box.

Considering functions of output section C and simulation world D, NetLogo program itself enables one potential model validation method, e.g. operational graphics and animation. Details are introduced in Chapter 3, and further discussed in Chapter 6.

3.7 Conclusion for Methodology

In this chapter, the research architecture was introduced, which includes two processes, i.e. research design process and research validation process, and three research stages, i.e. research problem definition, conceptual model building, and simulation model development. A thirteen-step research procedure was developed to implement the research activities involved in the research architecture.

In the research design process, distinct design strategies were employed at different research design stages to introduce and address the identified research problem. As a result, case study method was applied for research problem definition, which was conducted by the case study owners. History method was employed for conceptual model building stage, which was co-conducted by both case study owners and the author. And experiment strategy was applied for simulation model development, which was solely conducted by the author.

In the research validation process, three primary validation stages were: conceptual model validation, simulation model validation, and simulation model application. Four common model validation strategies are self-validation, co-validation, independent validation, and scoring validation. Model validation principle used in the research is applying appropriate validation strategies to different model validation stages.

As a result, co-validation strategy was employed for conceptual model validation, which was co-conducted by the case study owners and the author. Self-validation strategy was selected for simulation model validation, which was conducted by the author. Co-validation strategy was employed for simulation model application, which was co-conducted by both case study owners and the author.

Three validation activities primarily conducted by the author were: simulation model verification, simulation model validation, and simulation model application. Appropriate model validation methods were applied to distinct simulation model validation situations, with implementing validation strategies specified. As a result, sensitivity analysis was employed for simulation model verification, which was conducted by the author. Animation method was applied for simulation model validation, which was also conducted by the author. And face validation method was selected for simulation model application, which was co-conducted by the case study owners and the author.

Agent-based simulation method was selected in this research, comparing with discrete-event simulation approach. And NetLog simulation tool was applied for simulating the case study new product introduction system in this research.

Chapter 4 Case Study: Exploring Vicious Circles in New Product Introduction System

This chapter implements the first four steps of the research procedure defined in Section 3.2: define research problem, specify purpose, collect data and information, and build up conceptual model.

Manufacturing organisations are facing so competitive a market environment that they have to focus on not only excellent product quality but also the performance of the system that develops and delivers both products and associated services to customers. With increasing management scope of the products and services management, the enterprises need extended new product introduction systems that cover the whole lifecycle of the products such as packaging, field installation, maintenance, recycling, and so forth (Grieves, 2006), (Cho and Eppinger, 2001), (Kerley et al, 2011), (Yin and Ma, 2012). This focus further requires new product introduction system managers to consider both products and the enterprises within which new product introduction is carried out. McKay et al (2009) proposed an enterprise engineering framework that builds up the view of an enterprise as an organic entity regarding the whole product lifecycle and different organisation functional aspects (Mckay et al, 2009). (See in Figure 4.1)

	Define	**Develop**	**Deploy**
Purpose	*Mission definition / strategy*	*Action programmes*	*Direction*
Agency	*Enterprise architectures*	*Enterprise operating system*	*Operation*
Products & services	*Product & service architectures*	*Products & services*	*Solutions*

This figure is adapted from (Mckay et al, 2009)

Figure 4.1 Enterprise engineering framework

McKay et al (2009)'s enterprise engineering framework comprises a series of produce development stages where a new product is gradually defined and developed. At each product development phase, different aspects regarding the product itself and the service associated are considered and implemented, e.g. purpose, organisations, and product/services. The core of the enterprise engineering framework is an enterprise operating system that mobilizes people & organisations and their capability to deliver value to stakeholders through solutions. It is a social technical system with which enterprises deliver solutions that meet their stakeholders' strategic intents (Perry, 2006), (Marujo, 2009), (Clegg, 2000), (Clegg, 1997). Due to its organisational characteristics, the enterprise operating system conveys a large volume of interactive product design and development activities (Wynn et al, 2007), (Wynn et al, 2011).

This research used a case study new product introduction system from an international manufacturing organisation. The reason for using a case study was to provide insights on a new product introduction system and its operational vicious circles phenomenon that has a significant adverse effect on performance of the system. As a final goal, the research expectations are to insight vicious circles phenomenon and explore potential management solutions that could mitigate vicious circles problems and their consequences.

With respect to the research design principles specified in Section 3.3, different design methods are applied at different research design stages. In doing so, research problem definition was carried out by using a case study method, and therefore the new product introduction system vicious circles problem is introduced as a descriptive way in Section 4.1. And history method is employed to build up a vicious circles conceptual model, using data and information collected from the case study organisation. The conceptual model was defined and introduced in Section 4.4.

In the rest of the chapter, the case study new product introduction system is introduced. New product development performance criteria related to the case study are specified. The vicious circles research problems is identified. A conceptual model is built up to represent the vicious circles problem. And, at the end of the chapter, conceptual model assumptions are declared.

4.1 Define Research Problem

In this section, the case study new product development process is introduced. Engineering communication system within the case study new product introduction system is illustrated. The new product introduction system operation system is demonstrated. The vicious circles research problem arisen in the case study new product introduction system is defined.

New product introduction system performance focusing on the case study is analysed.

4.1.1 New product introduction systems

New product introduction systems are collections of people and organizations that develop and deliver products and/or services to customers (Ruffles, 2000). In order to achieve a final business goal, product related data and information is collected by the marketing section from potential customer communities. Relevant departments analyse potential business opportunities and product profits, and develop satisfied products to fulfil customers' needs. Finally, the products and associated services are launched to the market and serves destination customers (Grieves, 2006). Within new product introduction process, different functional work teams contribute distinct contribution to the new product development at different design stages (Ruffles, 2000).

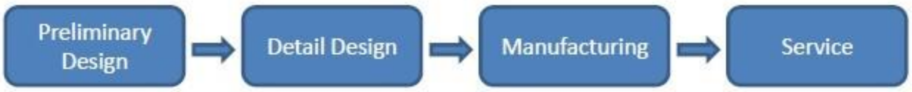


Figure 4.2 Case study new product development process

Figure 4.2 outlines the new product development process, defined as a four-stage process for the new product introduction system case study used in this research. It includes four work teams: preliminary design, detail design, manufacturing, and service. Within the new product development process, work teams at different stages carry out distinct design activities in order to complete product design specifications in an interactive and collaborative way. The design commission responsibility to each work team may vary in different organisations at different regions according to different production specifications. In this case study, each work teams' design commission was specified in Figure 4.3, with comparison with other reference models defined in the literatures (Ulrich and Eppinger, 2012), (Cooper, 2008), (Lloyd, 2006), (Ruffles, 2000), (Challenger et al, 2010).

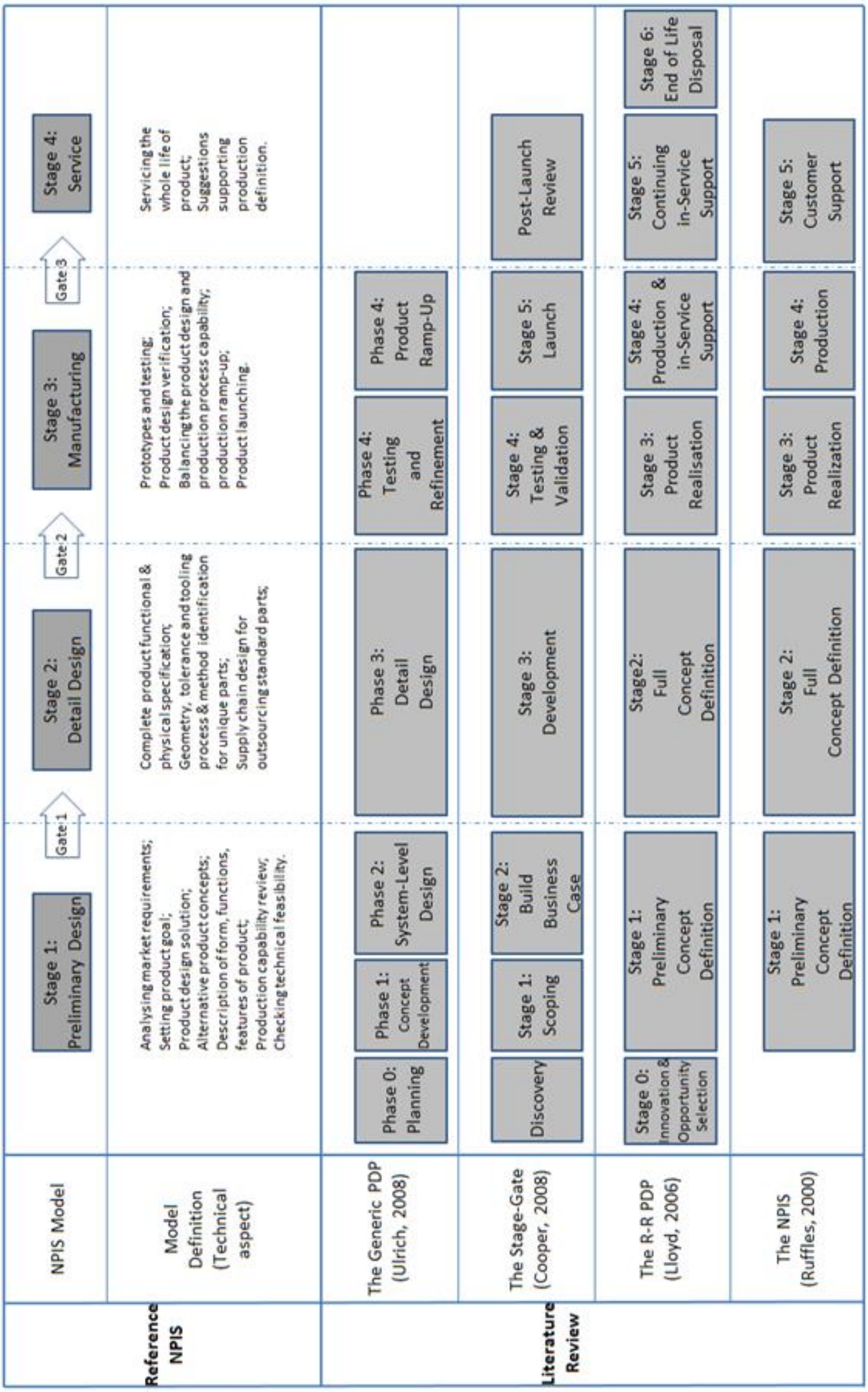


Figure 4.3 NPIS design stage commission

At the preliminary design stage, a series of business activities and investigations are carried out to conceive a potential product development project. For example, business opportunities and requirements are collected from the market, the product development goal is set, product design solution and alternative product concepts are specified, the product form, functions, and features are described, enterprise production capability is analysed, and organisation technical feasibility is verified.

When the product design package proceeds to the detail design stage, the functional and physical specifications for the product and all parts are identified with sufficient details. For those unique parts, the geometry, tolerance, and tooling processes & methods would be specified. For the huge volume of standard components, supply chain network is formed for outsourcing them. Detail design consumes a large proportion of product development time resource, determines majority of the product development budget, and has a great influence on the product quality and the whole system performance. Along with the physical parts and the product delivery through new product introduction system, a large volume of product related information and data is generated and communicated with the system at this stage. Therefore, detail design is a very complex and important product development phase.

At the manufacturing stage, the supply chain is running for outsourcing the standard components, and the unique parts are manufactured, applying specific tooling methods and processes. The product design and production capability is balanced, regarding cost-effectiveness and other factors. Design iteration inside or across work teams might be needed due to various reasons, e.g. design uncertainties involved in the product package, machining method changing, etc. As a result from this stage, product conceptual model is prototyped and tested according to specification documents, product prototype functions are verified applying appropriate testing methods. Finally the production process is implemented and the products are launched to market place.

Once the products and associated services are served to market place, the service section starts its commissions. The final goal is to provide customers with reliable product use, product operation, maintenance, warranty, and other after-sale services. The product service section is usually involving with or partially supported by the detail design work team, because majority of technical documents are primarily created in detail design and manufacturing stages. At the same time, feedbacks and comments from the customers and market would be used as suggestion for the next generation new product development or improvement at the preliminary design stage.

The four functional development stages form a continuous and organic product lifecycle within enterprise engineering framework, supporting sustainable new product development.

4.1.2 Engineering communication system

As demonstrated in Section 4.1.1, the new product introduction system carries out a series of product development activities that associate either physical components delivery or manufacturing information communication. Therefore, two primary interactive subsystems involved in new product introduction system are: material delivery system and manufacturing communication system (Coyle, 2012).

Material delivery system is related to delivery of parts, subassemblies, or the whole machine through the product development system, which is also referring to as supply chain networking in the manufacturing companies (Loch and Terwiesch, 1998). The engineering communication system conveys product related data and information through the system, from product conceive, design, developing, marketing, distribution, maintenance, until recycling (Grieves, 2006), (Cho and Eppinger, 2001). Both material delivery system and engineering communication system interact with each other within new product introduction system, with expectation to develop successful products for destination customers. The engineering communication system and its relationship with the new product introduction system are demonstrated in Figure 4.4.

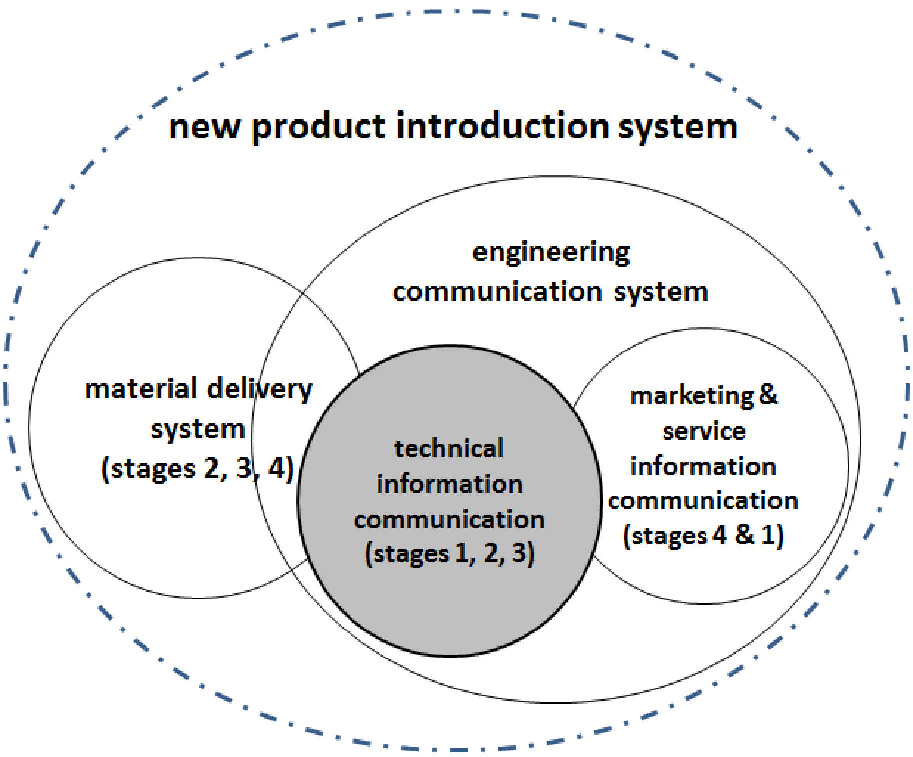


Figure 4.4 Engineering communication systems in NPIS

Focusing technical perspective of the new product introduction system, engineering communication system is primarily linking with product design and development process, which associates with the product development stages 1, 2, and 3 in Figure 4.4. From the marketing and service consideration, the engineering communication system is largely linking between stage 4 and stage 1 in Figure 4.4. The research is focusing on how manufacturing communication performs within the case study new product introductions system, with respect to understand its influence on technical perspective of product development process. Therefore, the research involves the three most related product development phases, i.e. preliminary design, detail design, and manufacturing stages in Figure 4.4.

The manufacturing communication system performs as an iterative system, rather than a linear process. The work team who undertakes the product design commissions often needs design information that is not available at current stage, they therefore have to request information to other work teams at down streams. Both information requests and the colleague's responses to the information requests form closed information loops. However, not all information requests get responded to in the real world operation system due to various reasons. As a consequence, design uncertainties are involved into the new product introduction system. At a particular design stage, the design uncertainties are eventually identified and defined as necessary rework tasks, in order to remove the design uncertainties, progress the product development, and guarantee product quality. The rework consumes extra time resource in the new product introduction system that could be used to responding more information requests which, in turn, might result in more rework needed in future products.

The intent to application of the case study was to explore how the manufacturing communication system performs within the new product introduction system and influences on the new product introduction system performance, therefore this research focused on engineering communication system and its performance.

4.1.3 New product introduction system's operation system

In the case study manufacturing organisation, the new product introduction system involves a series of parallel product design projects located at different design stages of the system at any given point in time. In terms of a specific new product design project, it is driven by predetermined deadlines through the new product introduction system. For example, when the preliminary design work team completes a design project (P1) commission at its work stage on the due date, the design project is delivered to the next design stage of detail design. At the same time, a new project (P2) is carried out at the preliminary design stage of the system.

The new product introduction system becomes more complicated when the design project (P1) proceeds to the third stage of manufacturing on its due date. Simultaneously design project (P2) progresses to the detail design stage on deadline, and another new product design project (P3) is initiated at the preliminary design stage again. The new product introduction system operational view is illustrated in Figure 4.5.

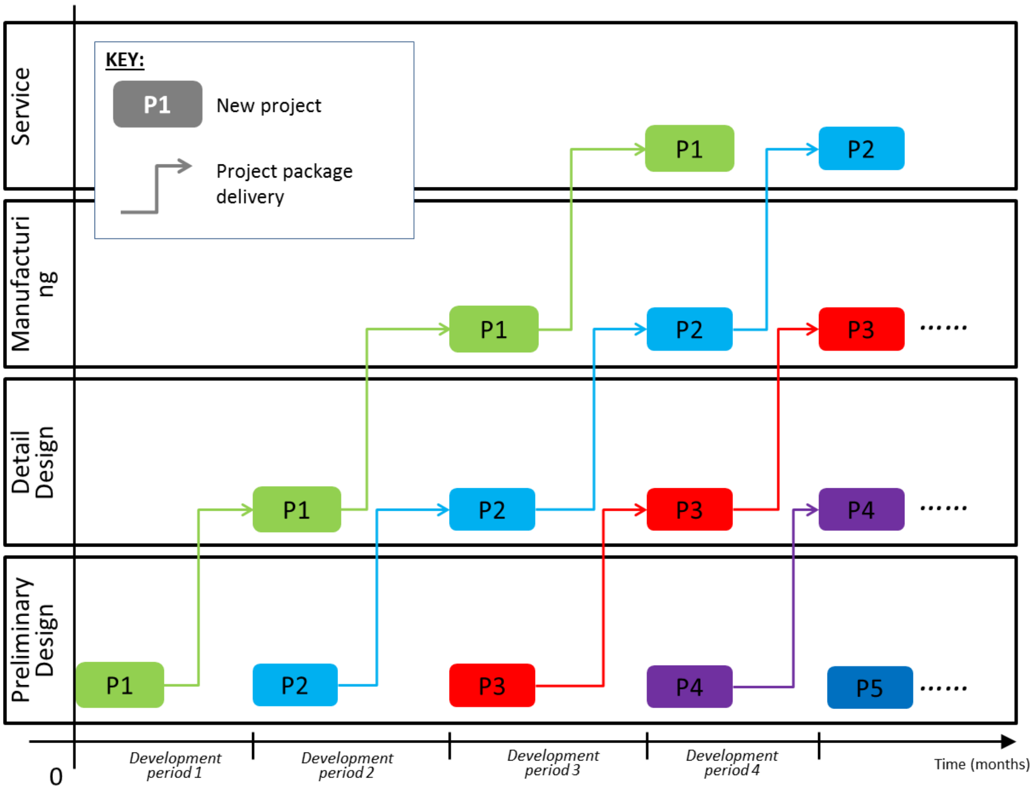


Figure 4.5 New product introduction system

In addition to the product projects delivery from one stage to another through the new product introduction system, product design related information is generated, communicated, and exchanged amongst different design stages regarding different product design packages. One example is that the work team who undertakes the product design project usually needs design information that is not available at current work stage, but might be available from other work teams. Therefore, the work team requests information from their colleagues working at downstream work teams. The colleagues' responses to the information requests enhance product design quality, given they are provided in a timely manner and accurate enough. However, their colleagues are often busy with their own work; this usually results in delays in responses to the information requests. As a result, the information requests that are not responded to in a satisfactory pattern produce design uncertainties, which, at later design stages, are further converted to rework necessitated to resolve design problems caused by the design uncertainties. Observations by experienced practitioners indicated that the volume of research increases with uncertainties in design data associated with limited information being available in the process. However, the quantification of this needs further research.

With a focus on the product design project (P3), information requests generated at each work stage and the responses to them from their colleague work teams are demonstrated in Figure 4.6.

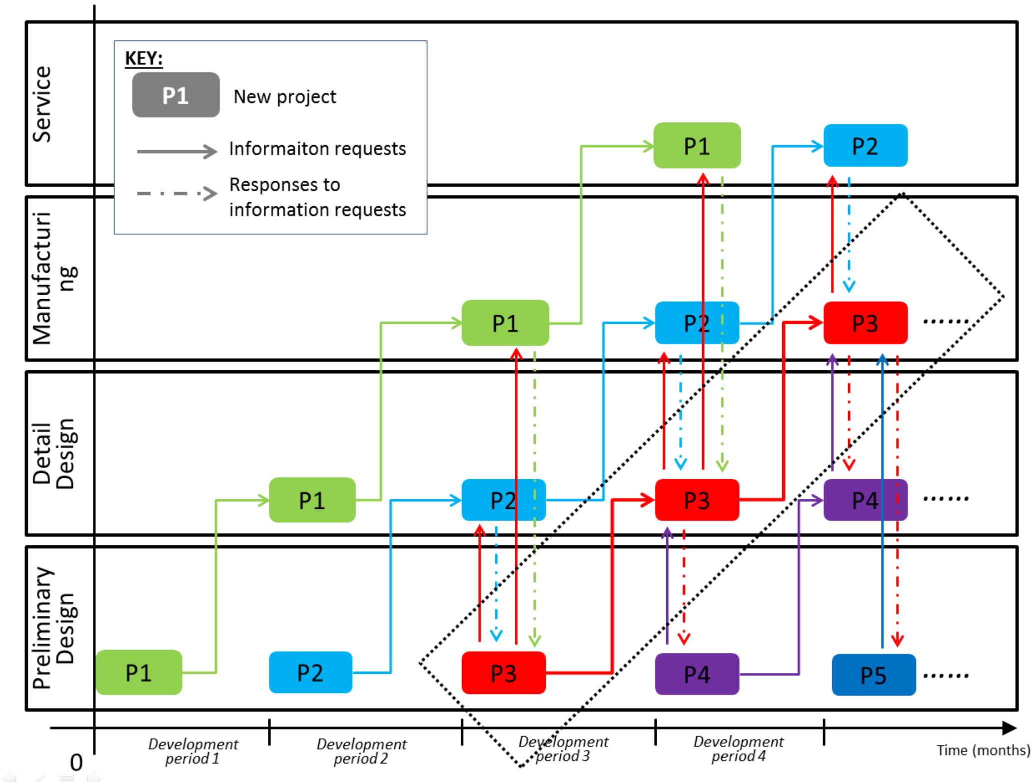


Figure 4.6 Engineering communication in NPIS

The reason why responses (in Figure 4.6) use dash-dot lines is based on the fact that some information requests are not responded to by their colleagues due to various influence factors. Given this situation, the work team has no better choice but to make assumptions for those information requests that do not get responded to. A consequence of this situation is that the product design project includes design uncertainties, which often causes design problems at downstream work teams in a particular design stage. In order to resolve design problems caused by the design uncertainties, downstream work teams have to request rework tasks to work teams who undertake the design commissions.

According to information collected by the case study owners from the case study organisation, all rework identified by the work teams are returned to detail design work team. Given the focus is still on the product design project (P3), the rework linked with the project (P3) within the development process are demonstrated in Figure 4.7.

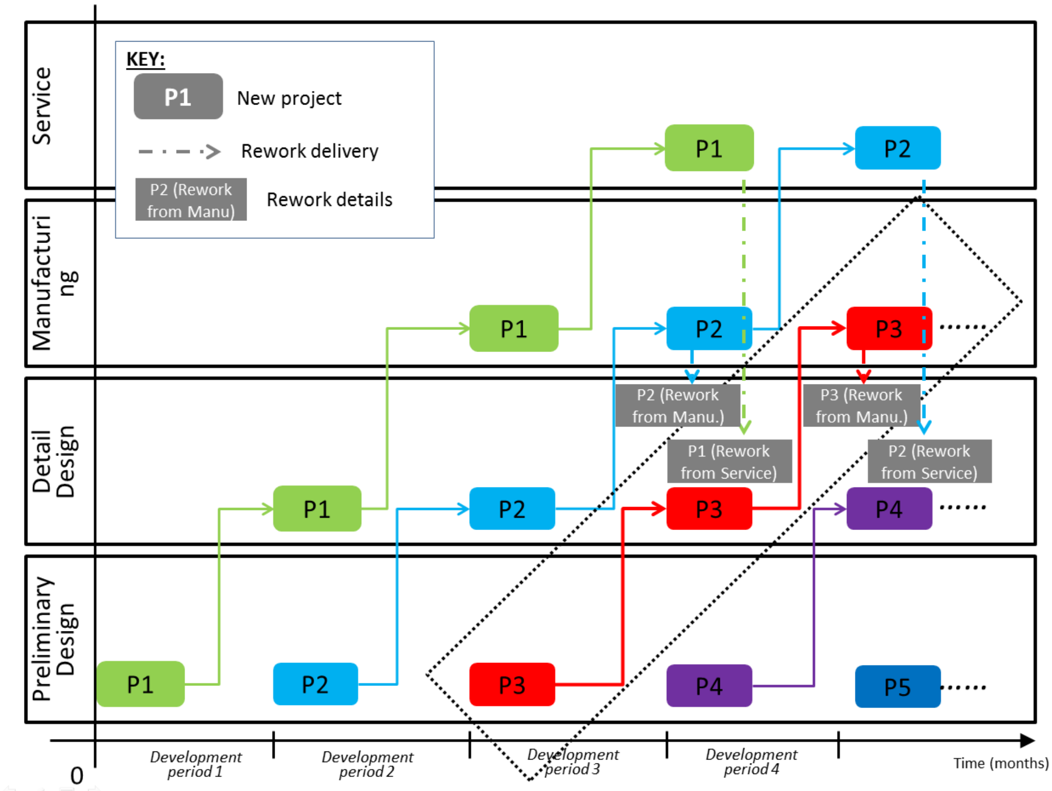


Figure 4.7 Rework in NPIS

In Figure 4.7, the product design project (P3) is influenced by reworks from previous projects (P1) and (P2) at the detail design stages. Similarly, the project (P3) produces reworks that affect itself (P3) and the future projects like (P4). The same pattern happens within the new product introduction system, which is considered as a concerned operational problem by the case study owners. All reworks are returned to detail design work team for completing, the detail design work team is therefore heavily influenced by the rework tasks. Rework associated with design project (P3) and their influence on the future projects is demonstrated in Figure 4.8.

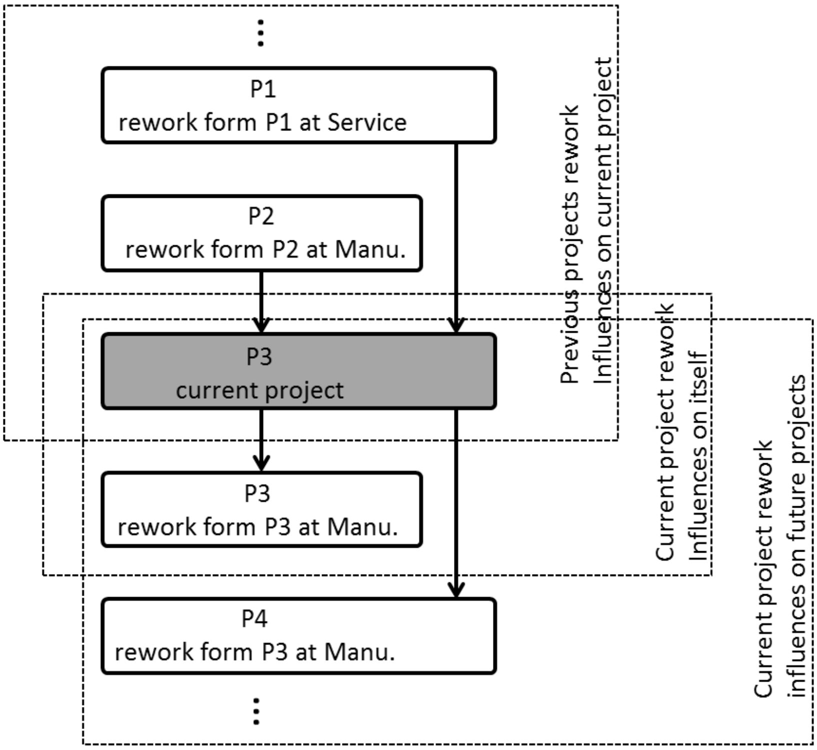


Figure 4.8 Rework and their influence on the NPIS

In the case study new product introduction system, the rework generated within previous projects due to low efficiency of information communication influences the current project which, as a consequence of this situation, results in more reworks that affect the current product development performance and future projects. This kind of deviation-amplifying operational phenomenon arisen in the case study new product introduction system is defined as vicious circles research problem in this research (Garud and Kumaraswamy, 2005), (Masuch, 1985), (Gowler and Legge, 1973).

4.1.4 New product introduction system performance

Considering the case study new product introduction system is a social-technical system, the system performance measurements and impacting factors are availably discussed at two interactive domains: social aspects and technical perspectives.

Regarding social related aspects, there are various system performance impacting factors on the new product introduction system, which dependent with different enterprise architecture and differentiated regions and culture. Toyota’s lean product development system considers the new product development system as a social-technical system, which involves three primary aspects: people, technology, and process (Eckert and Clarkson, 2010). An insight of new product introduction system performance and impacting factors are described as a social-technical hexagon: people, work & structures, systems & procedures, technology, goals & metrics, and culture (Le et al, 2010).

From the engineering perspectives, the case study new product introduction system performance is typically considered from three primary aspects: time, cost, and quality (Turner, 1993), (Krause and Kimura, 1997), (Ulrich and Eppinger, 2012). The product development is considered as a success, if the products are designed on determined schedule, within budget, and meet specific quality requirements.

Considering the case study new product introduction system is a typical complex manufacturing system, this research used the traditional performance measurements. In addition, it was revealed that up to 80% of production design and cost budget is fixed at the early stage of product development process (Layer, 2002). Furthermore, the time related system performance is interested by the case study owners and therefore is focused on in this research. The consideration of time related performance as primary new product introduction system performance measurement was discussed in many literatures and practices (DTI, 1994), (Wynn, 2007), (Challenger et al, 2010), (Kerzner, 2013). Therefore, the new product introduction system performance is referring to time-related perspectives in this research, which is considered as an independent performance measurement from the other two criteria.

The definition of the research scope in this research considers both research problem definition and research purpose specified. First of all, each work team has fixed deadlines for completing their design commissions at their design stages. The engineering communication system of the case study new product introduction system is highlighted in this research, as discussed in Section 4.1.2. Within engineering communication system, the information requests need get responded to within a satisfactory time frame. And both information requests and responses consume the work teams' time resources within the new production introduction system. Due to time pressure on each work team, the information loops, i.e. information requests and responses, often break down.

Low efficiency of information communication produces design uncertainties, which results in design problems at later work stages that further lead to a consequence of reworks are necessitated. Rework consumes more additional time resources within the system, and may trigger the vicious circles problem in the new product introduction system. With respect to research purpose of insight vicious circles phenomenon and explore potential management interventions to tackle vicious circles problems and their consequence, the research scope of time-related performance with the system performance measurement is determined.

4.1.5 Summary

As introduced in above sections, the case study new product introduction system includes a series of functional work teams, which one undertakes distinct design commissions in a collaborative environment (Ulrich and Eppinger, 2012). Two primary subsystems involved in the new product introduction system are: material delivery system and engineering communication system (Coyle, 2012). Material delivery system is referring to as supply chain networking that carries on delivery of physical product and affiliated components through the system (Loch and Terwiesch, 1998). This research focuses on the performance of engineering communication system and its influence on the new product introduction system. Engineering communication system, as core parts of new product introduction system, conveys a large volume of design and manufacturing related information generation and communication (Cho and Eppinger, 2001), (Browning et al, 2006).

Technical perspective of the engineering communication system associates with the first three work stages: preliminary design, detail design, and manufacturing team. Work teams in the new product introduction system often need design information that is not available at the current work stage, but might be available from downstream work teams (Cho and Eppinger, 2001). They therefore request information from colleagues working at downstream work teams. However, their colleagues are often busy with their work and not able to issue ample time to reply the information requests (Challenger et al, 2010). Due to the organisational nature of the new product introduction system (Clegg, 2000), the information requests are often ignored and therefore the information loop breaks down. Under this circumstance, the work team has to make assumptions that usually introduce design uncertainties into the system (Wynn et al, 2011), (Challenger et al, 2010). The design uncertainties cause design problems at downstream work teams and are further identified as rework (Wynn et al, 2007). All rework are returned to detail design work team for implementation.

Rework consumes a large quantity of time resource which, could otherwise be used to responding to more information requests that might result in more rework needed in the future projects. This kind of deviation-amplifying operational phenomenon in the case study new product introduction system is considered as vicious circles (Masuch, 1985), (Garud and Kumaraswamy, 2005).

The case study new product introduction system focuses on the time-related performance. This specified research scope is based on the fact that the engineering communication system performance is highly associated with time management at each work teams, especially when the work team's deadline is predetermined.

4.2 Specify Purpose

The research purpose is to understand how and why vicious circles arise from new product introduction system and explore the impacting factors that result in vicious circles. The final goal is to explore potential management interventions that might mitigate vicious circles and their influence on new product introduction system performance. The research aim and objectives have been demonstrated in Chapter 1.

To the end of addressing the research purpose, four research questions were identified by the case study owners:

1) What if all the information requests are responded to in time?

2) What if none of the information requests are replied by the colleague work teams at all?

3) What if the detail design deadline is flexible within the new product introduction system?

4) What can be done to shorten the new product development cycle?

By addressing the four research questions, potential management interventions in new product introduction system are expected to be issued, in order to mitigate the vicious circles and their consequences.

4.3 Collect Data and Information

Data and information needed to demonstrate the case study new product introductions system and inform vicious circles conceptual model was collected by the case study owners from the case study organisation (Coyle, 2012). The data and information is illustrated in Table 4.1.

Table 4.1 Data collected to inform the conceptual model

The data was collected by (Coyle, 2012)

information	data
How often would preliminary design team request information from detail design team?	~ monthly
How long would it take the detail design team to respond to a request from preliminary design team on average?	~ 4 weeks
How often would detail design actually respond to those information requests?	~ 80 %
How long would detail design team need to respond to an information request from preliminary design team?	~ 2 weeks
How long would detail design work on a new product design takes for first definition?	~ 12 months
On each new design project, how many requests will preliminary design team make on the detail design team?	~ 25

According to research validation method specified in Chapter 3, the conceptual model was primarily built up and verified with the case study owners, and data validity is therefore ensured by the case study owners.

The data and information included in Table 4.1 was parameterised along with conceptual model development in Section 4.4, and further applied to develop a computer-based simulation model in Chapter 5.

4.4 Build-up Conceptual Model

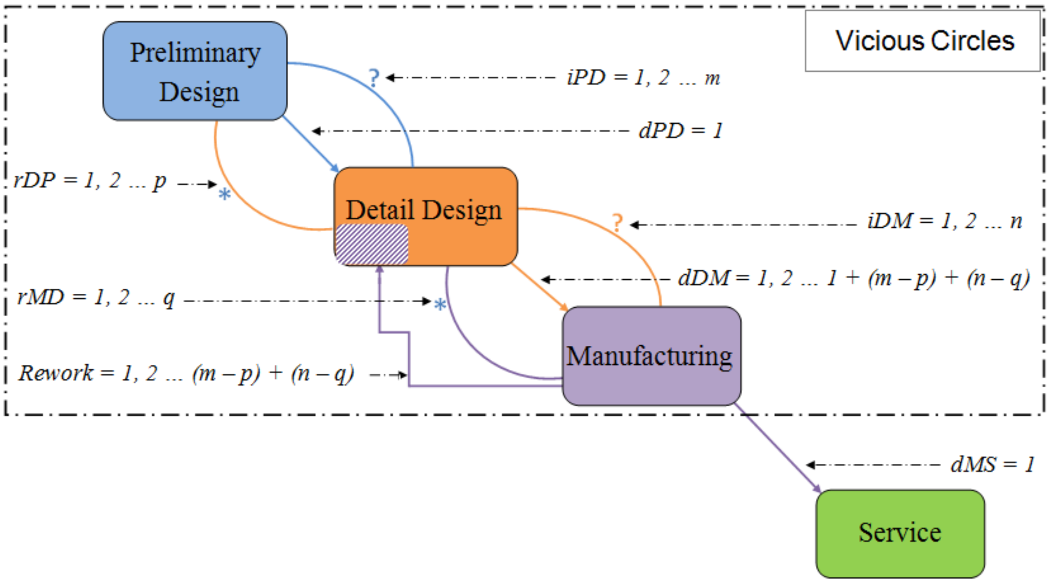
The case study new product introduction system conceptual model includes three work teams: preliminary design, detail design, and manufacturing. When a product design project is carried on through the new product introduction system, the engineering communication system plays an important role of conveying and exchanging information & data related to product design and development. Due to social nature of the new product introduction system, information communication efficiency is influenced and design assumptions are generated within the system. The design assumptions are further converted to design uncertainties when the product design package proceeds to the next stage. Design uncertainties cause problems at the manufacturing stage; therefore rework tasks are identified in order to resolve the design problems. All rework tasks are returned to detail design team for completing no matter which team makes this. Rework consumes large volume of time resource of detail design team. At its extreme condition, the detail design team is not able to complete entire rework within acceptable time frame, which means the new product introduction system breaks down and collapses.

The vicious circles conceptual model focuses on one product design process, i.e. (P3) in Figure 4.6 and Figure 4.7. The conceptual model demonstrates both information requests from the work teams and responses to these requests issued by downstream work teams. In addition, the delivery of product design package is displayed as well. Rework tasks identified by the manufacturing work team are demonstrated.

4.4.1 Conceptual model structure

Figure 4.9 displays a conceptual model operation process of the case study new product introduction system. The conceptual model focuses on the first three work teams, i.e. preliminary design, detail design, and manufacturing work teams. And the service work team was exclusive of the vicious circles conceptual model.

Key reasons behind the identification of this research scope lay in the fact that engineering communication between manufacturing work team and service section is the same pattern with any other two work teams. In addition, the detail design work team consumes large quantity of product design resources, and plays a key role in the new product introduction system, with respect to the vicious circles phenomenon. Therefore, the conceptual model involving first three work teams simplifies the scale of new product introduction system vicious circles phenomenon, without influencing the primary characteristic of the case study new product introduction system.



Key:

- The straight arrows represent the delivery of design package from one work team to another,
- The curved line with a question mark stands for the information request, from the upstream work teams to downstream work teams,
- The curved line with a star mark means the responses to the information requests issued,
- The folded lines are returning of design output, which will require rework of the relevant parts or the whole product design, and
- The shaded area in detail design stage is the time resource consumed for rework.

This diagram was developed by (Coyle, 2012)

Figure 4.9 Vicious circles conceptual model

The parameters used in Figure 4.9 was further defined in Table 4.2. More information and detail could be found in Sections 4.4.2 and 4.4.3.

Table 4.2 Conceptual model parameters definition

parameters	**definition**	**examples**

iPD	Preliminary design team requests information from the detail design team.	If *iPD* = *m*, then preliminary design team requested *m* information questions from detail design work team at preliminary design stage.
rDP	Detail design team responses to the requests from preliminary design team.	If *rDP* = *p*, then detail design team responded *p* preliminary design requests at product preliminary design stage. *(p <= m)* At this stage, the number of design uncertainties in the system is (*m* – *p*).
dPD	Preliminary design team delivered the design package to detail design team.	On due deadline, preliminary design team proceeds design package to detail design work team, therefore, *dPD* = 1.
iDM	Detail design team requests information from manufacturing team.	If *iDM* = *n*, then detail design team requested *n* information questions from manufacturing work team at detail design stage.
rMD	Manufacturing team responses to the requests from detail design team.	If *rMD* = *q*, then manufacturing team responded *p* detail design requests at detail design stage. *(q <= n)* At this stage, the number of design uncertainties generated in the system is (*n* – *q*).
Rework	All design uncertainties found by the manufacturing team will be returned to detail design work team for rework.	The rework volume that should be completed at detail design stage is (*m* – *p*) + (*n* – *q*).
dDM	Detail design team delivers the design package to manufacturing team.	Detail design team proceeds product design package to Manufacturing work team. Considering the rework, total number of design project delivery at this stage is 1+ (*m* – *p*) + (*n* – *q*).
dMS	Manufacturing team delivers the final product to the service section.	Manufacturing team delivers final product package to the service section, therefore, *dMS* = 1.

Figure 4.9 and Table 4.2 demonstrate the conceptual model architecture and logical relationship within the engineering communication system of the case study new product introduction system, with focus on the project (P3) in Figure 4.6 and Figure 4.7. The following paragraphs demonstrate the product development process in a descriptive way.

At the beginning of the project design process, preliminary design team requests information support from people working in other work teams, e.g. detail design team (iPD). The number of requests issued by preliminary design team at preliminary design stage is m. However the detail design team is often so busy with their work that they cannot provide responses quickly enough to the requests (rDP). Before the project package is delivered to the next work stage of detail design team under restrict deadline, the number of valid responses received by the preliminary design team is p ($p <= m$). For the preliminary design team, it has no better choice but to make assumptions for those requests that do not get responded to when the deadline is due. This introduces design uncertainties within the new product introduction system. And as a result, the number of design uncertainties generated at the preliminary design stage is ($m – p$), before the product design package is delivered to next stage of detail design.

The similar situation repeats when detail design stage carries on the product design package. When receiving information requests from detail design team (iDM), the manufacturing team could not issue sufficient time resource or just does not pay full attention to respond to the information requests (rMD). Total number of requests issued by detail design team is n, while total number of responses issued by the manufacturing team in a timely manner and valid way is q ($q <= n$). As a results, the number of design uncertainties produced at the detail design stage is ($n – q$).

When the product design package is delivered to the manufacturing team, they find that parts or the product cannot be manufactured, due to design problems caused by the uncertainties produced at previous two design stages. As a result, the manufacturing team has no better choice but returning the product package back to detail design team for additional rework on it. The reworks are considered as priority tasks and consume large volume time resource of detail design team. At its extreme condition, all of available time resource at detail design team is still not sufficient for completing all rework tasks necessitated. Under this circumstance, the system is assumed out of control and breaks down. Finally, the case study new product introduction system collapses as defined in the conceptual model.

In summary, the conceptual model represents one product design project within the new product introduction system and involves three work stages, i.e. preliminary design, detail design, and manufacturing teams. The conceptual model demonstrates engineering information communication for the specific product and associated services. The conceptual model demonstrated why vicious circles arise in the new product introduction system, and focuses on rework impact on the performance of the system in Figure 4.8.

4.4.2 Conceptual model characteristics

There are no 100% accurate models to represent a social phenomenon, but some models are useful (Kleijnen, 1995). Each useful model has characteristics and applicability fields, according to model definitions and assumptions. Focusing on the case study new product introduction system definition in ChapterChapter 4, vicious circles conceptual model used in this research possesses the following characteristics.

- The new product introduction system conceptual model focuses on one product design project within the case study new product introduction system.

- The conceptual model involves the first three design stages of the product development process, i.e. preliminary design, detail design, and manufacturing phases.

- The conceptual model involves the product design related information communication, e.g. information requests, responding, uncertainties, rework, and so forth.

- The conceptual model focuses on time-related system performance, which was considered as an independent performance measurement from the other two performance criteria, i.e. product development cost, and product quality. In doing so, it is assumed that changing time related management strategy has no influence on product development budget issues and product quality concerns.

- All work teams in the conceptual model are arranged with fixed deadlines, which means the product design package must proceed to the next work team once the deadline is due.

- Each work team involved in the conceptual model requests information to the next work team directly and solely. For example, preliminary design team requests information support to the detail design team, and detail design team enquires information to the manufacturing team.

- All rework tasks caused by design uncertainties are identified by the manufacturing team and returned to detail design work team.

- The project rework influence within the new product introduction system is focused on the current project, as defined in Figure 4.8 and demonstrated in Figure 4.9 and Table 4.2.

4.4.3 Conceptual model assumptions

In addition to the new product introduction system conceptual model characteristics introduced in Section 4.4.2, the author made a series of assumptions when defining the logical relationship within the new product introduction system conceptual model. The model assumptions are defined at the conceptual model development stage in this chapter, and are implemented in the new product introduction system simulation model in Chapter 5. The conceptual model assumptions and limitations are declared as followings.

- At preliminary design and detail design work stages, those information requests that are not responded to timely are converted to design uncertainties when the product design package proceeds to the next stage.

- Before the design uncertainties are detected, they have no influence on any design activities within the system. That is, the design uncertainties produced at preliminary design stage have no influence when the detail design team carries on this project.

- All design uncertainties produced in both preliminary design and detail design stages are resulting in design problems at manufacturing stage.

- The manufacturing team identifies design problems caused by the design uncertainties generated within the two previous stages, and identifies them as rework tasks in order to complete the design project.

- All reworks identified by the manufacturing team are returned to detail design work team, where the rework is considered as priority tasks.

- The case study new product introduction system conceptual model is perfect, if all information requests are responded to in a timely manner. By doing so, there is no design uncertainties involved in the system, no design problem caused, and therefore no rework is needed within the new product introduction system.

- The case study new product introduction system conceptual model is smooth, if the identified rework tasks are entirely completed by the detail design team within a satisfactory time frame. By doing so, a new product is developed, produced, and served to the market place, although the detail design work team performance is influenced by the reworks.

- The case study new product introduction system conceptual model collapses, if the detail design work team is not able to provide sufficient time resource to complete all rework tasks needed within a reasonable time frame. This is an extreme consequence.

4.5 Summary

This chapter introduced a case study new product introduction system employed by an international manufacturing organisation. Engineering communication system within the new product introduction system was introduced. The author demonstrated the new product introduction system operational process, where the vicious circles research problem was defined. The research focuses on time-related new product introduction system performance, with respect to the research problem definition and research purpose.

A new product introduction system conceptual model was built up to represent the vicious circles research problems, using data and information collected from the case study organisation. The author demonstrated the conceptual model characteristics, and declared the conceptual model assumptions and characteristics. Four case study research questions were identified by the case study owners, with respect to identified research purpose.

Chapter 5 Simulation Model Development

This chapter describes the implementation of the steps 5, 6, and 7 of the research procedure defined in Chapter 3, i.e. select simulation method, choose simulation tool, and develop simulation model.

In this chapter, distinct modelling and simulation methods are introduced and compared, and specified for this research. Different simulation tools used to simulate operational systems were introduced, and specified simulation method and tool were selected for the research. Considering key elements of new product introduction systems and key concepts that underpin agent-based simulation methods and tools, a simulation mapping was developed for this research.

Applying specified simulation method and simulation tool, a simulation model is developed to represent the conceptual model defined in Chapter 4, with respect to research problem definition. A simulation model user manual is attached as appendix 1.

5.1 Select Simulation Method

Two common simulation methods used for operational system simulation are discrete-event simulation (DES) and agent-based simulation (ABS). In this subsection, a comparison is made between agent-based simulation method and discrete-event simulation method. Characteristics of the different simulation methods are discussed when applying the methods to distinct research problems. Considering both new product introduction system characteristics and simulation method modeling architecture, a simulation mapping of mirror relationship diagram is developed for this research.

5.1.1 Simulation methods comparison

Agent-based simulation and discrete-event simulation have their own advantages and shortcomings for modelling and simulating specific real-world operational systems (Garcia, 2005), (Smith and Conrey, 2007), (Siebers et al, 2010). The adaptability and applicability of each simulation method depends on the research problem defined for specific research purpose. Therefore, the issue of which one will dominate the next generation of operational simulation community is under discussion, and obviously it is not easy to reach an agreement at the moment (Siebers et al, 2010), (Chan et al, 2010). With focus on the case study new product introduction system defined in this research, Table 5.1 outlines key advantages and availabilities of the two simulation methods: discrete-event simulation (DES) and agent-based simulation (ABS).

Table 5.1 Simulation methods characteristics

This table is developed from (Siebers et al, 2010)

advantages of discrete-event simulation	advantages of agent-based simulation
Top-down modelling approach.	Bottom-up modelling approach.
The focus is on modelling the process system in details.	The focus is on modelling the individual agents and interactions among them.
A centralized system, i.e. one thread of control.	A decentralized system, i.e. each agent has its own thread of control.
Macro system performance is modelled and highlighted.	Macro system performance is not modelled, but emerges from each individual agent's actions, interactions, and decision makings.
Queues are a key consideration.	Queues issues are not defined.
Model inputs are often based on objective data.	Model inputs are often based on theories or subjective data.
The entities intelligence, i.e. decision making, is modelled as part of the model.	Agent intelligence associates with each individual agent characteristics.
Entities are passive to carry on actions and decisions.	Individual agents themselves can take on the initiative to do decision makings.

As described in Table 5.1, discrete-event simulation method is one way to build up simulation models as a top-down architecture, and observe time-based entities behaviour and performance within a system (Siebers et al, 2010). Applying discrete-event simulation method, macro-level system performance is modelled and focused. Each entity within the model is passive to carry on due actions and decision makings through the system, according to specified simulation procedure. Many discrete-event simulation procedures and software have been developed to guide simulation model development and guarantee their credibility (Banks et al, 2010), (Klingstam and Gullander, 1999), (Thunnissen, 2005).

Agent-based simulation method builds up system models as a bottom-up infrastructure (Macal and North, 2007), (Macal and North, 2010), (Heath et al, 2009). Within agent-based simulation environment, individual agents act and interact with each other under specified simulation rules, which could be applied to mimic actions and interactions among different work team in real world organisation (Crowder et al, 2009), (Perry, 2006). Due to the characteristics of agent-based simulation, each individual agent itself can take on the initiatives to carry on independent actions and decision makings. Therefore, macro-level system performance is not modelled, but emerges from individual agent's actions and interactions with each other. Applying agent-based simulation, the macro-level system performance is influenced and finally determined by the micro-level agents' actions, interactions, and decision makings (Macal and North, 2010).

The agent-based simulation method was selected for this research. One reason behind this choice lay in the fact that the real-world situation is regarded by the case study owners as one where each work team (at the micro level) operates as an autonomous entity. Any queues are within the work team entities and so would not be visible in the simulation model. Key decisions made by the work teams influence the behaviour of the whole design system (at a macro-level). For example, a given team can decide how much effort to devote to responding to information requests from other work teams. This has an impact on the information communication system quality and, further influences the new product introduction system performance. Agent-based simulation method is suitable for modelling new product introduction system in this research from this view.

Application agent-based simulation method to understanding new product introduction system performance is a novel research subject. In this research, the author builds up a simulation model to represent the new product introduction system conceptual model defined in Chapter 4, applying agent-based simulation method.

5.1.2 Application agent-based simulation to NPISs

The case study new product introduction system owns three primary characteristics, as introduced in Chapter 4. Firstly, it is comprised of a series of independent but interactive functional work teams (Ulrich and Eppinger, 2012). Secondly, engineering communication system highly associates with new product introduction system and significantly influences the system performance (Cho and Eppinger, 2001). The third and finally, new product introduction system operates in a socio-technical environment in the real world (Perry, 2006). In new product introduction system, macro-level system performance is influenced and determined, as it should be, by the micro-level work team's performance. The three elements forming a new product introduction system are listed in Table 5.2.

Table 5.2 New product introduction system characteristics

NPIS	explanation
who	A series of independent but interactive work teams.
how	The work teams communicate design and manufacturing information with each other.
where	An operational environment.

Agent-based simulation builds up simulation models as bottom-up architecture in a simulation world. Within a simulation model, specific agents act and interact with each other (Macal and North, 2010), (Garcia, 2005), to mimic activities happened among individual agents in the operation system. When interacting with each other, the agents create and communicate information and data through the simulation system. Finally, the macro-level model performance is influenced and finally determined by the micro-level individual agents' performance. With focus on application agent-based method to operational system simulation, three characteristics of agent-based simulation method were concluded in Table 5.3 (Macal and North, 2010), (Garcia, 2005).

Table 5.3 Agent-based simulation characteristics

ABS	explanation
who	A set of individual agents with their own characteristics and independent behaviours.
how	The functional agents act and interact with each other, communicating and delivering information within the model.
where	A simulation world.

Both new product introduction system and agent-based simulation method have similar structure and architecture, with respect to specific research problems and identified research purpose. This research explored application of agent-based simulation method to understand a new product introduction system operation performance. In doing so, the author developed a simulation mapping which demonstrated the relationship between key elements of new product introduction systems and key concepts that underpin agent-based modelling and simulation, based on above discussion. It is demonstrated in Figure 5.1.

	New Product Introduction System	mirror ⇔	**Agent-Based Modelling & Simulation**
who	functional work teams	⇔	individual agents
how	engineering information communication within teams	⇔	information communication amongst agents
where	an operational environment	⇔	an simulation world

Figure 5.1 Simulation mapping

The Figure 5.1 demonstrated mirror relationships between the agent-based simulation architecture and the case study new product introduction system structure, with respect to the research problem specified and research purpose identified in Chapter 4. Within the simulation mapping, each functional work team in new product introduction system could be represented by individual agents in an agent-based simulation model. Large volume of manufacturing information generated and communicated within different work teams could be implemented by information communication within individual agents under specified simulation rule specifications. Finally, the simulation world where individual agents act and interact with each other mimics the real world new product introduction system operation environment. Based on the simulation mapping, this research applied agent-based simulation method to understand the case study new product introduction system research problem.

5.1.3 Summary

This section introduced two common simulation methods for operational system simulation, i.e. discrete-event simulation and agent-based simulation. The advantages and disadvantages of both simulation methods were discussed, considering potential application the simulation method to the case study new product introduction system problems solving. A simulation mapping was developed to demonstrate the relationships between key elements of new product introduction systems and key concepts that underpin agent-based simulation methods. Finally, agent-based modelling and simulation method was employed in this research, with respect to research problem definition and identified research purpose.

New product introduction systems have three primary characteristics: functional work teams, engineering communication system, and operational environment. Agent-based simulations include three key elements, i.e. individual agents, information communication networking, and simulation world. Both characteristics of agent-based simulation methods and new product introduction systems form a mirror relationship that was used in this research to build up a simulation model of the case study new product introduction system.

5.2 Choose Simulation Tool

Agent-based modelling and simulation is still a developing approach to be applied in social related research domains (Gilbert and Bankes, 2002), (Axelrod, 2003), (Smith and Conrey, 2007), (Heath et al, 2009). Agent-based simulation has a symbiotic relationship with computing technology (Gilbert and Bankes, 2002). At its early development phase, diverse simulation platforms, methods, tools, and language are developed, which has advantages on maturity of the agent-based simulation methods (Gilbert and Bankes, 2002), (Heath et al, 2009).

The application of agent-based simulation methods and tools to distinct operational systems are reported in many literatures (Macal and North, 2010), (Heath et al, 2009), (Sklar, 2007). And many agent-based simulation methods application to distinct applicability are reported, for example, Repast (Macal and North, 2010), JADE (Perry, 2006), (Sim et al, 2009), NetLogo (Barbosa and Leitao, 2011), (Garcia, 2005), Spread sheets (Macal and North, 2007), and others (Heath et al, 2009).

NetLogo was selected in this research. The reasons why NetLogo is selected may be varying in general, but is clear in this case study research. The primary reasons include the followings:

- NetLogo was firstly introduced by the supervisors, and early research results are promising;
- Documentations and self-learning tutorials are well organised and free downloadable from the website (Sklar, 2007);
- It was developed by high level language Java, which means simple codes express complicated relationships in the model (Wilensky, 2009);
- It provides a user forum, where up-to-date publications related to NetLogo application are listed and shared (Wilensky, 2009);
- Graphics functions for plots and controls are built in (Gilbert, 2010);
- The animation function of NetLogo could be used for model validation in later research stage; and
- The NetLogo software is available for free download.

NetLogo is one of agent-based modelling and simulation software (Wilensky, 2009), (Sklar, 2007). It is built upon Java-based programming language environment. NetLogo software possesses typical characteristics of agent-based simulation methods. The NetLogo software architecture includes three primary elements, i.e. a series of functional agent, information communication networking, and a simulation world. Within the simulation world, the NetLogo interface includes three primary functional sections, i.e. model input section, simulation world, and model output section, which are introduced with details in Section 5.3.

With respect to the case study new product introduction system, NetLogo provides sufficient functions regarding modelling and simulating operational process of the case study new product introduction system. The parameters' value is imported from the model input section. The conceptual model logical relationships amongst different work teams are implemented by model procedure. And the simulation world demonstrates system operational process, which was considered as potential simulation model validation method in Chapter 3.

5.3 Develop Simulation Model

In this section, the simulation model architecture and model parameter definitions are demonstrated. Simulation model performance measurements are defined. Three primary sections of the simulation model interface, i.e. model input section, simulation world, and model output section are introduced. Simulation rule specifications that guide the simulation model operation are specified.

5.3.1 Simulation model concepts

In this subsection, the new product introduction system simulation model interface is generally introduced. The simulation model performance measurements are discussed.

5.3.1.1 Simulation model structure

Applying agent-based simulation tool NetLogo, a simulation model was developed, to implement the case study new product introduction system conceptual model. It is demonstrated in Figure 5.2.

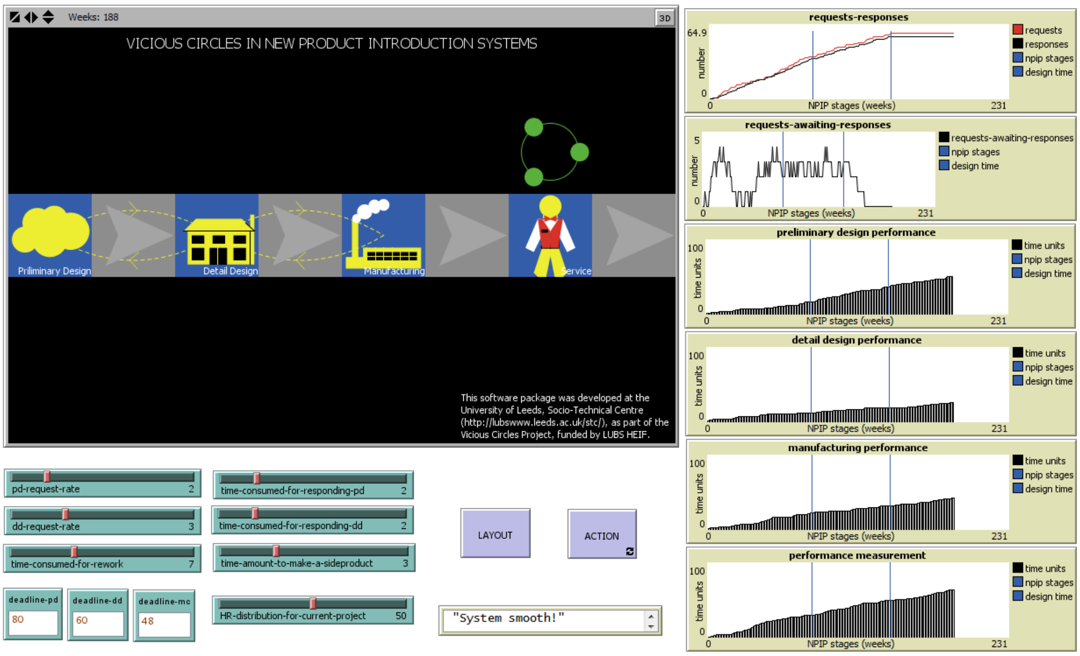


Figure 5.2 Simulation model interface

The model interface includes three primary sections: model input section (left bottom), simulation world (left top), and model output section (right hand). Functions for each section are illustrated as follows:

- Model input section, where model parameters value specified for the conceptual model are initialed and imported to the simulation model;

- The simulation world, where individual functional agents act and interact with each other under simulation rule specifications defined. The new product introduction system operation process is graphically demonstrated; and

- Model output section, where new product introduction system performance related to the system level (macro-level) and team level (micro-level), i.e. information requests, responses, design uncertainties, and rework are reported.

5.3.1.2 Simulation model architecture

The simulation model includes three work stages of new product introduction system, i.e. preliminary design, detail design, and manufacturing, with respect to case study description and conceptual model definition in Chapter 4. The simulation model focuses on time-related performance of new product introduction systems, in order to reveal impacting factors on the case study new product introduction system operation scenarios. In this simulation model, one new product development project is presented, i.e. the P3 project demonstrated in Figure 4.6. Time related issues, e.g. rework and its influence on the design system, are simulated and demonstrated by using this simulation model.

The simulation model interface and structure are presented in Sections 3.6 and 5.3.1.1. The original NetLogo programs code is attached with the Thesis as an Appendix. The description of simulation rules and decision-making mechanism is demonstrated in Table 5.4.

Table 5.4 Simulation rules and decision-makings

elements	simulation rules and decision-making
preliminary design	The preliminary design work team is presented by one agent in the simulation model, who carries out preliminary design of product development commissions. It undertakes daily design activities and request information to detail design team, according to definition of the case study conceptual model in Chapter 4.
detail design	The detail design work team is presented by one agent in the simulation model, who carries detail design tasks of new product development. It undertakes normal design jobs, provides responses to the information requests from the preliminary design team, and requests design information to the manufacturing team when necessary. Another primary role of detail design team is that the reworks produced in later stages will be returned to detail design and completed here, according to definition of the case study new product introduction system description in Chapter 4.
manufacturing	The manufacturing team is presented by one agent as well in this simulation model. The manufacturing team completes manufacturing related commissions of the product development. It undertakes daily works, and replies information requests from detail design team. Another important role of manufacturing is that all

	design uncertainties are detected in this stage and defined as rework requests to detail design team.
time resources allocation	The simulation model was designed as a pre-determined deadline pattern. Each work team proceeds the design project to the next stage. The proportion of time resource allocated for the current project could be set and adjusted in the model input section.
priorities management	For each work team, the rework-related tasks are highest level of priorities. And the priority level of response to information requests could be modified in the programing.

Furthermore, simulation model input parameters definition is illustrated in Table 5.5, and simulation rule specifications are given in Table 5.7.

5.3.1.3 Simulation model performance measurement

In the simulation model, the work team who undertake the design commissions devote a specific proportion of time resource on the project, and the rest of time is available for other duties, for example completing other design commissions. The amount of spare design time resources is flexible within each work teams according to specific operation situation happened with each work team. The volume of spare time maintained within each work team is considered as a performance measurement of the work teams in this simulation model. That is, the work teams with more flexible spare time resources have better performance.

5.3.2 Model input section

The model input section in Figure 5.2 is enlarged in and displayed in Figure 5.3.

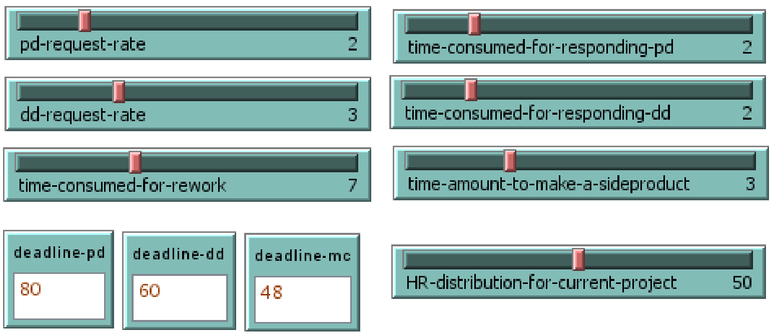


Figure 5.3 Model input section

Model input parameters in the Figure 5.3 were defined and explained in Table 5.5.

Table 5.5 Model input parameter definitions

parameter	definition	example
pd-request-rate It is related to preliminary design work team.	How often the preliminary design team requests information from detail design team?	If pd-request-rate = 3 then, on average, the preliminary design team requests information from detail design team every three weeks.
time-consumed-for-responding-pd It is related to detail design work team.	How long would it take the detail design team to respond to a request on average?	If time-consumed-for-responding-pd = 2, then the detail design team spends approximately two weeks to respond to a request from preliminary design team.
dd-request-rate It is related to detail design work team.	How often the detail design team requests information from manufacturing team?	If pd-request-rate = 3 then, on average, the detail design team requests information from manufacturing team every three weeks.
time-consumed-for-responding-dd It is related to the manufacturing work team.	How long would it take the manufacturing team to respond to a request on average?	If time-consumed-for-responding-dd = 2, then the manufacturing team spends approximately two weeks to respond to a request from detail design team.
time-consumed-for-rework It is related to detail design work team.	The amount of time resource consumed by the detail design for each rework.	If time-consumed-for-rework = 10, then the detail design team spends around ten weeks to complete a rework task.
time-amount-to-make-a-sideproduct It is related to all work teams.	This is the time unit to measure spare time maintained with work teams.	If time-amount-to-make-a-sideproduct = 3, then a time unit is 3 weeks in this simulation model.
deadline-pd		

It is related to preliminary design work team.	The time amount for the preliminary design team to complete their design commissions for a new product design project.	If deadline-pd = 80, then the preliminary design team should complete and deliver the product design results within eighty weeks.
deadline-dd It is related to detail design work team.	The time amount for the detail design team to complete their design commissions for a new product design project.	If deadline-dd = 60, then the detail design team should complete and deliver the product design results within sixty weeks.
deadline-mc It is related to the manufacturing work team.	The time amount for the manufacturing team to complete the design commissions for a new product design project.	If deadline-mc = 48, then the manufacturing team should complete and deliver the product design results within forty eight weeks.
HR-distribution-for-project It is related to each work team who undertake the current product design commissions.	The percentage of time resource for each work team devoting into the new product design project.	If HR-distribution-for-project = 50, then the work team undertaking the current project allocates 50% of total time resource for the product design. The maximum value is the variable is 100.

5.3.3 Simulation world

NetLogo provides a simulation world where the case study new product introduction system operation process is represented. The operational process of the new product introduction system was graphically demonstrated in the simulation world when the simulation model runs. The simulation world is shown in Figure 5.4.

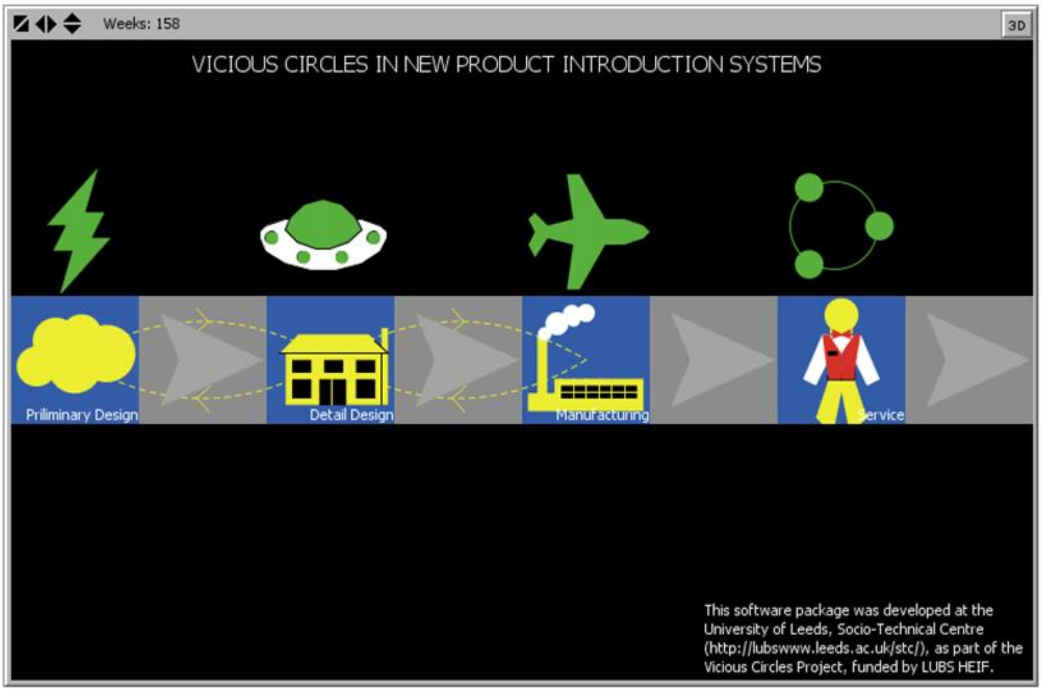


Figure 5.4 Simulation world

In simulation world, the Cloud icon represents the preliminary design work team, the Building icon stands for the detail design work team, the Factary icon represents the manufacturing work team. The Technician for the service section, which is not included within the scope of the research. The product displays different shapes when it locates at different design stages. For example, the product shows a Lighting shape when it is at preliminary design stage, it is a UFO shape when at detail design stage, an Airplane shape at manufacturing stage, and a Service Circle at in-service section.

When a product design project allocates at different new product introduction system stages, distinct design activities are carried out in order to coplete product design commisions discussed in Chapter 4. For example, when the design package is at preliminary design work team, represented by the Lighting icon, the preliminary design team carries on their design commisions. However, they often find some design information is needed but not available at current design stage. They therefore request information from the detail design work team, who is usually able to issue sufficient time resource to respond to the requests within a satisfactory time frame. While, the information requests sometimes are not responded to in a timely way or simply ignored by the work teams due to various reasons. The preliminary design team has to make assumptions for those information requests that are not responded to before deadline. When the deadline-pd is due, preliminary design team delivers the product design project to the next work stage of detail design work team, involving the design assumptions. The design assumptions are further converted to design uncertainties at the detail design stage. The same patterns go on through the design system untill the product design project proceeds to the manufacturing team.

The manufacturing team finds they can not manufacture relevant parts or the whole product due to design problems caused by those design uncertainties. The manufacturing team has no better choice but to identify these design problems as rework, and return them to the detail design work team for completing. According to the conceptual model assumptions, the detial design team considers the rework as priority task, implements them as soon as possible, and delivers them to the manufacturing team again. This kind of rework activities may occur many times between the manufacturing and detial design teams, regarding how many design problems are generated within the product development process.

All design information and activities related to the product development process are recorded and graphfically demonstrated in the simulation world in this simulation model. For example, the information requests, responses, product design delivery, rework, and so forth. This kind simulation world function demonstrate the new product introduction system operational process in a real time fashion, and enables visualisation the performance of the new product introduction system. With respect to NetLogo performance visualisation function, a animation method was considered as potential simulation model validation approach in Chapter 6.

5.3.4 Model output section

When the simulation model runs, a series of performance plots are produced in the model output section, including both macro-level system performance and micro-level work team performance. Given the model inputs are as in Figure 5.3, the model outputs generated are displayed in Figure 5.5.

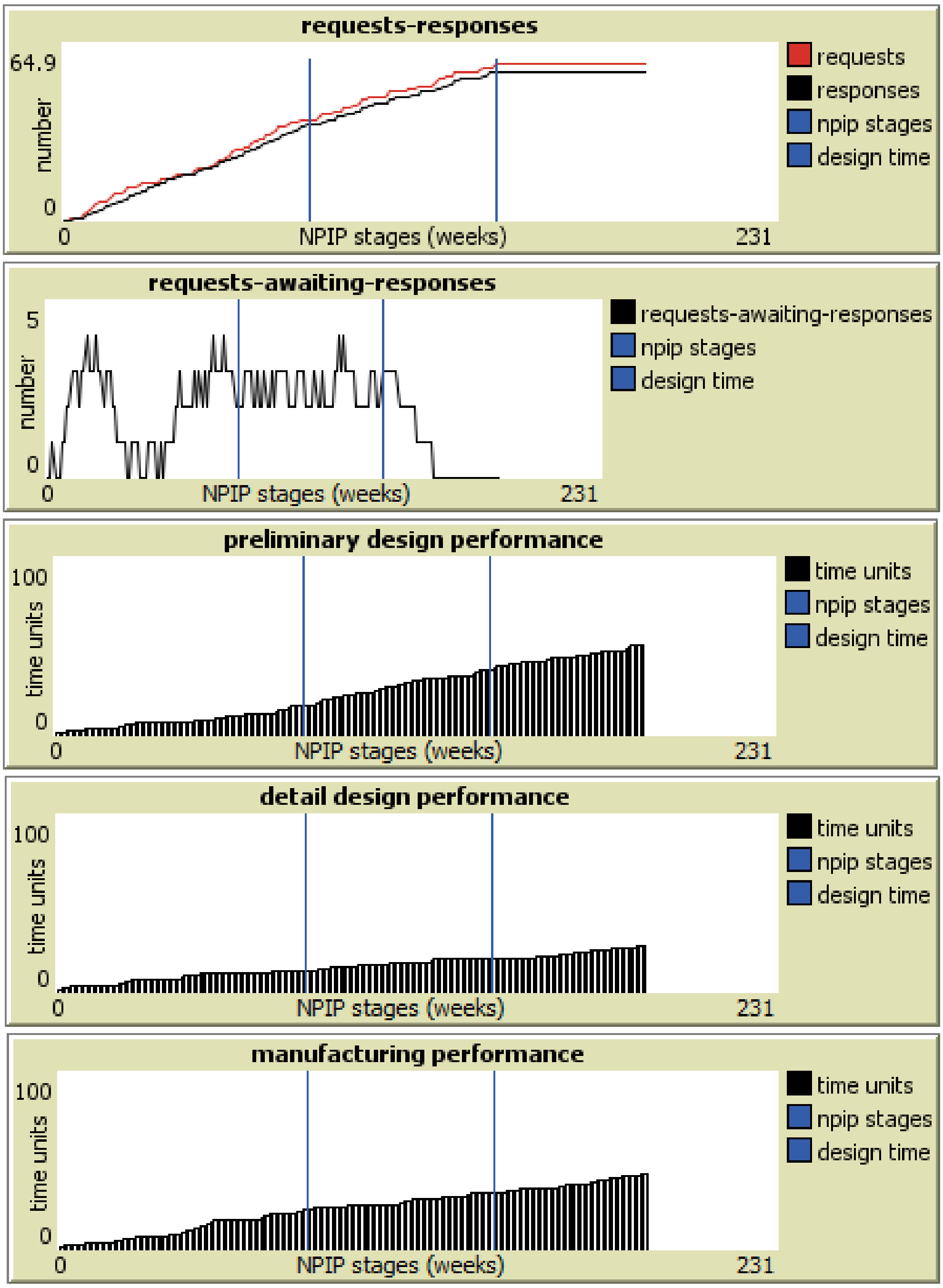


Figure 5.5 Model output section

In Figure 5.5, the X axes of each plot stand for different product development stages, i.e. preliminary design stage, detail design stage, and manufacturing stage. They are separated by two vertical blue lines. In the top two system-level performance plots, the Y axes are numbers of occurrence of the parameters. In the three team-level performance plots, the Y axes are time unites that are free and available for other activities in this case study.

The top two plot boxes in Figure 5.5 display system-level performance. That is, they demonstrate the numbers of requests, responses, and requests-awaiting-responses generated as the product development process progresses. The difference between requests curve and responses means those requests do not get responded to. The requests-awaiting-responses are converted to design assumptions at the current work stage, which are further identified as design uncertainties at the next work stage. The design uncertainties result in design problems at the manufacturing stage, and finally are identified as reworks that are returned to detail design work team. The rework consumes detail design work team additional time resource.

The following three plot boxes in Figure 5.5 display team-level performance, including the preliminary design, detail design, and manufacturing work teams. Each work team performance is measured by the free time resource volume maintained within each work team as the product design project passes through the system. Therefore, the research associates work team performance with free time resource maintained within each team work. For example, a work team has better performance if the work team has more available time resource for carrying out other product design activities. For this model output, the detail design work team performance is worse than the other two work teams, because the available time resource possessed by detail design team is less than the other two.

In terms of system general performance, there are three levels defined in this simulation model, i.e. system perfect, system smooth, and system collapse. They are defined in Table 5.6.

Table 5.6 System general performance

system performance	explanation
perfect	All information requests are responded to in a timely manner and satisfactory pattern. There is no design uncertainties involved in the system, no design problem caused, and therefore no rework is needed with the new product development.
smooth	All rework tasks are entirely completed by the detail design team before product development deadlines. The new product is developed, produced, and proceeded to the

	service section, although the detail design work team is influenced by the rework tasks.
collapse	The detail design work team is not able to provide sufficient time resource to complete all rework tasks needed within a reasonable time frame, therefore the new product introduction system breaks down.

In the simulation output of Figure 5.5, the new product introduction system produced design uncertainties at preliminary design and detail design work teams. Further, the design uncertainties resulted in design problems that were identified as rework tasks by the manufacturing work team, and returned to detail design work team. Fortunately, all reworks are completed by detail design team, although they consumed extra detail design work team time resource, and finally influenced detail design team performance. Therefore, the new product introduction system performed as smooth in this example as displayed in Figure 5.6.

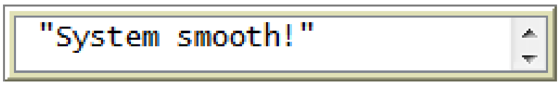


Figure 5.6 System general performance

5.3.5 Simulation rule specifications

The simulation rule specifications are model instructions, informing how the agents act and interact with each other. The simulation rules are implemented by model programming using NetLogo language. According to the case study definition in Chapter 4, simulation rules specified in this research, instructing the simulation model operation and agents' behaviour, are demonstrated in Table 5.7.

Table 5.7 Simulation rule specifications

regarding	**simulation rule specifications**
requests generation	Information requests are generated as an average frequency of pd-request-rate at preliminary design team and dd-request-rate at detail design team.

responses issued	The information requests are responded to as soon as the work teams are able to do so. That is, the responding to information requests are considered as priority tasks.
deadlines	Each work team is arranged fixed deadline, which means the product design project must be delivered to the next design stage on due deadlines.
design assumptions	When the product design project is delivered to next work stage, all information requests that are not get responded to are defined as design assumptions.
design uncertainties	When the work team receives the product design package from its upstream teams, all design assumption involved in the design project are converted to design uncertainties at the same time
rework identified	When the product package is finally proceeded to manufacturing stage, it detects all design problems, and identifies them as rework tasks, in order to eliminate design problems and complete the product development project.
rework completed	The reworks are returned to the detail design work team for further work on them. And detail design work team considers and completes the rework as absolute priority tasks.
design priority	The product development project is priority to any other design activities. And the rework tasks are the most priority tasks.
design project	This case study considers one product design project running through the new product introduction system.
time arrangement	When the work teams are free of both current product design commissions and rework tasks, the rest of time is free and could be used to carry on other commissions.
performance measurement	The work team performs better if it has more available time resource.
system performance	System perfect if: there is no rework generated within the new product introduction system.
	System smooth if: all rework are eventually completed by the detail design work team within a reasonable time frame, and the new product is produced finally.

	System collapses if: the detail design work team is not able to provide sufficient time resources to complete all rework tasks within a satisfactory time frame, and the new product introduction system finally breaks down.

5.4 Summary

With respect to the research procedure developed in Chapter 3, the research steps 5, 6, and 7 were carried out and implemented in this chapter. The results from these steps are reported as follows.

This chapter discussed both advantages and disadvantages between agent-based simulation and discrete-event simulation. A simulation mapping was development to demonstrate the relationships between key elements of new product introduction system and key concepts that underpin agent-based simulation method. As a result, agent-based simulation method was specified for this research, considering its feasibility and advantage on simulating the case study new product introduction system. And agent-based simulation tool NetLogo was selected as simulation tool for this research, considering availability and feasibility of the software functions.

A simulation model was developed to represent the vicious circles conceptual model of the case study new product introduction system defined in Chapter 4, applying agent-based simulation method and NetLogo simulation tool. The author discussed the simulation model architecture and performance measurements used in the simulation model. The simulation model interface provides three primary sections, i.e. model input section, simulation world, and model output section. Finally and very important, the simulation rule specifications applied in the simulation model were defined.

Chapter 6 Simulation Model Verification and Validation

This chapter describes the implementation of the steps of 8, 9, 10, and 11 in research procedure specified in Chapter 3, i.e. conduct verification experiments, verify the simulation model, conduct validation experiments, validate the simulation model. There are totally 7 experiments were conducted based on the simulation model, in order to verify and validate the model. Results from these experiments are reported in this chapter.

Model verification and validation activities are to make sure a simulation model possesses sufficient accuracy to represent a research problem or a research interest (Sargent, 2013), (Balci, 2010), (Gilbert, 2010), (Macal, 2005), (Thacker et al, 2004), (Carson, 2002), (Robinson, 1999). The final goal is to guarantee the simulation model is logically correct, reasonable, reliable, and accurate enough to represent the new product introduction system vicious circles problems. With respect to the case study research problem definition and research purpose, both simulation model verification activity and simulation model validation activity are carried out from different perspectives focusing different levels on the simulation model.

Simulation model verification is to determine whether the simulation model accurately represents the new product introduction system conceptual model defined in Chapter 4, with focusing on their logical relationship specifications (Thacker et al, 2004). Model verification process is therefore dealing with both mathematical relationship and simulation rule specifications associated with the simulation model (Macal, 2005). In other words, Model verification activity is checking whether the simulation model is a right model to represent the vicious circles conceptual model, with focus on arithmetic aspects (Balci,1997).

The model verification activities are carried out from three different levels, i.e. quantitative analysis, qualitative analysis, and sensitivity analysis. Both quantitative analysis and qualitative analysis use the results from one experiment. And the sensitivity analysis employed a set of five experiments.

Simulation model validation is to determine whether the simulation model possesses sufficient accuracy to represent the new product introduction system vicious circles phenomenon and provide potential solutions to solve the research problems, with respect to specified research purpose (Macal, 2005), (Thacker et al, 2004). Therefore, model validation process considers the degree of accuracy when applying the simulation model to understand vicious circles phenomenon and suggest management solutions to mitigate the problems (Thacker et al, 2004). In other words, simulation model validation is checking whether the simulation model is an accurate enough model to represent the real world vicious circles problems (Balci, 1997), (Riha et al, 2006). The model validation activity employed another experiment, applying animation function of the NetLogo software.

6.1 Simulation Model Verification

Simulation model verification is to determine whether the simulation model is an accurate model to represent the new product introduction system conceptual model. In order to test the correctness of the simulation model regarding its arithmetic perspective, three levels of model verification activities are carried out in the rest of this subsection. They are quantitative analysis, qualitative analysis, and sensitivity analysis (Kumar, 2011), (Neuman, 2007), (Saltelli et al, 2000), (Gilbert, 2010). The functions and purpose of each verification activity are demonstrated in Table 6.1.

Table 6.1 Simulation model verification activities

verification activities	quantitative analysis	qualitative analysis	sensitivity analysis
intent & purpose	testing whether the simulation model is logically correct to represent the vicious circles conceptual model	testing whether the simulation model is a reasonable model to represent the vicious circles conceptual model	testing whether the simulation model is a reliable model to represent the vicious circles conceptual model

Both quantitative analysis and qualitative analysis are based on a verification experiment and its simulation outputs. Quantitative analysis focuses on checking whether the simulation model is logically correct to represent the vicious circles conceptual model, considering simulation rule specifications. And qualitative analysis focuses on testing whether the simulation model is a reasonable model to represent the vicious circles conceptual model, with respect to the conceptual model operational process.

Sensitivity analysis is to determine whether the simulation model is a reliable model to represent the vicious circles conceptual model, with operating the simulation model many times. Therefore, sensitivity analysis activity involves

5 experiments in this research and analyses the simulation model performance.

6.1.1 Quantitative analysis and qualitative analysis

In this section, a verification experiment was designed and conducted, with respect to specified verification purpose. Three primary sections of the verification experiment are demonstrated: simulation model input, simulation model output, and simulation world. This verification experiment provided sufficient simulation results, data & information, operation process details, for verifying the simulation model at this stage.

Both quantitative analysis and qualitative analysis are carried out based on the simulation results from this experiment from different verification purpose. Quantitative analysis is to verify the correctness of the simulation model with conceptual model, with focusing on the logical relationship. Qualitative analysis is to check whether each work team with the simulation model performs in a reasonable way, which is partially based on the verification results of quantitative analysis.

6.1.1.1 Conducting the quantitative and qualitative experiments

In this subsection, a verification experiment was designed and conducted. As introduced in the simulation model user manual, the simulation model verification experiment includes three sections: model input section, simulation world, and model output section, which are introduced focusing on the verification activity.

6.1.1.1.1 Model input section

Data and information used to inform the new product introduction system conceptual model development was demonstrated in Table 4-1. Simulation model input parameters were defined in Table 5-4. With respect to both Table 4-1 and Table 5-4, the verification experiment input variable values were designed and set up as follows in Table 6.2.

Table 6.2 Quantitative and qualitative experiment input

variable	value	rationale for data values used
pd-request-rate	4	On average, the preliminary design team requests information form detail design team every 4 weeks.

time-consumed-for-responding-pd	4	The detail design team consumes approximately 4 weeks to respond to a request from preliminary design team.
dd-request-rate	3	On average, the detail design team requests information form manufacturing team every **3** weeks.
time-consumed-for-responding-dd	3	The manufacturing team consumes approximately 3 weeks to respond to a request from detail design team.
time-consumed-for-rework	10	The detail design team spends around 10 weeks to complete a rework task.
time-amount-to-make-a-sideproduct	2	This is a unit of time when measuring work team's performance. That is, a time unit is 2 weeks in this simulation model.
deadline-pd	100	The preliminary design team should complete and deliver their product design project on due deadline of 100 weeks.
deadline-dd	80	The detail design team should complete and deliver their product design project on due deadline of 80 weeks.
deadline-mc	50	The manufacturing team should complete and deliver their product design project on due deadline of 50 weeks.
HR-distribution-for-project	50	The work team undertaking the current project distributes 50% of total time resource for the product design. The maximum value variable is 100.

6.1.1.1.2 Simulation world

When the simulation model program operates, design actions and interactions among the three work teams were demonstrated in simulation world with full scale details. One screenshot of the simulation model was captured and displayed in Figure 6.1.

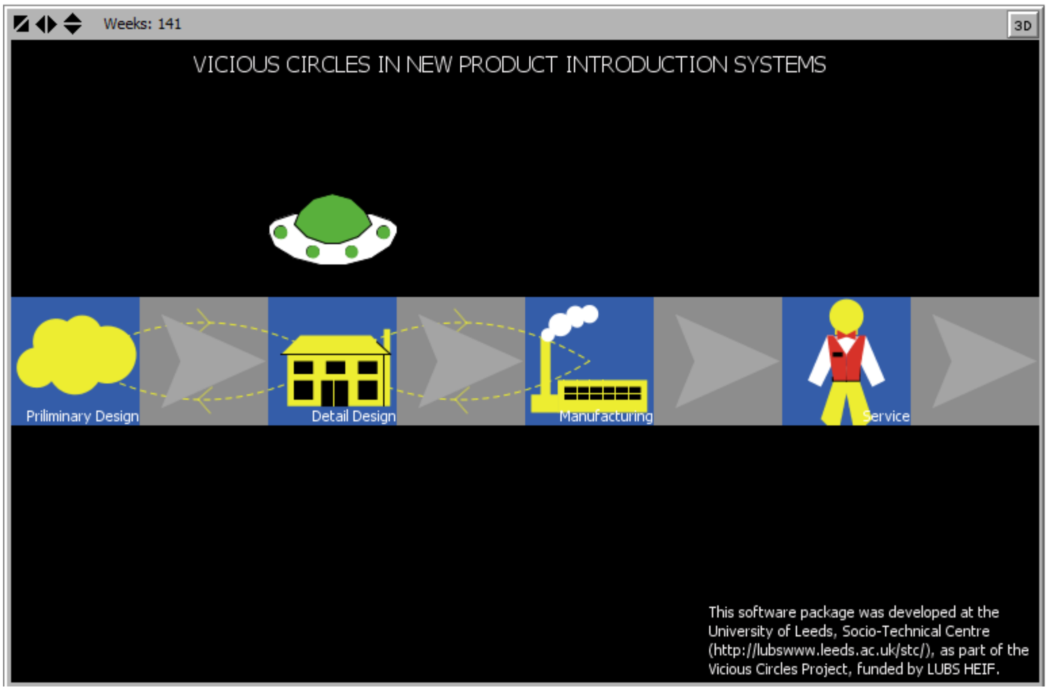


Figure 6.1 Quantitative and qualitative experiment simulation world

The simulation model is deadline driven style, according to the conceptual model definintion in Chapter 4 and Chapter 5. If there is no vicious circles phenomenon happens within the system, the simulation model runs for the whole new product development cycle, i.e. 100 weeks + 80 weeks + 50 weeks = 230 weeks. If the simulation model breaks down due to vicious circles situation, the simulation model runs to the breaking down time point.

As a result, the verification experiment was running in a smooth way. And the genaral system performance was recgonised as smooth which was displayed in the information board in Figure 6.2. In addition, the Command Center reported the verification experiment test date & time as in Figure 6.3.

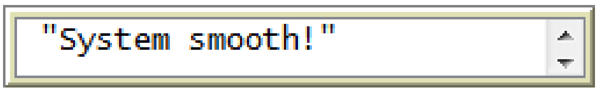


Figure 6.2 Quantitative and qualitative experiment information board

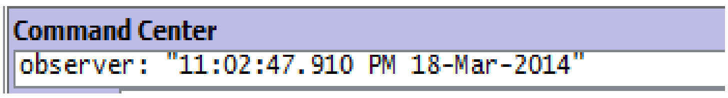


Figure 6.3 Quantitative and qualitative experiment date and time

6.1.1.1.3 Model output section

When simulation model program runs, the system-level impacting factors were tracked and displayed in plot boxes. For example, the requests-responses relationship and the requests-awaiting-responses mantained in the system were recorded in Figure 6.4 and Figure 6.5. At the same time, three work team's performance was also recorded and demonstrated in Figure 6.6, Figure 6.7, and Figure 6.8. Both system-level and team-level performance of the new product introduciton system were recorded and displayed in the following five figures.

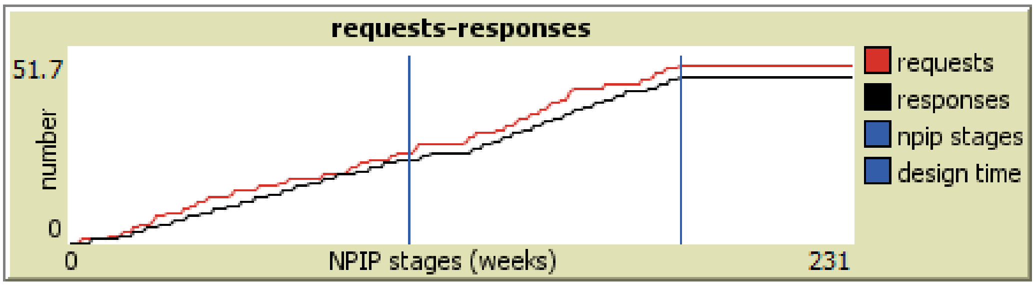


Figure 6.4 The requests-responses curves

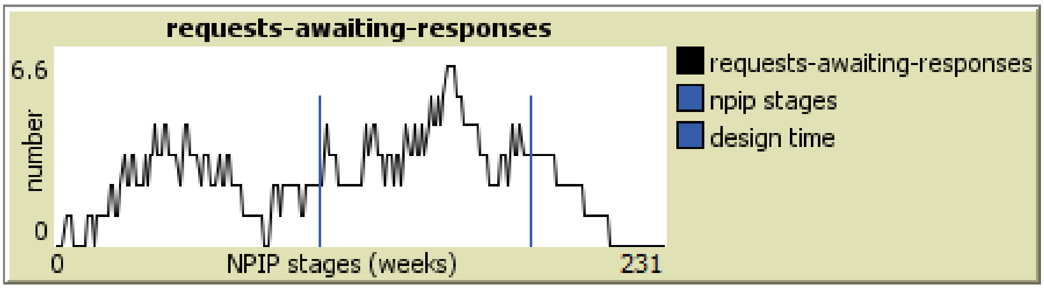


Figure 6.5 The requests-awaiting-responses curve

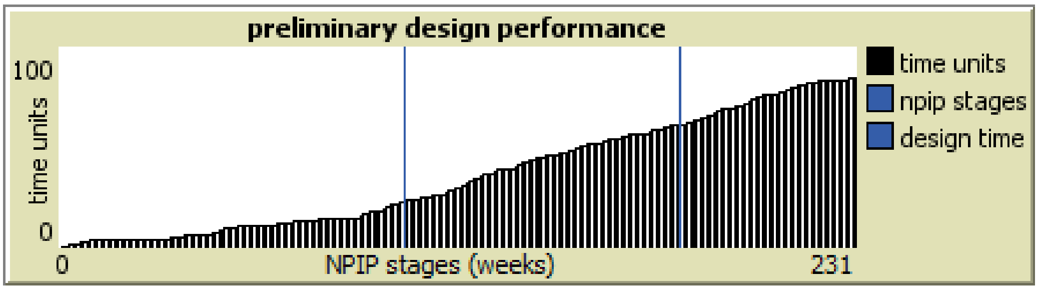


Figure 6.6 Preliminary design team performance chart

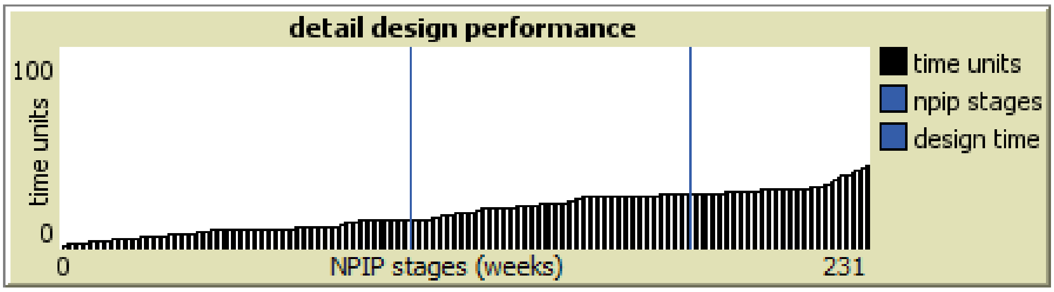


Figure 6.7 Detail design team performance chart

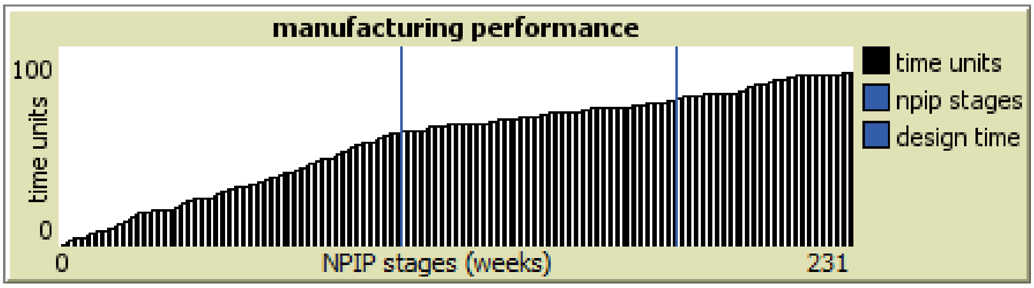


Figure 6.8 The manufacturing team performance chart

The vicious circles conceptual model involved preliminary design, detail design, and manufacturing three work teams in this research. Therefore, the simulation model gave three work teams' performance plots when the product design project passed through the operation system. Two vertical blue lines in each figures separate the new product introduction period into three design stages, i.e. preliminary design stage, detail design stage, and manufacturing stage.

6.1.1.2 Quantitative analysis

Quantitative analysis approach (Kumar, 2011), (Neuman, 2007) was specified at this research stage. Generally speaking, quantitative analysis emphasises precisely measuring variables and testing hypotheses that are linked to general causal explanations (Neuman, 2007). With respect to research problem definition and research purpose in this research, quantitative analysis at this stage is to check whether the logical relationship associated with the simulation model is proper for implementing the conceptual model description. The primary impacting factors involved within simulation model logical relationship are: requests generated at each work team, responses issued by relevant work teams, and requests-awaiting-responses maintained within the operation system, and so forth. The results of these impacting factors from the experiment were displayed in Figure 6.9, which merges Figure 6.4 and Figure 6.5, with intent to compare three factors' value with each other.

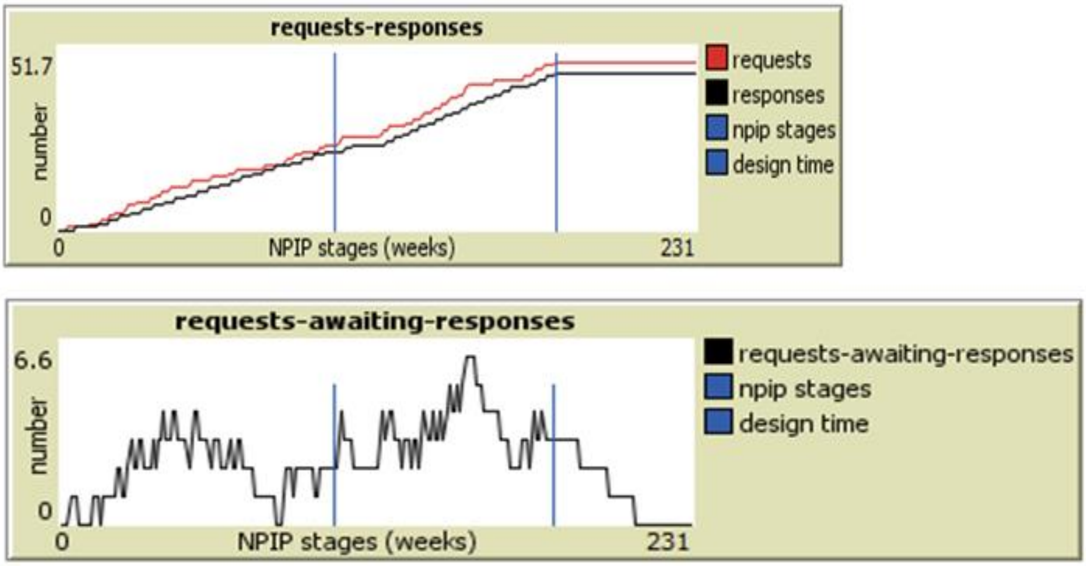


Figure 6.9 Quantitative analysis

At top of Figure 6.9, the red curve represents number of information requests generated within the work teams. And the black curve is number of respondings made the down stream work teams to these information requests. As a common knowledge, the black curve should be always kept below of the red curve.

At bottom of the Figure 6.9, the folded line represents the number of requests-awaiting-responses maintained within the system, which are those information requests waiting for responses from colleague work teams. The requests-awaiting-responses introduced design uncertainties into the system, which further result in design problems at a particular work stage and cause rework necessariated in the system.

The number of requests-awaiting-responses equals to the value difference between the requets curve and responses curve. In other words, the number of requests is the sum of the responses and the requets-awaiting-responses. This kind of logical relationship appropately implemented the simulation rule specifications defined in Table 5-6. Therefore, the quantitative analysis test approved that the simulation model is a logially correct model to implement the defined simulation rule specifications.

6.1.1.3 Qualitative analysis

Qualitative analysis method (Neuman, 2007), (Kumar, 2011) was employed at this stage in the research. Generally speaking, qualitative analysis is to understand, explain, explore, discover, and clarify situations, perceptions, values, and experiences of a group of people or organisations (Kumar, 2011). With respect to research purpose identified with this research stage, the qualitative analysis is to check whether each individual work team within the vicious circles simulation model performs in a reasonable way, regarding the real world operation scenario. Therefore, quantitative analysis guarantees the simulation model makes sense with real world research problem understanding. Each team's performance was recorded in performance plots and demonstrated in Figure 6.10.

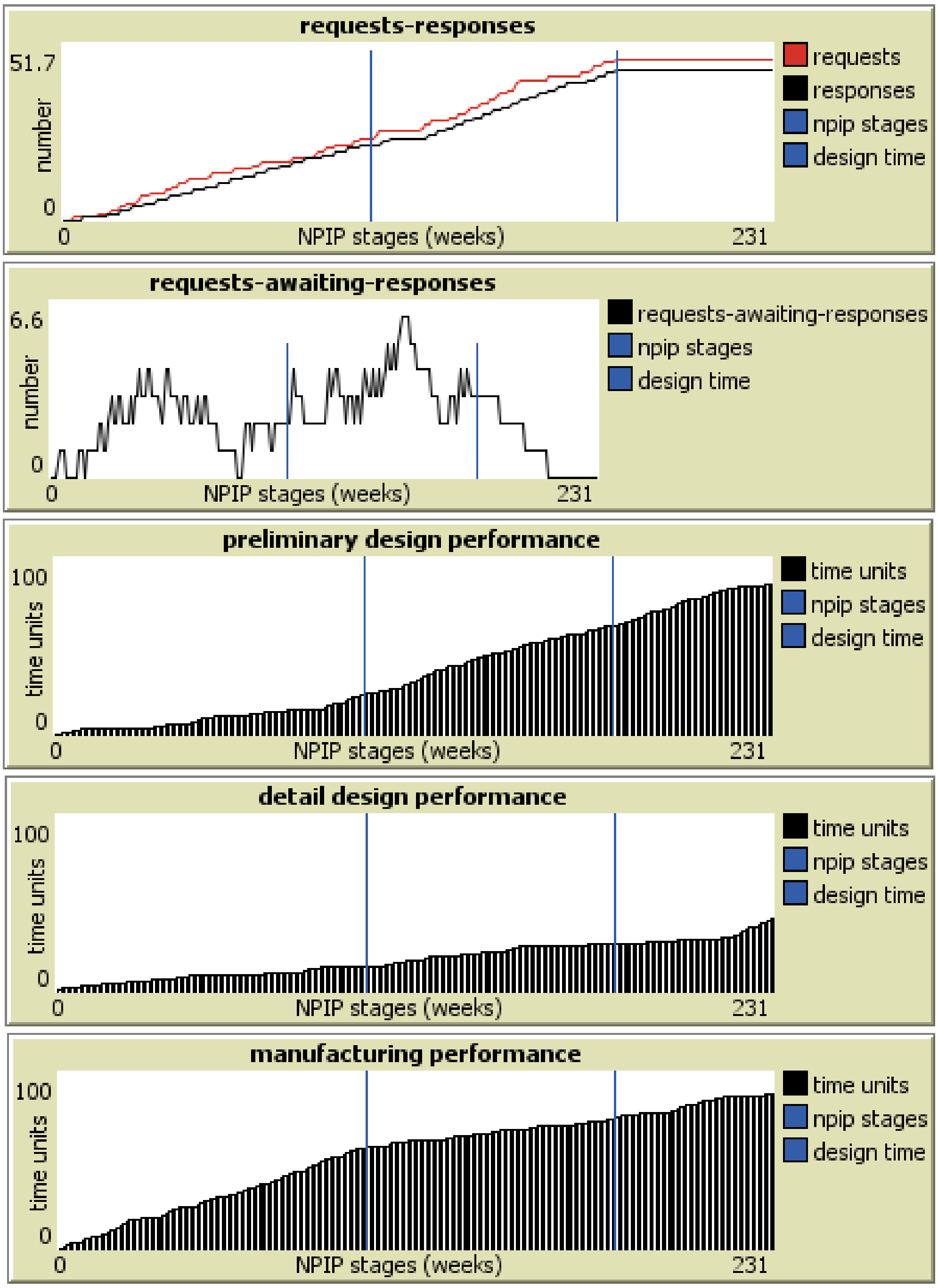


Figure 6.10 Qualitative analysis

As discussed in the Section 5.3.1.2, work teams' performance is measured by the free available time resources maintained within them. The more time resource maintained within the work teams, the better performance of the work teams. In above work team performance plots, the time resource is measured by time units as defined in Table 5-4 and Table 5.7.

In Figure 6.10, preliminary design team obtains 85 time units within the whole product development period, detail design team has 40 time units as the worst performance team, and the manufacturing team maintains 86 time units in total. According to data reflected in Figure 6.10, each work team's performance was varying a lot within the whole new product introduction system. Further, each work team's performance at different product development stages is different. In Table 6.3, each work team's performance was demonstrated and the reasons were explained as well.

Table 6.3 Interpretation of simulation results

	preliminary design team	**detail design team**	**manufacturing team**
product preliminary design stage	performance: low	performance: low	performance: normal
	Reason: the preliminary design team undertakes the current project, which consumes large proportion of time resource (50%).	Reason: the detail design team spends time resource to responding to the information requests from preliminary design team.	Reason: the current design project has no influence on the manufacturing team at this stage.
product detail design stage	performance: normal	performance: low	performance: low
	Reason: the design project has no influence on preliminary design team at this stage.	Reason: the detail design team undertakes the current project, which consumes large proportion of time resource (50%).	Reason: the manufacturing team spends time resource to responding to information requests from detail design team.
product manufacturing stage	performance: normal	performance: low	performance: low
	reason: the design project has no influence on preliminary design team at this stage.	reason: the detail design team completes rework as priority tasks, which consumes large volumes of time resource.	reason: the manufacturing team undertakes the current project, which consumes large proportion of time resource (50%).

general performance	low + normal + normal	low + low + low	normal + low + low

As a result from Table 6.3, the preliminary design team experienced one low performance period at the product preliminary design stage. The detail design team encountered three low performance periods within the product development cycle. The manufacturing team experienced two low performance phases at detail design and manufacturing stages. The detail design work team has the worst performance within the new product introduction system in this experiment.

It can also be seen that the detail design work team implemented three rework tasks at the product manufacturing stage. The reworks are considered as its priority jobs; therefore the detail design work team focuses all design resource on the rework tasks at this period. This is why it did not have free time resource at early stage of the product manufacturing stage. This is implied by the horizontal part of the curve of detail design work team performance at that period.

Qualitative analysis test demonstrated that the new product introduction system produces reworks due to low efficiency of information communication within the simulation model. The rework tasks influence the both system-level and team-level performance of the system, especially the detail design work team. This kind operation scenario is echoing the research problem definition in Chapter 4. With focus on new product introduction system operational perspective, the simulation model is reasonable to help understanding the case study vicious circles phenomenon and insight why vicious circles arise in the case study new product introduction system.

6.1.2 Sensitivity analysis

Sensitivity analysis is used to explore how the impacts of the different options within the model would influence the output of the model (Saltelli et al, 2000). In the case study simulation model verification section, sensitivity analysis includes a series of experiments with changing simulation model input parameter values, and observing the influence on the performance of the whole system. The purpose of sensitivity analysis test is to make sure both simulation model and simulation results are reliable to represent the vicious circles conceptual model. Five experiments were designed and five sets of input variables’ values were specified as following in Table 6.4.

Table 6.4 Sensitivity analysis experiments input

category	variable	experiment 1	experiment 2	experiment 3	experiment 4	experiment 5
A	pd-request-rate	4	4	4	4	4
B	time-consumed-for-responding-pd	2	3	4	5	6
A	dd-request-rate	3	3	3	3	3
B	time-consumed-for-responding-dd	1	2	3	4	5
C	time-consumed-for-rework	10	10	10	10	10
C	time-amount-to-make-a-sideproduct	2	2	2	2	2
D	deadline-pd	100	100	100	100	100
D	deadline-dd	80	80	80	80	80
D	deadline-mc	50	50	50	50	50
D	HR-distribution-for-current-project	50	50	50	50	50

Category A, which is related to system performance of information requests volume needed with a new product development. Changing the values of Category A implies potential management solution regarding how to reduce the information requests.

Category B, which is related to system performance of how fast each work team provide answers to the information requests. Changing the values of Category B implies potential management solution regarding how to answer information requests faster.

Category C, which is related to system performance of what each work team design capability is. Changing the values of Category C implies potential management solution by improving all or specific work team design capability.

Category D, which is related to the definition of new product development time management. Changing the value of Category D implies potential management solutions with focus on reducing product development failure by allowing product development cycle extension.

Sensitivity analysis could focus on each category in the Table 6.4, with respect to specified research purpose. Considering case study definition in Chapter 4, the author changed Category B and observed the simulation results changing with different model input.

In the five experiments, the frequency of responding to the information requests is gradually decreasing, i.e. time-consumed-for-responding-pd and time-consumed-for-responding-dd. For example, the detail design work team issues a responding to information request from preliminary design work team every two weeks on average in the experiment 1. However the frequency reduced to every six weeks in the experiment 5. The same patterns of parameters' change occur in other experiments in Table 6.4.

6.1.2.1 System-level sensitivity analysis

The five sensitivity experiments were conducted, applying input values specified in Table 6.4. Simulation results regarding system-level performance are collected and analysed as follows in Table 6.5.

Table 6.5 Sensitivity analysis results (system-level)

	requests	responses	requests-awaiting-responses	rework	system stability
experiment 1	50	50	0	0	perfect
experiment 2	53	50	3	3	smooth
experiment 3	46	42	6	6	smooth
experiment 4	51	34	17	n/a	collapse
experiment 5	41	30	11	n/a	collapse

In Table 6.5, the number of requests generated within the system does not vary too much, between 41 and 53, because the work team deadlines and frequency of information requests are kept the same for the five experiments. The number of responses to information requests decreased from 50 to 30 in the five experiments. This kind of change happened due to that the information requests in latter experiments need waiting longer time to be responded to than the formers. For example, the time-consumed-for-responding-pd increased from 2 to 6 and the time-consumed-for-responding-dd increased from 1 to 5 respectively. As a consequence, the number of requests-awaiting-responses maintained in system increased correspondingly from 0 to 17.

Considering all requests-awaiting-responses involved in the system result in design uncertainties at the next design stages which, are further leading to design problems at later stages which, finally cause rework is needed within the system. The rework volume increased from 0 to 4 in the first three experiments. The system collapsed when the rework volume was greater than 4. The key reason is that the detail design team is not able to provide sufficient time resource to complete all rework tasks, the product design project cannot be completed, the new product introduction system model therefore breaks down under this circumstance.

By analysing the system-level new product introduction system performance, the rework generated within the case study new product introduction system greatly influences the system performance. Therefore, the rework is considered as an impacting factor on new product introduction system performance.

6.1.2.2 Team-level sensitivity analysis

The team-level performance is measured by the time resource that is maintained and available for other potential design commissions. The volume of spare time units maintained by each work team can be reflecting the performance of the work teams.

Each work team’s performance, i.e. the number of free time units, is tracked in the real time and recorded by the simulation model output section. Relevant data was collected, analysed, and demonstrated in Table 6.6. The orange colour cells are preliminary design work team performance; the blue colour cells represent detail design work team performance; and the red colour cells are the manufacturing work team performance.

Table 6.6 Sensitivity analysis results (team-level)

		preliminary design stage			detail design stage			manufacturing stage		
experiment 1	preliminary design team	21			40			21		
	detail design team		31			15			25	
	manufacturing team			54			37			11
experiment 2	preliminary design team	25			40			23		
	detail design team		26			23			19	
	manufacturing team			51			21			14
experiment 3	preliminary design team	22			40			24		
	detail design team		24			22			10	
	manufacturing team			56			19			16
experiment 4	preliminary design team	32			39			n/a		
	detail design team		7			26			n/a	
	manufacturing team			48			12			n/a
experiment 5	preliminary design team	26			43			n/a		
	detail design team		11			21			n/a	
	manufacturing team			48			10			n/a

In order to measure each work team's performance against the same criterion, the author made all values at detail design stage column multiplied by (100/80), which was due to design periods at preliminary design stage and detail design stage are 100 weeks and 80 weeks separately. Similarly, all values at the manufacturing stage column were multiplied by (100/50), considering two design periods are 100 weeks and 50 weeks respectively. By doing this, the Table 6.6 was translated and modified in Table 6.7.

Table 6.7 Sensitivity analysis results (team-level) – modified

		preliminary design stage			detail design stage			manufacturing stage		
experiment 1	**preliminary design team**	21			50			42		
	detail design team		31			19			50	
	manufacturing team			54			46			22
experiment 2	**preliminary design team**	25			50			46		
	detail design team		26			29			38	
	manufacturing team			51			26			28
experiment 3	**preliminary design team**	22			50			48		
	detail design team		24			28			20	
	manufacturing team			56			24			32
experiment 4	**preliminary design team**	32			49			n/a		
	detail design team		7			33			n/a	
	manufacturing team			48			15			n/a
experiment 5	**preliminary design team**	26			54			n/a		
	detail design team		11			26			n/a	
	manufacturing team			48			13			n/a

The team-level sensitivity analysis is carried out with the Table 6.7. And Sensitivity analysis test is focusing on the first three experiments, because the rest two experiments (with grey background) collapsed and could not provide sufficient testing data. The reason of model collapse is that excessive reworks could not be completed by detail design team under a predetermined deadline style.

At product preliminary design stage, the preliminary design work team undertakes product design task, which occupied 50% of total time resource. As a result, the preliminary design work team has 68 (21 + 25 + 22) free time units for the three experiments in total. At the same stage, the detail design fulfilled responsibility to responding to information requests from preliminary design work team. Finally, the detail design work team possesses total 81 (31 + 26 + 24) available time units at this stage. Manufacturing work team is free of impacting from the current product design package at this stage, and owns 161 (54 + 51 + 56) time units.

At product detail design stage, the detail design work team undertakes further product design commissions, which consumed the same 50% of its time resource. Finally, the detail design work team maintains 76 (19 + 29 + 28) time units. At the same design stage, the preliminary design work team is free of design work and the requests-responses tasks. As a result, the preliminary design work team owns 150 (50 + 50 + 50) free time units, which is almost twice of the number (68) possessed when it was at the preliminary design stage. Comparing 161 time units owned at preliminary design stage, the manufacturing work team has only 96 (46 + 26 + 24) spare time units at this phase. The manufacturing work team is greatly influenced by issuing responses to information requests from detail design work team in this stage.

At manufacturing stage, the manufacturing work team fulfils the duty of developing and manufacturing the product. As a result, the manufacturing work team has 82 (22 + 28 + 32) spare time units, which is far less than time units volume maintained at preliminary design stage (161 time units). The preliminary design work team kept a stable performance by possessing 136 (42 + 46 + 48) available time units, comparing 150 time units at detail design stage. The detail design work team consumed additional time resource to implement rework from manufacturing work team at this stage, which affected the detail design work team performance. Finally, the detail design work team owns 108 (50 + 38 + 20) time units at this stage.

Focusing on detail design work team, the number of available time units obtained in the three experiments decreased as dramatic trend. Detail design work team owns 50 and 38 time units in the experiment 1 and 2. It just has 20 time units (in experiment 3) that are just 40% of the experiment 1. The reason behind this situation is that the rework volume increased from 0 to 6 in the first three experiments, which consumed large volume of time resource of detail design team. As a consequence, the rework consumes additional detail design work team's time resource and further influenced detail design work team's performance. In experiments 4 and 5, the detail design work team cannot provide sufficient time resource to complete the heavily increasing rework volume (17 and 11 separately); therefore the simulation model collapses due to the vicious circles phenomenon caused by large volume of rework.

In summary, the sensitivity analysis test included a series of five experiments, with changing the model inputs and observing model output. By analysing both system-level performance and team-level performance, the simulation model and simulation results are reliable to reflect the operation scenario in the real world new product introduction system. Therefore, the simulation model is approved as a reliable model to represent the new product introduction system research problem defined in Chapter 4.

6.1.3 Simulation model verification results

Total six experiments were designed and conducted, in order to verify the simulation model. Three model verification levels are quantitative analysis, qualitative analysis, and sensitivity analysis. The quantitative analysis and qualitative analysis used the same output from the first experiment, with respect to test whether the simulation model is a logically right and reasonable model to represent the conceptual model. The sensitivity analysis employed a set of five experiments that are checking the simulation model reliability to mimic the operational situation in the new product introduction system. The application of verification method and tools considers research problem definition and research purpose specification.

- Quantitative analysis results guaranteed the simulation model is a logically right model to represent the new product introduction system conceptual model, with focus on the logical relationship within the conceptual mode. That is, the simulation rule specifications in the simulation model properly implements the logical relationship defined in the conceptual model.

- Qualitative analysis results ensured that the simulation model is a reasonable representation of the case study new product introduction system operation process, with respect to defined research problem.

That is, the simulation model could be used to understand the real world new product introduction system operation scenario. This provides organisational foundation to study the social-related vicious circles problems in the case study new product introduction system.

- Sensitivity analysis results approved that the simulation model is a reliable model to represent the new product introduction system vicious circles problems. In addition, the experiment results implied that the potential solutions to solve the vicious circles problems may be reducing the rework volume generated in the system.

6.2 Simulation Model Validation

Simulation model validation is to determine which degree the simulation model precisely represents the real world research problems with respect to specified research purpose (Macal, 2005), (Thacker et al, 2004). Simulation purpose specified for this research was to understand new product introduction system vicious circles problems and explore potential management strategies to mitigate vicious circles and their consequences. Therefore, the simulation model validation section was checking whether the simulation model performs as expected, in order to improve understanding vicious circles phenomenon and provide management solutions informing decision making in the real world.

Agent-based simulation tool NetLogo provides a simulation world demonstrating area, where each agent's actions and interactions involved in the vicious circles system are graphically demonstrated with sufficient details (Chan et al, 2010). Taking advantage of the enabled animation function, the author employed animation validation method to check whether the simulation model performs properly, i.e. with sufficient accuracy, to represent and then address the new product introduction system vicious circles problems.

6.2.1 Animation validation method

Animation validation method (Liu and Wang, 2007) is a way to validate a model's correctness by observing the agents' behaviours and interactions. Integrating selected NetLogo simulation tool's graphical functions with validation purpose specified in the research, animation method was employed in this research (Chan et al, 2010).

With respect to the case study new product introduction system research purpose, animation method is to observe individual agents' behaviour as the simulation model runs over time and determine whether the agents' behaviour and interactions are accurate enough to implement the vicious circles research problem. In this research, the animation validation activity is carried out within the simulation world, where all individual agents and their actions and interactions are recorded and graphically demonstrated with full scale details.

When simulation model runs, the whole process of information generation and communication within all work teams is visualised and displayed in the simulation world. That is, the requests generated from each work team and responses issued by the work teams are demonstrated in a real-time pattern. In addition, the delivery of product design project through the system and the rework occurred between the manufacturing and detail design work teams are also graphically demonstrated with a real-time fashion. Therefore, the NetLogo simulation world provides sufficient evidence to determine whether the simulation model is accurate enough to represent the vicious circles problems and research interests.

Applying animation validation method, the simulation model is expected to be approved as an accurate enough model to represent the new product introduction system vicious circles research problem, and provide appropriate potential solutions to address the problems.

6.2.2 Validation experiment input

The simulation model validation experiment input was designed as follows in Table 6.8. Considering verification experiments conducted in Section 6.1 and verification results, the input values was chosen within a feasible and reasonable range.

Table 6.8 Validation experiment input

Variable	Value
pd-request-rate	4
time-consumed-for-responding-pd	4

dd-request-rate	3
time-consumed-for-responding-dd	3
time-consumed-for-rework	10
time-amount-making-a-sideproduct	2
deadline-pd	100
deadline-dd	80
deadline-mc	50
HR-distribution-for-project	50

6.2.3 Validation experiment output

The simulation model is operated with the model input in Table 6.8. Considering both system-level performance and individual team-level performance, the simulation results are displayed in Figure 6.11.

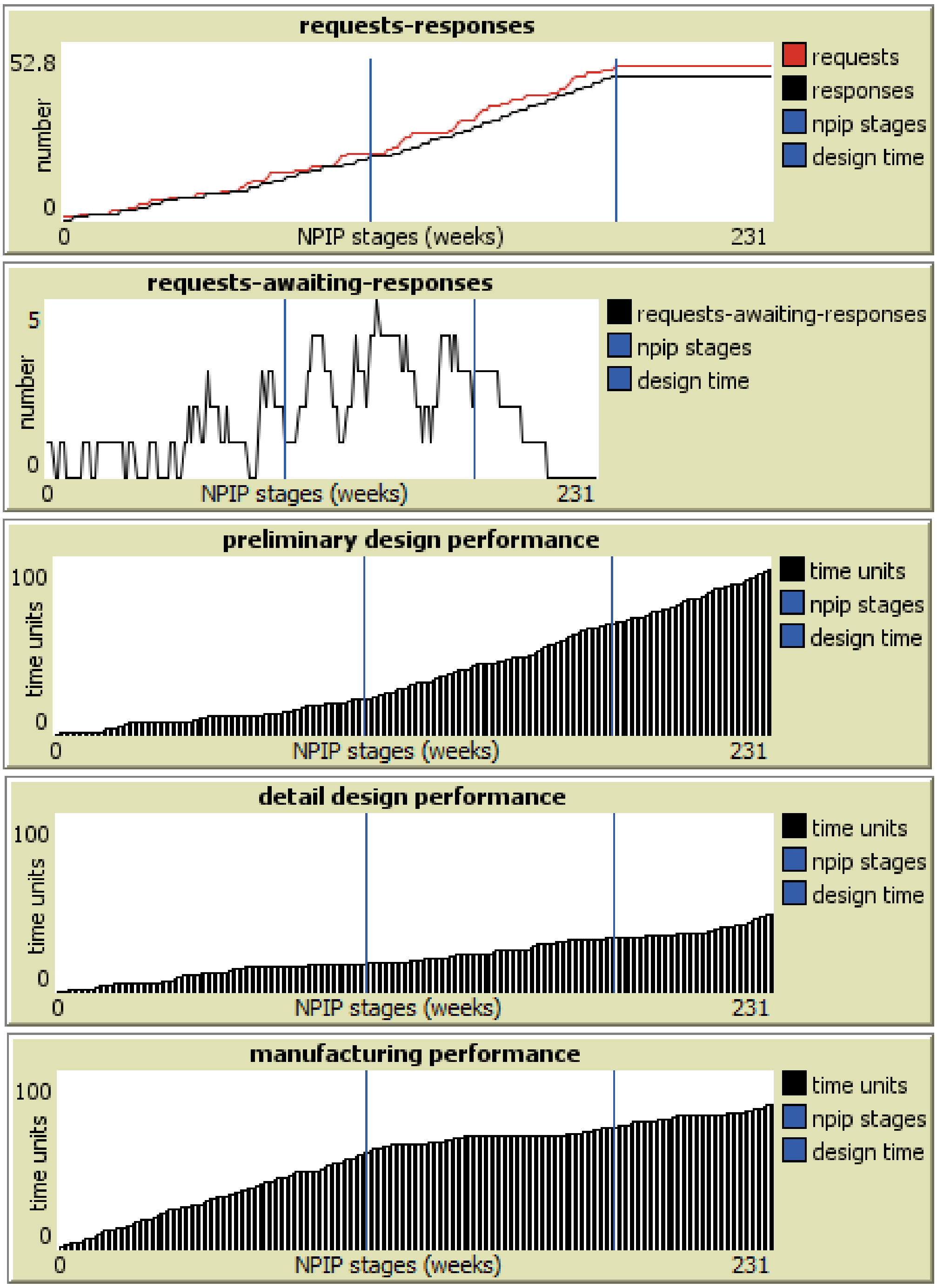


Figure 6.11 Validation experiment output

Considering the simulation model operation scenario, one screenshot of the simulation world was captured and displayed in Figure 6.12. And the whole process of the simulation model operational performance was displayed in the simulation world in a real time pattern.

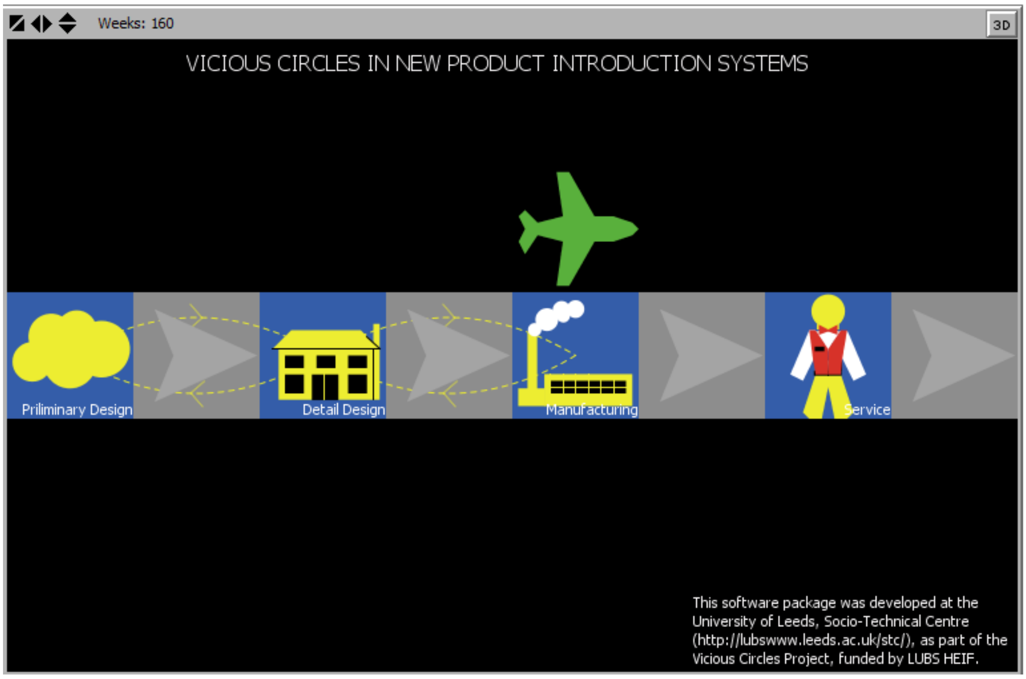


Figure 6.12 Validation experiment simulation world

6.2.4 Simulation model validation

When the simulation model operates, a series of simulation results was generated within the model output section. At the same time, the agents within the simulation model representing functional work teams in the new product introduction system act and interact with each other in the simulation world in a real time style.

At beginning of the product development process, preliminary design work team carried out preliminary design tasks of the product design project, and requested information to the detail design work team. Due on the preliminary design deadline, the design project proceeded to the detail design work team. And those information requests that were not replied by the detail design team before converted to design uncertainties at this stage. The detail design team kept working on the design project, and requested information as well to the downstream team of manufacturing. When the product design project finally passed over to the manufacturing team, all information requests that did not get responded to caused design problems. And reworks had to be identified by manufacturing team and returned to the detail design team for completing them. Rework tasks consumed additional time resource of the design system, especially the detail design team. Therefore, reworks were considered as one outstanding impacting factor on new product introduction system time-related performance.

The simulation model and simulation results have been approved as a logically correct, reasonable, and reliable representation of the case study new product introduction system research problem definition in the Section 6.2.3. The simulation model validation activity is to observe the agents' activities and performance, with comparison of the verification experiments' results. If the system operation process displayed in the simulation model accurately explains the simulation results demonstrated in the model output section, the simulation model is valid model to represent the vicious circles conceptual model, and the case study new product introduction system vicious circles problems.

6.2.5 Simulation model validation results

Simulation model validation is to check whether the simulation model is an accurate enough model to represent the case study new product introduction system vicious circles research problems, with respect to research problem definition and specified research purpose.

This research used an animation validation method, applying animation function enabled by the NetLogo simulation tool (Chan et al, 2010), (Wilensky, 2009). In doing so, the validation activities were carried out by observing system operation process and agents' actions and interactions demonstrated in the simulation world and comparing with the work teams performance plots displayed in model output section. The validation process considered system-level performance, individual work team's performance, and product design project delivery through the system.

Specially, the process of rework generated within the system was observed and displayed in the simulation world. The insight of how rework arises in and influences on the case study new product introduction system performance was directly gained. As a result, the rework was suspected as a primary indicator for the vicious circles problems within new product introduction system. And how to reduce rework volume with the system was identified as the key point to tackle vicious circles problems and their consequence on the system.

Animation validation results showed that the simulation model possesses sufficient accuracy to represent the case study new product introduction system vicious circles problems, with respect to research purpose specified for this research. And potential management strategy used to tackle vicious circles was suggested as reducing rework volume within the system in this research.

6.3 Summary

This chapter introduced the implementation of the steps of 8, 9, 10, and 11 in the research procedure defined in Chapter 3. Simulation model verification and simulation model validation activities were carried out and a series of 7 verification and validation experiments were conducted upon the simulation model.

Simulation model verification activities include three levels, i.e. quantitative analysis, qualitative analysis, and sensitivity analysis (Saltelli et al, 2000), (Kumar, 2011), (Neuman, 2007). The results from model verification experiments approved that the simulation model is logically correct, reasonable, and reliable to represent the case study new product introduction system conceptual model defined in the research.

Simulation model validation employed animation validation method, considering the strong animation function enabled by the agent-based simulation tool NetLogo (Chan et al, 2010), (Wilensky, 2009). The model validation activities were carried out by observing agents' performance and activities within the simulation world and comparing with system performance plots displayed in model output section. Results from the model validation activity approved that the simulation model is accurate enough to represent the case study new product introduction system vicious circles problems.

Overall, the simulation model was approved as logically correct, reasonable, reliable, and accurate enough to represent the new product introduction system vicious circles problems. In addition, the model verification and validation process revealed that the rework generated within the system is a primary performance indicator on the case study new product introduction system vicious circles problems. Therefore, the potential management intervention may be focusing on how to reduce the rework volume within new product introduction system.

Chapter 7 Simulation Experiments for the Management of Vicious Circles in New Product Introduction Systems

This chapter reports use of the simulation model to provide insights to the management questions posed in Section 4.2. Four simulation experiments were carried out, in order to address the four research questions. Potential management interventions to each question are recommended in each subsection in this chapter.

7.1 What if all the information requests are responded to in time?

This experiment considered an operational scenario, where all information requests from each work team are responded to by the downstream work teams as soon as the request is received. The purpose of the experiment was to reveal how the new product introduction system performance would be affected if all work teams try their best to provide responses to the information requests from their colleague work teams, with full positive manner. The strategy used in this experiment was to define activities of responding to information requests as priority tasks for all work teams (it is implemented by simulation model procedure programming).

7.1.1 Input data

The input data used in this simulation experiment is given in Table 7.1. The values of these variables was determined, with respect to model verification and validation experiments discussed in Chapter 6. The definition and explanation of the variables could be found at Table 5.5.

Table 7.1 Input data (experiment 1)

variables	values	unit
pd-request-rate	4	weeks
time-consumed-for-responding-pd	2	weeks
dd-request-rate	3	weeks
time-consumed-for-responding-dd	2	weeks
time-consumed-for-rework	10	weeks
time-amount-to-make-a-sideproduct	2	weeks
deadline-pd	100	weeks

deadline-dd	80	weeks
deadline-mc	50	weeks
total development cycle	230	weeks
HR-distribution-for-project	50	%

7.1.2 Results

Both system-level and team-level performance was tracked and recorded in the plot boxes in Figure 7.1. Two vertical blue lines in each chart divide the X axis into three design stages, i.e. preliminary design, detail design, and manufacturing.

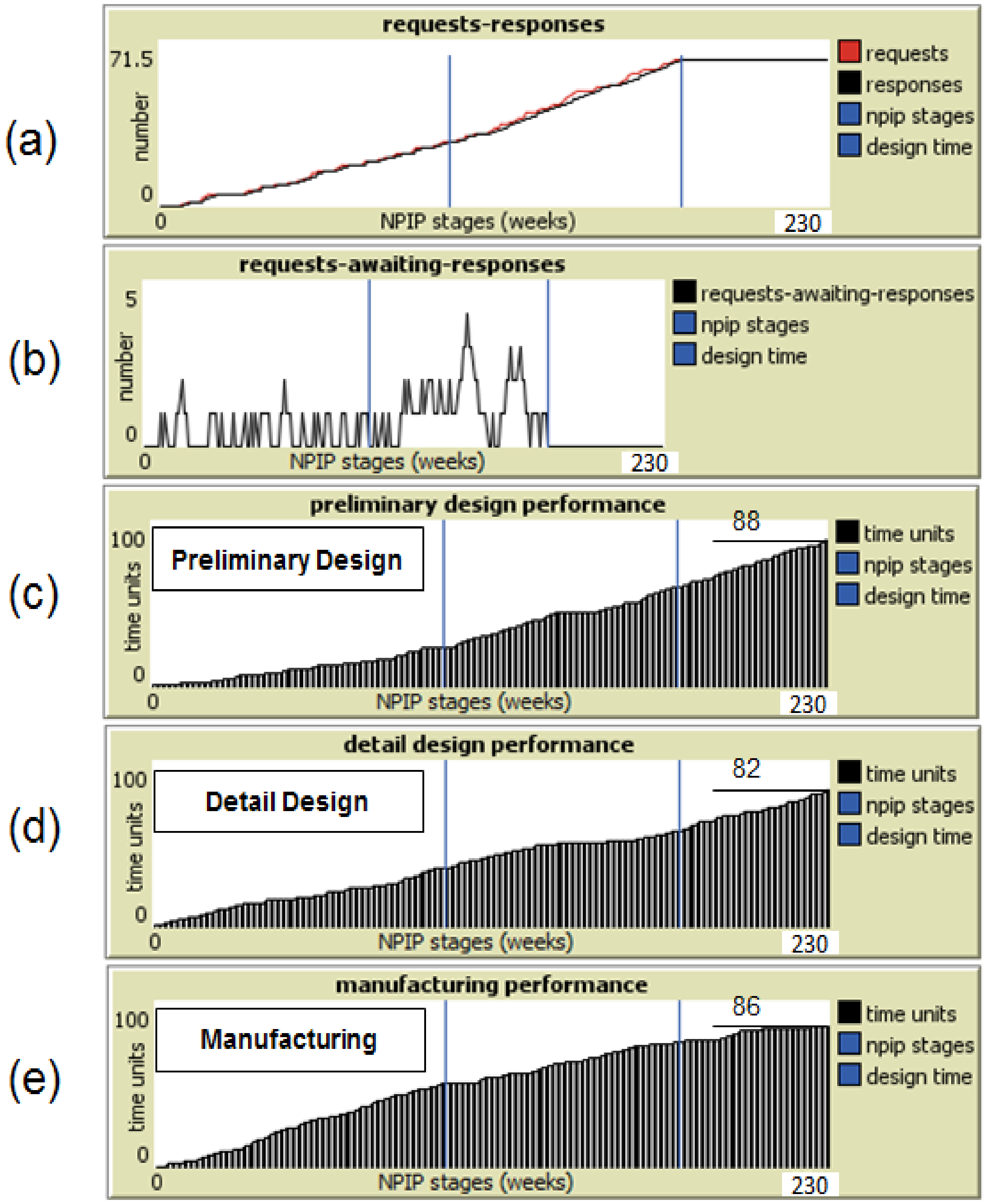


Figure 7.1 Results (experiment 1)

It can be seen (from Figure 7.1 (a)) that every request was responded as soon as the response could be made in this experiment. The time-used-for-responding was calculated in the simulation model in a statistical way, with respect to the model input defined in Table 7.1. By doing so, all information requests issued at each work stage were replied in a timely manner by the downstream work teams. There were no design uncertainties resulting from unprocessed requests for information maintained at each design stage in the system. And there were no design problems when the design project finally proceeded to the manufacturing stage.

The system-level new product introduction system performance measured by number of outstanding requests is shown in Figure 7.1 (b). There were some requests that are waiting for responses at both preliminary design and detail design stages, but all information requests are responded to before the deadlines. There were no design uncertainties and design problems involved within the system in this experiment. Therefore, the simulation scenario in the experiment 1 does not need reworks. As a simulation result, the general performance of the new product introduction system was recognised as “perfect” in the simulation model. It is displayed in the information board in Figure 7.2.

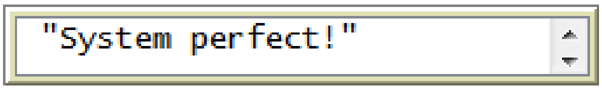


Figure 7.2 System performance (experiment 1)

The team-level performance of the new product introduction system is demonstrated in Figure 7.1 (c, d, e). All work teams work on their current design commissions and make side products when they are free of the current design project. Each work team uses available spare time to make side products as many as they can, in order to win a final bonus. Each work team performance is measured by the amount of spare time. The system performance measurement was defined in 5.3.1.2. the simulation rules were defined in Table 5.7.

The amount of spare time, i.e. the numbers of side products made by each work team in this experiment are displayed in Table 7.2.

Table 7.2 Work team performance (experiment 1)

work teams	**the amount of spare time (side products)**	**rework(s)**
preliminary design team	88	n/a
detail design team	82	0
manufacturing team	86	n/a

In this experiment, three work teams of preliminary design, detail design, and manufacturing had similar performance, based on the simulation results in Table 7.2.

All information requests were responded to in a timely manner, and therefore there were no rework tasks identified by the manufacturing team. The detail design work team did not need to spend additional time resources to complete rework tasks. As a simulation result, the new product introduction system performed as a perfect status, and there were no vicious circles problems occurred in this experiment.

7.1.3 Discussion of results

The experimental strategy was that all information requests from different work teams were considered as priorities, so that the information requests were responded to as quickly as possible. The results from the simulation experiment indicated that there no rework was identified by the manufacturing work team, and vicious circles were removed from the new product introduction system in this experiment. The finding from this experiment was that the vicious circles phenomenon is closely associated with reworks in new product introduction system.

The simulation results of no rework is an extreme situation within new product introduction system operation environment, which is just happened within simulation model. In the real world, the new product introduction system could try to reduce the volume of reworks, in order to mitigate the vicious circles influence on the system. With respect to product design iteration nature, the number of information requests generated with a design project could not be reduced. An alternative solution might be improving the engineering communication efficiency, and reducing the number of requests that wait for responses at each work stage. By doing so, the rework volume in the new product introduction system could be reduced.

When operating a new product introduction system, the manager should make sure each work team arrange sufficient time resources for responding to information requests from the upstream work teams for a specific design project. In this way, the rework volumes associated with the design project could be reduced, and the new product introduction system could avoid vicious circles problems. At the same time, there are difficulties these management strategies. Each work team try to complete their design duties and save time resource as much as they can, in order to achieve better performance. And the key work teams does no realise the importance of these information requests from its upstream work teams for a specific design project, which finally might result in reworks with the design project.

7.2 What if none of the information requests are replied by the colleague work teams at all?

This simulation experiment considered an reverse extreme operational scenario, where none of the information requests are responded by the downstream work teams at all. The purpose of this experiment was to reveal how the new product introduction system performs if all work teams do not reply the information requests from other work teams. The strategy used in this experiment was assuming none of work teams consider the information requests from other work teams (it was implemented by the simulation model program procedure). In order to address the experiment strategy applied in this experiment, the simulation model procedure was recoded, and the responding function section was removed from the simulation model procedure.

7.2.1 Input data

The input data used in this experiment is the same as the simulation experiment 1, which was given in Table 7.1. The intent of this experiment was to highlight the difference of the simulation results, with different management strategies.

7.2.2 Results

The simulation experiment 2 was conducted. Both system-level and team-level performance was recorded in the plot boxes, and displayed in Figure 7.3.

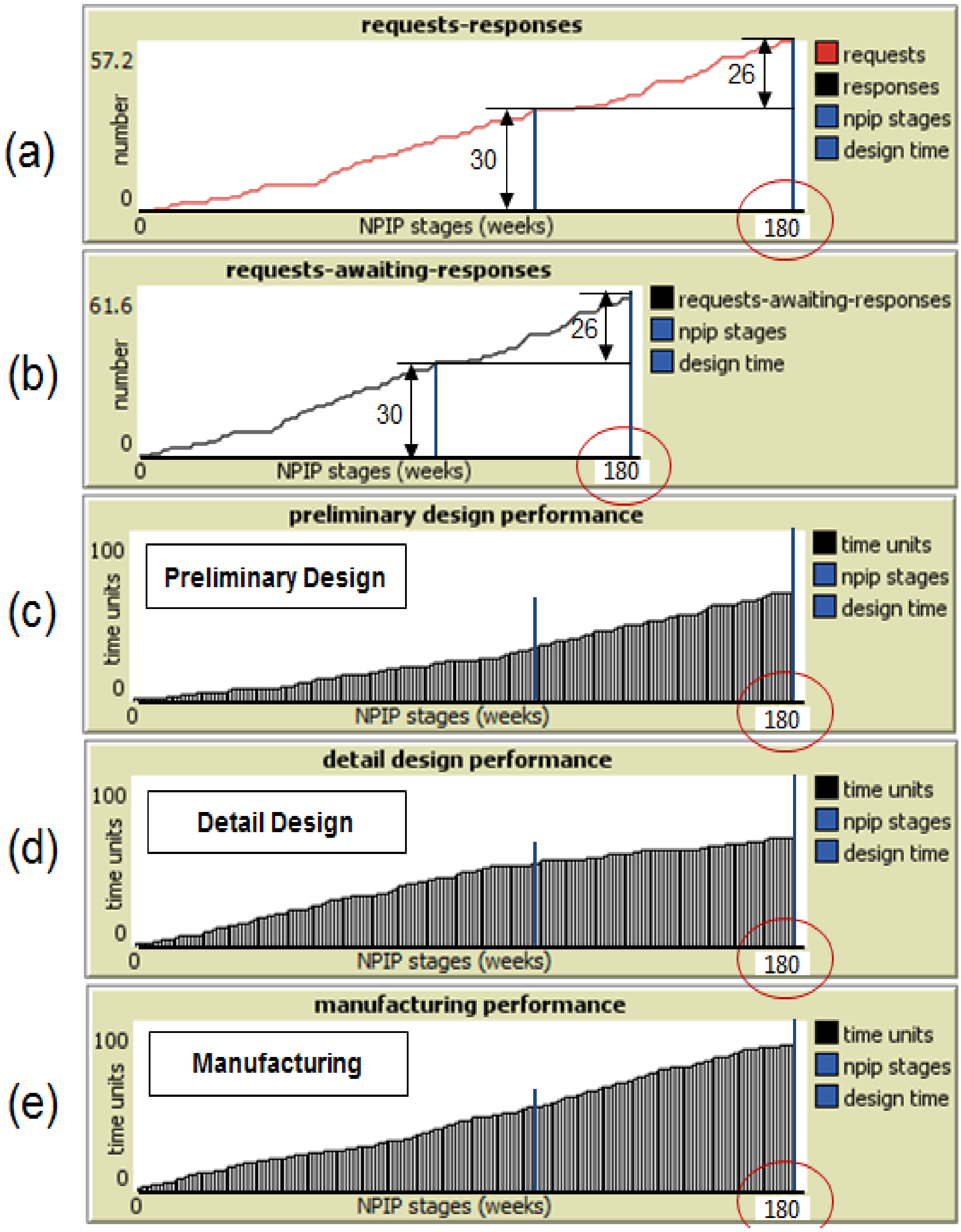


Figure 7.3 Results (experiment 2)

As shown in Figure 7.3 (a), none of the information requests issued by both preliminary design and detail design work teams were replied by their downstream work teams. All information requests were waiting for responses in the system, but all of them are ignored (Figure 7.3 (b)). When the design project proceeded to the manufacturing team, all the information requests that were not replied caused design problems, which needs reworks. Excessive rework tasks make the new product introduction system broken down, when the system runs for 180 weeks (see the red circles of each chart in Figure 7.3). The system-level performance is illustrated in Table 7.3.

Table 7.3 System performance (experiment 2)

	requests issued	responses received	design uncertainties generated	design problems raised	rework requested
preliminary design	30	0	30	n/a	n/a
detail design	26	0	26	n/a	n/a
manufacturing	n/a	n/a	n/a	56	56

In experiment 2, 30 design uncertainties were generated at preliminary design stage, because none of the 30 information requests were replied. At detail design stage, 26 design uncertainties were produced, because all of 26 information requests were not responded to at all. All design uncertainties caused design problems when the project proceeded to the manufacturing stage, therefore the manufacturing team encounters 56 design problems totally. All design problems are identified as rework tasks and returned to the detail design work team.

As a consequence, the detail design work team needs to complete 56 rework jobs within the manufacturing deadline, in order to complete the design project within the predetermined deadlines. Considering the detail design team consumes 10 weeks to complete each rework task, the overall rework volume would need 560 weeks (56 rework * 10 weeks / rework) which is even far longer than the whole new product introduction cycle 230 weeks (100 weeks + 80 weeks + 50 weeks) for this case study. Finally, the new product introduction system collapsed in this experiment because of excessive rework generated within the system. It is displayed in the information board in Figure 7.4.

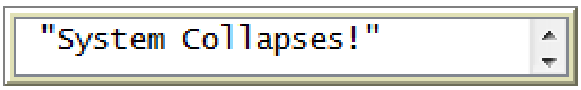


Figure 7.4 System performance (experiment 2)

7.2.3 Discussion of results

The management strategy used in this experiment was that all work teams ignored the information requests from their upstream work teams. By doing so, all information requested were not replied at all, and converted to design uncertainties when the design project proceeded to the next design stage. The rework tasks were necessitated to complete the design project at manufacturing stage. The result from this experiment is that excessive rework tasks make the new product introduction system collapse. The findings from this experiment was that the vicious circles phenomenon is triggered by excessive reworks within the system.

This is another extreme operation situation appeared in the simulation world, in terms of none of information requests are replied at all. In the real world, each work team often ignores the information requests from other work teams. The reasons vary, regarding different companies, distinct operation procedure, and differentiated business strategies applied. The simulation results provide management recommendations for the operation managers.

The managers could arrange a proportion of time resources with specific work teams for responding to the information from their upstream work teams. The performance of each work team should be balanced between their hand-on work and contributions for future projects. The final goal of these management strategies is to encourage all work teams see the whole forest rather than one tree. There are some difficulties when applying these management interventions. For example, all work teams focus on their own design commissions in order to perform better in the current project. The downstream work teams could not recognise those information requests that are vital for the future project. Those ignored information requests might cause design problems in the future design project, and result in the system breads down.

7.3 What if the detail design deadline is flexible within the new product introduction system?

The results from experiment 1 & 2 showed that the engineering communication efficiency is a key impacting factor on the new product introduction system performance. And because detail design could not complete all rework tasks within fixed deadlines, the new product introduction system performance was greatly influenced.

This initiated the third experiment that allows the detail design work team works on a flexible deadline pattern. In this experiment, the detail design deadline will be determined by how much time resource will be needed for completing all rework tasks. Because the simulation model was designed as predetermined deadlines for each work team in Chapter 5, the programing procedure in this experiment needs rewriting, and the simulation rule specifications (Table 5.7) need to be modified accordingly.

The experiment purpose was to explore how the new product introduction system performs if the detail design work team works on a flexible deadline style. The strategy used in this experiment was to allow the detail design team works on a flexible deadline pattern, which ensured detail design team has sufficient time resources to complete all rework tasks necessitated with the product development.

In order to implement the experiment strategy, both model input parameter definitions and simulation rule specifications were modified. The simulation model was modified as well, according to the modified simulation rule specifications.

7.3.1 Modify simulation rule specifications

The model parameter definitions defined in Table 5.5 were modified with highlighted bold items in Table 7.4.

Table 7.4 Modified model input parameter definitions

parameter	definition	example
pd-request-rate It is related to preliminary design work team.	How often the preliminary design team requests information from detail design team?	If pd-request-rate = 3 then, on average, the preliminary design team requests information from detail design team every three weeks.
time-consumed-for-responding-pd It is related to detail design work team.	How long would it take the detail design team to respond to a request on average?	If time-consumed-for-responding-pd = 2, then the detail design team spends approximately two weeks to respond to a request from preliminary design team.
dd-request-rate		

It is related to detail design work team.	How often the detail design team requests information from manufacturing team?	If pd-request-rate = 3 then, on average, the detail design team requests information from manufacturing team every three weeks.
time-consumed-for-responding-dd It is related to the manufacturing work team.	How long would it take the manufacturing team to respond to a request on average?	If time-consumed-for-responding-dd = 2, then the manufacturing team spends approximately two weeks to respond to a request from detail design team.
time-consumed-for-rework It is related to detail design work team.	The amount of time consumed by the detail design for completing each rework task.	If time-consumed-for-rework = 10, then the detail design team spends around ten weeks to complete a rework task.
time-amount-to-make-a-sideproduct It is related to all work teams.	This is the time unit to measure spare time maintained with work teams.	If time-amount-to-make-a-sideproduct = 3, then a time unit is 3 weeks in this simulation model.
deadline-pd It is related to preliminary design work team.	The time amount for the preliminary design team to complete its design commissions for a new product design project.	If deadline-pd = 80, then the preliminary design team should complete and deliver thee product design results within eighty weeks.
deadline-dd **It is related to detail design work team at detail design stage.**	**The time amount for the detail design team to complete the design commissions for a new product design project.**	**If deadline-dd = 60, then the detail design team must complete and deliver the design results to the manufacturing team within sixty weeks.**
deadline-mc It is related to the manufacturing work team.	The time amount for the manufacturing team to complete the manufacturing commissions for a new product design project.	If deadline-mc = 48, then the manufacturing team should complete and deliver the completed product within forty eight weeks.
deadline-dd-extension	**The time period for detail design team to complete**	**If detail design work team needs 50 weeks to complete the**

It is related to detail design team works on rework of the project.	**rework tasks recognised by the manufacturing team. Therefore, this parameter value is open.**	**reworks, then the deadline-dd-extension = 50 weeks.**
HR-distribution-for-project It is related to each work team who undertake the current product design commissions.	The percentage of time resource for each work team working on the new product design project.	If HR-distribution-for-project = 50, then the work team undertaking the design project distributes 50% of total time resource for the design commissions. The maximum value of this parameter is 100.

The simulation rule specifications defined in Table 5.7 were also modified, in order to implement the experiment strategy identified for this experiment. It is demonstrated and highlighted in Table 7.5.

Table 7.5 Modified simulation rule specifications

regarding	**simulation rule specifications**
requests generation	Information requests are generated as an average frequency of pd-request-rate at preliminary design stage or dd-request-rate at detail design stage.
responses issued	The information requests are responded as long as the work teams are able to do so. That is, the responding to information requests are considered as priority tasks.
deadlines	Each work team is arranged fixed deadline, which means the product design results must be delivered to the next design stage on due deadlines. **It is allowed that detail design team spends additional time on rework tasks, and therefore the whole product development cycle might be extended.**
design assumptions	Before the product design results are delivered to the next work stage, all information requests that are not get responded are defined as design assumptions.
design uncertainties	When downstream work team receives the product design results, all design assumption made at previous work stages are converted to design uncertainties.

rework identified	When the product design project is proceeded to manufacturing work team, it detects all design problems caused by the design uncertainties, and defines them as rework tasks.
rework completed	All rework is returned to the detail design work team. And detail design work team completes these reworks as absolute priorities.
design priority	The current product design project is prior to other design activities. And the rework tasks are the most priority tasks.
design project	This case study considers one product design project running through the new product introduction system.
time arrangement	When the work teams are free of both current product design commissions and rework tasks, the rest of time is free and could be used to carry on other commissions.
performance measurement	The work team performs better if it has more available time resource.
system performance	System perfect if: there are no rework tasks generated within the new product introduction system.
	System smooth if: all rework are eventually completed by the detail design work team within a satisfactory time frame, and the new product is produced finally.
	System collapse: there is no definition of this condition in this operation environment.
	Product develop delayed if: the detail design work team needs additional time to complete all rework tasks. And the product development cycle is extended.

7.3.2 Input data

The input data used in this experiment is given in Table 7.6.

Table 7.6 Input data (experiment 3)

variables	values	unit
pd-request-rate	4	weeks
time-consumed-for-responding-pd	4	weeks

dd-request-rate	3	weeks
time-consumed-for-responding-dd	3	weeks
time-consumed-for-rework	10	weeks
time-amount-to-make-a-sideproduct	2	weeks
deadline-pd	100	weeks
deadline-dd	80	weeks
deadline-dd-extension	?	weeks
deadline-mc	50	weeks
total development cycle	100 + 80 +?, if deadline-dd-extension > deadline-mc	weeks
	100 + 80 + 50, if deadline-dd-extension < deadline-mc	
HR-distribution-for-project	50	%

7.3.3 Results

Both system-level and team-level performance were recorded in plot boxes, and displayed in Figure 7.5.

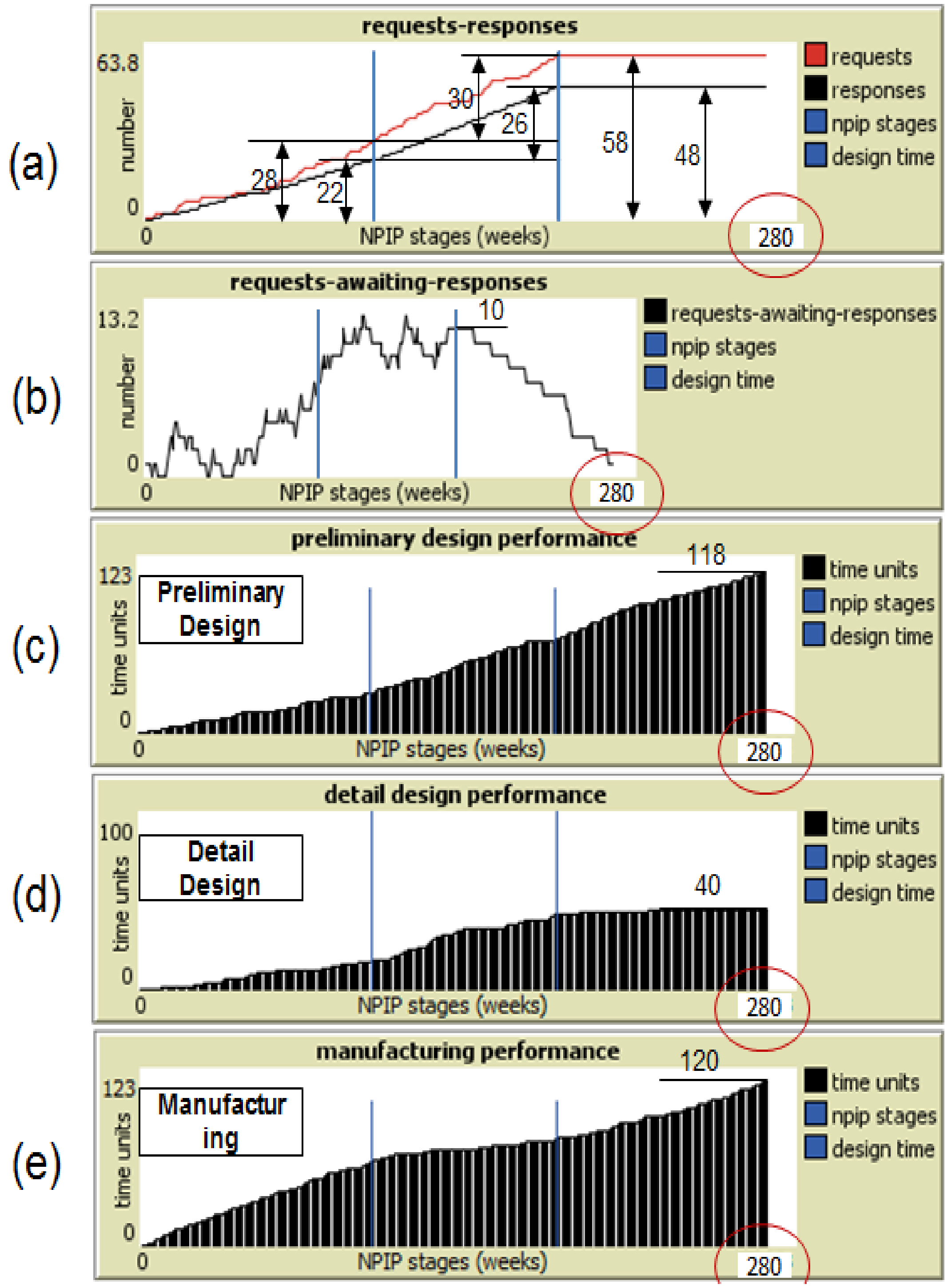


Figure 7.5 Results (experiment 3)

It can be seen from Figure 7.5 (a), the responses curve is lagged below of the requests curve. This means some information requests were not responded to in this experiement, which caused design problem at manufacturing stage. Therefore, reworks were needed in order to eliminate the design problems. The new product introduction system system-level is demonstrated in Table 7.7.

Table 7.7 System-level performance (experiment 3)

	requests issued	responses received	design uncertainties generated	design problems caused	rework requested
preliminary design	28	22	6	n/a	n/a
detail design	30	26	4	n/a	n/a
manufacturing	n/a	n/a	n/a	10	10
total	58	48	10	10	10

In this experiment, the detail design deadline was set as flexible pattern. Applying this management intervention, detail design work team could provide additional time resource for particular design project where excessive rework tasks are necessary.

As shown in the simulation results (in Figure 7.5 (b) & Table 7.7), 10 design uncertainties were generated when the product design package proceeded to manufacturing stage in this experiment. Therefore, 10 design problems emerged as a consequence of these design uncertainties, and 10 rework tasks were requested by manufacturing team to detail design team. Under felxible design environment, detail design work team spent addtitional 100 weeks (10 reworks * 10 weeks / rework), in order to complete all rework tasks.

Finally, the new product was developed and proceeded to the service section in this experiment. As a results, the detail design team spent additional 100 weeks (10 rework * 10 weeks / rework) to complete all rework tasks. Because the deadline-dd-extension is greater than deadline-mc in this experiment, the total new product development cycle is 280 weeks (100 weeks + 80 weeks + 100 weeks) in this experiment. It is highlighted with red circles in Figure 7.5. It is indicated by the information board in Figure 7.6.

Figure 7.6 General performance (experiment 3)

Considering the deadline-dd-extension of 100 weeks overlaps with the manufacturing period of 50 weeks, therefore total new product development cycle was extended by 50 weeks (100 weeks – 50 weeks) in this experiment. It is demontrated in Figure 7.7.

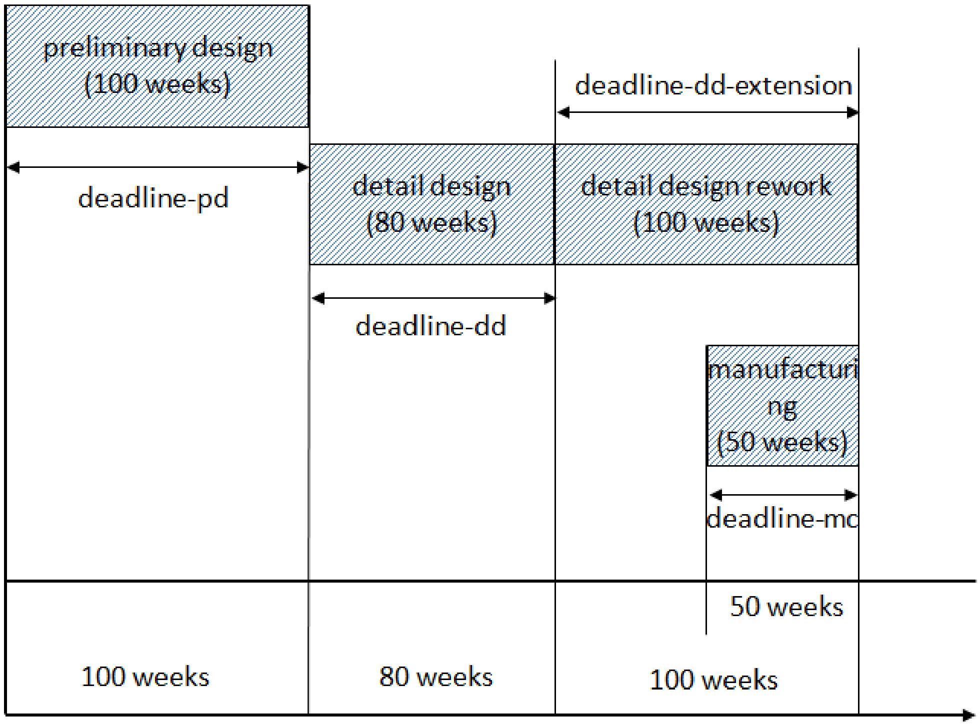


Figure 7.7 Extended product development cycle

In this experiment, the detail design team was enabled flexible design deadlines, and therefore excessive rework tasks could be completed within an extended deadline. In terms of team-level performance, the detial design performance was greatly influeced by the 10 rework tasks. Finally, the new product was developed in 280 weeks, which is 50 weeks longer than the original product development cycle.

7.3.4 Discussion of results

This experiment applied flexible deadline with detail design work team, in order to provide sufficient design time for detail design to complete excessive rework tasks. The results from this experiment was that the new product was developed using 280 weeks, and the development cycle was extended 50 weeks. The findings from the simulation results was that flexible detail design deadline for a particular design project could overcome vicious circles problems. But new product development cycle might be extended for those projects that involve excessive rework tasks. At the same time, the project budget would be increasing with product development cycle extension.

In this experiment, the new product design project was completed with extended development cycle and increased project budget. In the real world, this kind of management intervention is often used, depending on various considerations. For those important design projects but excessive reworks are inevitable, product development cycle extension may be a necessary sacrifice for saving pre-invested budget and achieving business goal.

The operation manager could apply flexible deadline style at particular work teams with a specific design project, where excessive reworks are inevitable. This could save the pre-invested budget and achieve essential business goals. The difficulties from real world are that the manager needs to make decision why and how to release a project’s deadlines. The management intervention considers many balances amongst business goals, market opportunities, extended development time, and increased project budget.

7.4 What can be done to shorten the new product development cycle?

Results from the experiments 1 & 2 showed that improved engineering communication efficiency could enhance new product introduction system design capability, and therefore mitigate vicious circles problems. Results from experiment 3 indicated that flexible deadlines within new product introduction system could be applied to complete those design projects that would be stopped under restrict deadlines. These led to the forth experiment, which considers both design capability improvement and flexible deadline pattern. The experiment intent is to explore potential management interventions to shorten total product development cycle.

The experiment purpose was to explore potential management interventions to shorten new product development cycle. Two strategies used in this experiment were activating flexible deadline style and enhancing specific work teams’ design capabilities. Four operation scenarios were designed and implemented using the simulation model. Experiment results and management recommendations for the real world system operation are demonstrated and discussed.

7.4.1 Input data

In order to implement the management strategies applied in this experiment, design capabilities at particular work teams were enhanced in four simulation scenarios. The input data used in the four operation scenarios is designed in Table 7.8.

Table 7.8 Input data (experiment 4)

variable	scenario 1	scenario 2	scenario 3	scenario 4
pd-request-rate	4	4	4	4
time-consumed-for-responding-pd	**4**	**3**	**2**	**1**
dd-request-rate	4	4	4	4
time-consumed-for-responding-dd	**4**	**3**	**2**	**1**
time-consumed-for-rework	10	10	10	10
time-amount-to-make-a-sideproduct	2	2	2	2
deadline-pd	100	100	100	100
deadline-dd	80	80	80	80
deadline-mc	50	50	50	50
HR-distribution-for-current-project	50	50	50	50

In Table 7.8, the values of both time-consumed-for-responding-pd and time-consumed-for-responding-dd were gradually decreased. This is one way to enhance the design capabilities of both preliminary design team and detail design team, because they could reply to information requests in a shorter time. For example, the preliminary design's information requests were responded to by detail design team every 4 weeks in scenario 1, which is reduced to 1 week in scenario 4.

In the real world, design capability could be enhanced, considering various factors. For example, the socio-technical hexagon (Challenger, Clegg et al. 2010) involves six aspects: goals, people, buildings / infrastructure, technology, culture, and processes / procedures. The lean manufacturing (Grieves 2006) considers people, process / practice, and information technology. There are other process / system performance indicators architectures, like, Six Sigma, Just in Time, the Kaizen, and others.

7.4.2 Results

The simulation results are demonstrated in the following Figure 7.8 to Figure 7.11.

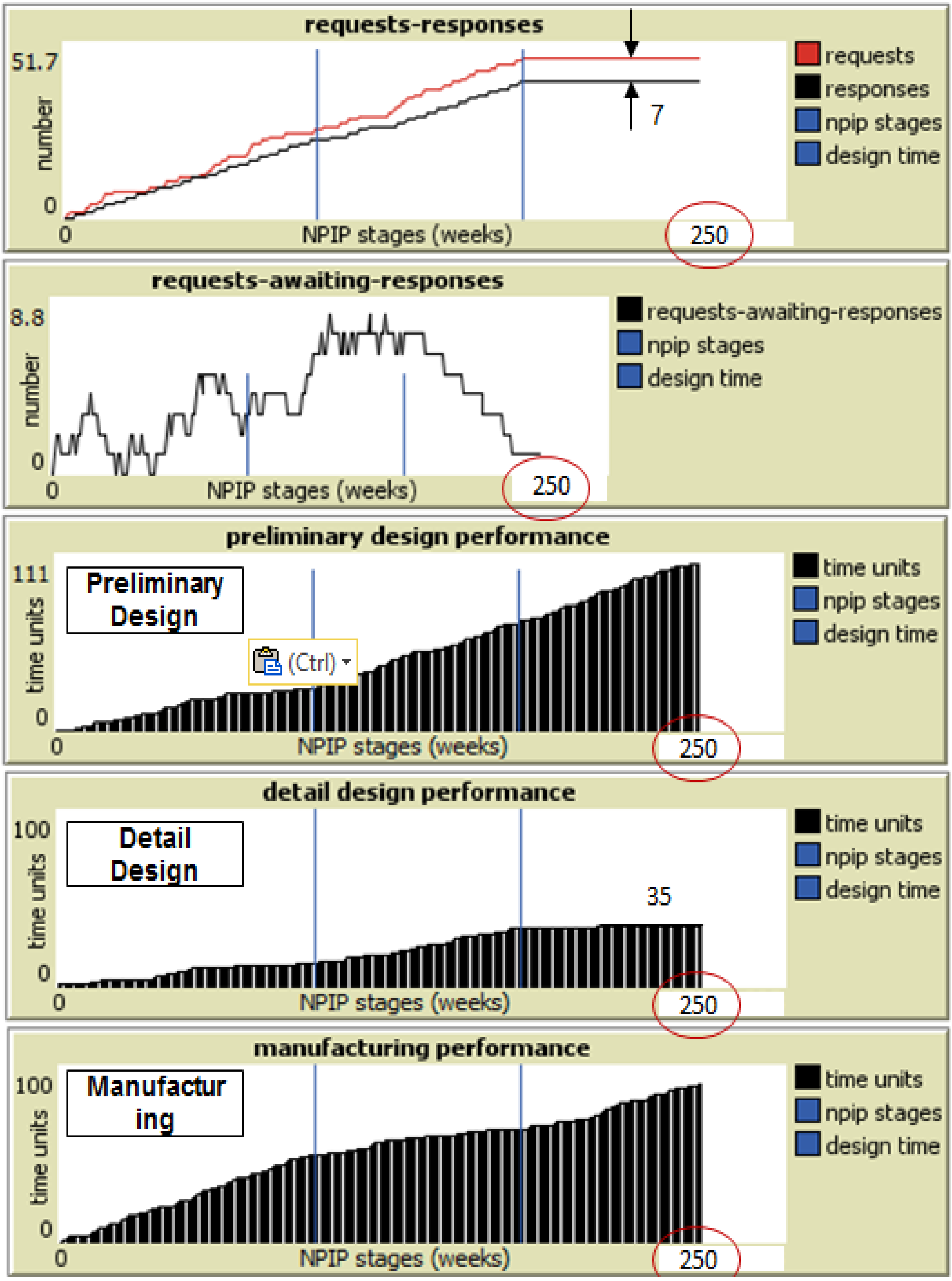


Figure 7.8 Results (experiment 4 - 1)

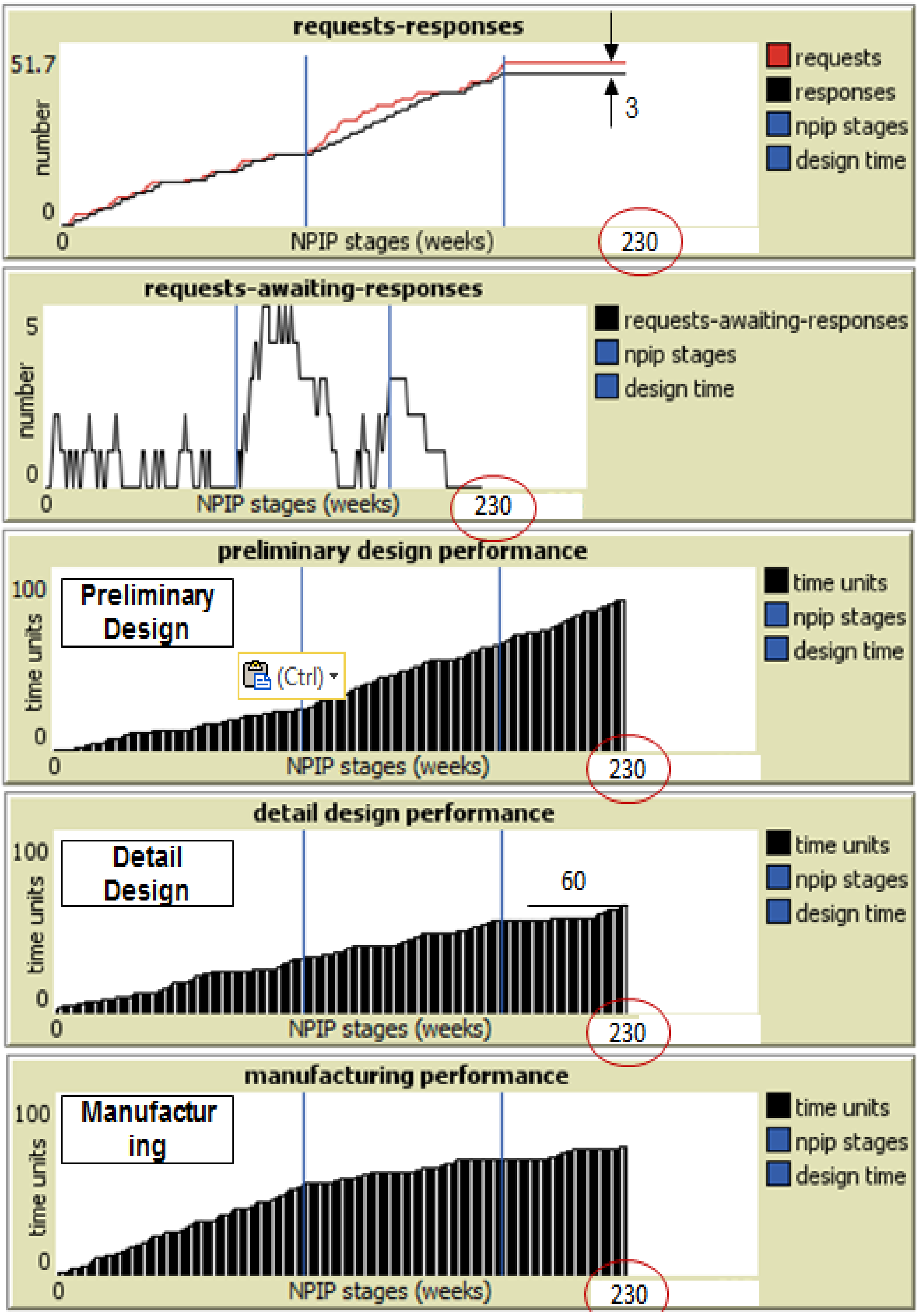


Figure 7.9 Results (experiment 4 - 2)

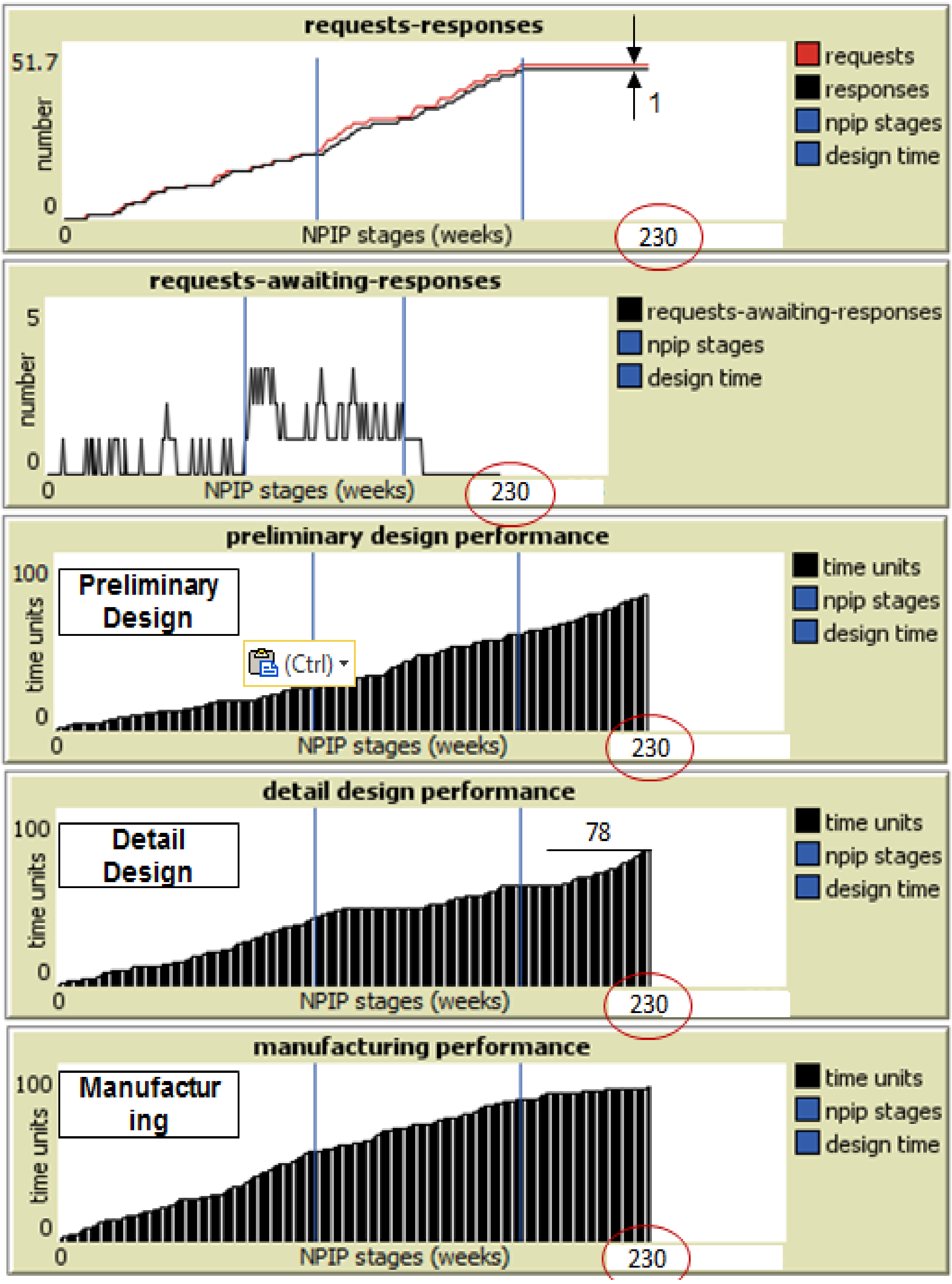


Figure 7.10 Results (experiment 4 - 3)

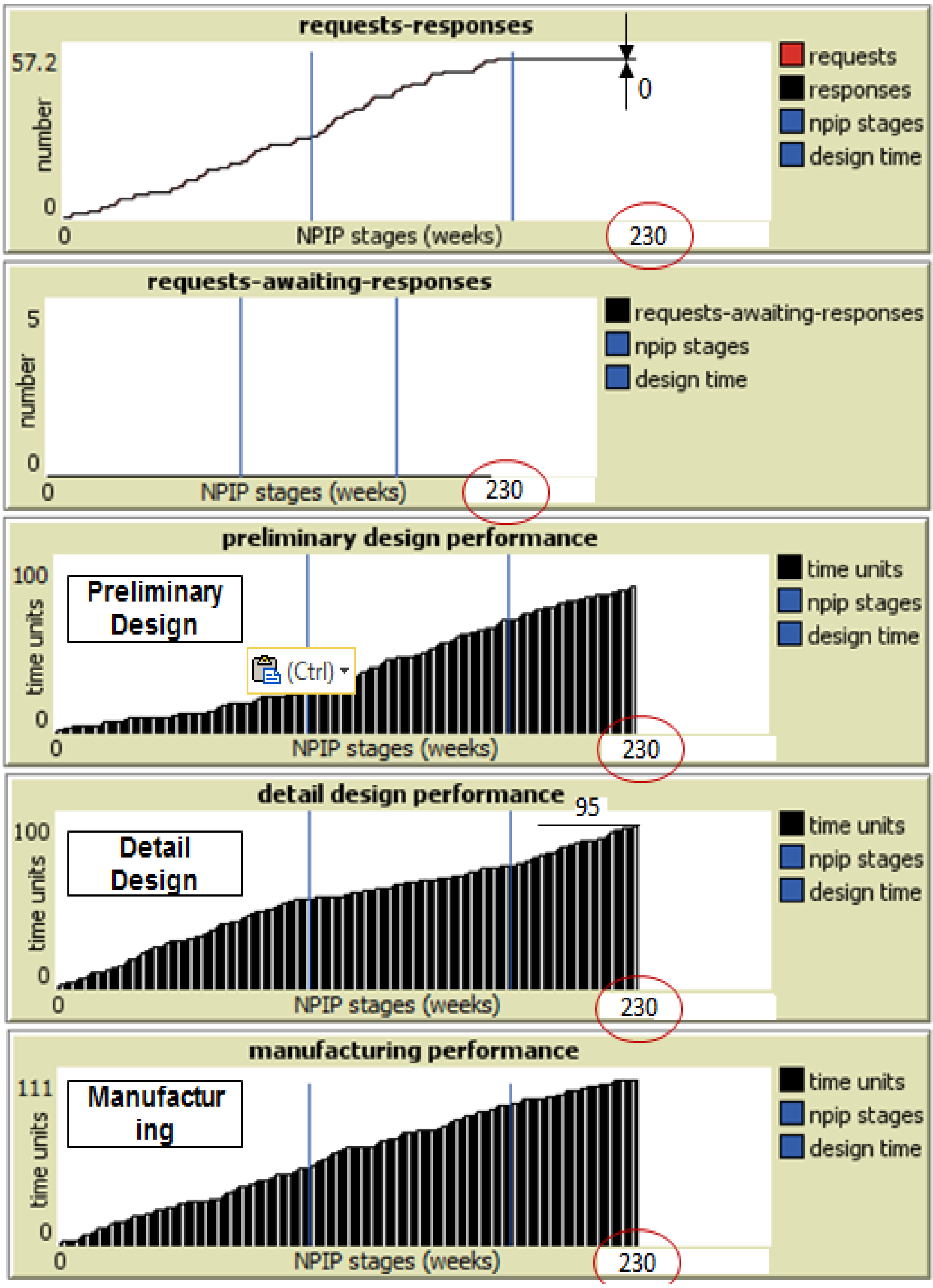


Figure 7.11 Results (experiment 4 - 4)

In these experiments, the design capability with both detail design and manufacturing work teams is increased gradually in four operational scenarios, by reducing the time to responding to information requests. Given a same new product design project was carried on within the four operation environments, the first experiment result is that the product development was delayed and the whole design cycle was 250 weeks (with 20 weeks extension), and the forth experiment result is the product development was successfully completed in 230 weeks with ample available time resource maintained in the detail design. They are demonstrated and highlighted in Figure 7.8 - Figure 7.11.

The experiment results indicated that product development cycle could be shortened by enhancing specific work team's design capability. And both system-level and team-level performance could be improved by doing so. The detail design work team is a key design stage in this case study, and therefore the detail design work team performance is highlighted and displayed in Table 7.9.

Table 7.9 System performance (experiment 4)

	scenario 1	scenario 2	scenario 3	scenario 4
time-consumed-for-responding-pd	4	3	2	1
time-consumed-for-responding-pd	4	3	2	1
reworks (the difference between requests and responses)	7	3	1	0
available time in detail design	35	60	78	95
product development cycle	250	230	230	230

It can be seen in Table 7.9, the design capability of detail design and manufacturing teams were gradually increased by reducing responding time, and the reworks necessitated for the design system was decreased accordingly. And therefore, the product development cycle was reduced from 250 weeks to 230 weeks. At the same time, the available elapse time maintained within detail design work team was increased. Given the new product introduction system focused on the current design project fully using the available time resources, the whole product development time could be reduced. This provides a potential management intervention with the aim to shorten new product development cycle.

7.4.3 Discussion of results

In these experiments, key work teams’ design capabilities were enhanced by reducing the responding time to information requests. In the real world, various strategies could be applied to achieve this management goal, for example, the socio-technical hexagon (Challenger, Clegg et al. 2010). The experiment results are that product development cycle was shortened, and the detail design possessed more available time resource for the design project. This time resource was used to produce side products in the experiments, with respect to the simulation model definition in Chapter 5. In the real world, the new product introduction system could make good use of the available time resource and focus on the design project, which provide a potentiality of development cycle reduction.

There are still some challenges ahead of this management intervention. Managers should make sure the design time within each work team being properly allocated to different design activities. Managers should make the work team focusing on the current design project, with intent to reducing product development cycle. On the other hand, managers must ensure each work team arrange sufficient time to support future design projects, in order to avoid vicious circles in the future.

7.5 Summary

In this chapter, results from four simulation experiments based on the simulation model were reported. The four experiments explored time-related aspects of the case study new product introduction system and the impacting factors on the new product introduction system performance. Results from the four experiments were reported and discussed, and potential management interventions were recommended to mitigate consequences of vicious circles problems.

The first two experiments discussed two extreme operational situations in the simulation model: (1) all information requests are replied in time and (2) no replies to information requests are given. These operational situations are unlikely to happen in the real world but represent two extremes that could occur. Applying these extreme conditions allowed simulation process and results to be used to explore the vicious circles phenomenon and reasons why vicious circles problems arise in new product introduction systems.

The first simulation experiment assumed all information requests were considered as high priorities in each work team, and therefore all of them were replied to as quickly as possible. In the real world system management, this management method could be applied, but might influence normal daily work of each work team, because there are usually multiple parallel projects carried out by each team. The simulation results showed that the product was developed on time, and no rework tasks were needed in order to eliminate design uncertainties, and as a result no vicious circles occurred in this simulation experiment.

The second simulation experiment addressed the extreme operational situation where all information requests were ignored by the work teams and no responses were provided. In this simulation experiment, since no information requests were replied, there was no information input to the design system, which led to all information requests being converted into design uncertainties in later design stages. These design uncertainties further caused design problems at the manufacturing stage, according to the conceptual model description and definition in Chapter 4. Each design problem needed a rework task resulting in excessive rework requests in the simulation model. The vicious circles problem finally arose due to the large volume of rework tasks in this simulation experiment and the system collapsed before the design had been completed.

Analysing results from these first two simulation experiments, design information communication efficiency can be seen to be an important impacting factor on new product introduction system performance. Low information communication efficiency produced additional rework tasks within system operational process, which consumed large volume of detail design time resource and directly resulted in vicious circles occurring in the simulation experiments.

As discussed at beginning of each simulation experiment, these types of extreme operational situations could not happen in the real world. It can be seen that issues such as communication efficiency and rework tasks produced significant influence on new product introduction system performance especially under a pre-determined deadline environment. In the second simulation experiment, design project failed because the detail design team was not able to provide enough time resource to complete all rework requests. The third experiment explored solutions regarding how to mitigate influence of vicious circles problems, with a focus on time resource for a particular work teams, the detail design team.

The third simulation experiment considered an alternative operational situation where the detail design deadline was flexible. This management strategy intended to ensure that the detail design team had sufficient resources (and, therefore, time) to eliminate the influence of excessive reworks on the detail design stage. One result from the third experiment was that the design project was completed but with a 50 weeks design cycle extension compared with the product development cycle time in the first two experiments. Considering results from this simulation experiment, the product design commission was successfully completed but with product development delay, which leads to increased time to market and further influence on business opportunity and project benefits in market. This management intervention could be applied in the real world, in order to save pre-invested budget on some important projects. On the other hand, this management strategy is detrimental to other projects given product development teams typically have limited resources. Overall, the managers need to consider carefully whether to extend project development cycle, which depends on various realistic considerations.

The third simulation experiment provided a potential solution to mitigate the influence of vicious circles on the new product introduction system performance, although it could produce other concerns within an enterprise-wide system. One of the concerns is that the product development cycle extension impacts product success in the marketplace, because time-related issue is one primary performance criteria, as introduced in Chapter 1. In order to explore potential alternative solutions, an additional simulation experiment was designed and conducted. The fourth simulation experiment applied experience from conducting sensitivity experiments in Section 6.1.2. Considering different input variables of the simulation model, there are many potential ways to improve new product introduction system design capabilities, e.g. reducing information requests volume, answering each information requests faster, and others. The fourth simulation applied two management strategies, in order to eliminate impact of product development cycle extension occurred in the third simulation experiment. The two management strategies were (1) improving design system capability by shortening time to answer information requests, and (2) relaxing the deadline of the detail design stage.

Simulation results from the fourth simulation experiment indicated that the product design project could be completed without development cycle extension if the design capability of detail design team was improved through management strategies applied in this simulation experiment. For example, in operational scenario one, detail design team needs four weeks to reply an information request of preliminary design team, while it was just one week in operational scenario four. There are a number of methods in the real world to achieve the design capability improvement, e.g. enhancing engineers skill, improving methodology & procedure, introducing new techniques. Further discussion of these methods are beyond of the scope of the research reported.

Chapter 8 Conclusions

New product introduction systems are complex socio-technical systems that are used to design, develop, and deliver products and services to users. Limitations in the communication of information, especially responses to information requests between work teams results in design uncertainties in the system. Design uncertainties have adverse effects on the performance of the whole system by creating a need for rework. New product introduction system performance is typically measured with three primary parameters: time, cost, and quality. Rework has a significant influence on these parameters, because it consumes additional resources such as the time of work teams and increases time pressure on the system. The resources used for completing rework could otherwise be dedicated to new product development tasks which could be creating more rework for the future due to lack of time for communication. An important consequence of vicious circles in new product introduction systems is that focusing on rework today leads to more rework in the future.

Problems associated with rework are described in the literature (Wynn et al, 2007), (Wynn et al, 2011), (Eckert and Clarkson, 2010), (Bao et al, 2011). However issues about how and why rework arises within a new product introduction system, with a focus on the limitations of engineering communication, are not found. In addition, there is no systematic research on how decision makers estimate the impact of such rework on the new product introduction system performance. This research formulated the relationship between limitations of engineering communication and design uncertainties that result in rework in later design stages, with a focus on exploring how and why rework is generated within new product introduction systems.

Vicious circles and solutions to tackle them have previously been reported in societal systems (Masuch, 1985), while vicious circles in new product introduction systems is a novel research area. No literature was found on how and why vicious circles arise in new product introduction systems, or regarding the impact of rework on the system performance. This research used a case study new product introduction system employed by an international manufacturing organisation to understand vicious circles problems in new product introduction systems and rework as an important performance impacting factor. Applying the case study new product introduction system, relationships between rework and vicious circles and their impacts on the system performance were demonstrated. This is reported in Chapter 4.

Modelling and simulation techniques are widely applied in a range of areas (Axelrod, 2003). Agent-based simulation, as an emerging simulation method, has advantages compared with traditional discrete-event simulation method when using to build understanding socio-technical system performance. Comparison between agent-based simulation and discrete-event simulation were discussed in extant researches (Siebers et al, 2010), and was further developed in this research, with respect to the case study new product introduction system. One finding was that agent-based simulation methods build up a model as a bottom-up architecture which is the same as a new product introduction system performs in the real world. This research developed a simulation mapping between key elements of new product introduction systems and key concepts that underpin agent-based simulation methods and tools, which demonstrates a mirror relationship with each other. A simulation model was developed to represent the vicious circles in the case study new product introduction system based on the simulation mapping. These contributions were primarily reported in Chapter 5.

With respect to the research purpose, four research questions were identified to explore management strategies to mitigate the vicious circles phenomenon in the case study new product introduction system. These questions are introduced in Chapter 4. Applying the simulation model developed in this research, four simulation experiments were conducted and results were presented in Chapter 7, in order to answer the four research questions. The experimental results led to management recommendations to inform decision-making and interventions in the real world.

8.1 Research Contribution

The contributions of this research are reported in this section against the research objectives that are reproduced from Chapter 1 in italics.

1) *To characterise the vicious circles phenomenon in new product introduction systems based on literature review and practitioners' experience.*

New product introduction systems are implemented by different organisational architectures, with respect to specific business strategies and goals. Primary characteristics of a typical new product introduction system include functional work teams, an engineering communication system, and stages & gates where information is communicated between teams. Key product development stages include such as business planning, conceptual design, detail design, manufacturing, in-service support, and disposal. Typical performance measurements for new product introduction systems are time, cost, and quality. Time-related performance is a primary measurement to new product development success.

Limitations in the communication of information, specially responses to information requests between work teams, create uncertainties within the system. These uncertainties cause problems in manufacturing and later stages, which produce the need of rework on the design project. The rework tasks are identified and returned to specific design stages in the real world, where the rework is considered as a higher priority than their daily work. Rework consumes large volumes of design resources, e.g. the time of work teams, and increases time pressure on the whole system. The time used for rework could be otherwise dedicated to new product design projects, where lack of design information might cause further design problems in the future. This was defined as vicious circles phenomenon in this research.

The vicious circles phenomenon and solutions to tackle their consequences have been widely reported in societal research (Masuch, 1985). While, exploring time-related aspects of vicious circles in new product introduction system is a novel area, and rework was considered as the primary impacting factor on time-related performance of new product introduction systems in this research.

2) *To define a case study new product introduction system, demonstrating the vicious circles phenomenon and its influence on time-related system performance.*

The case study presented in Chapter 4 was distilled from discussion with case study owners and researchers with experience of the new product introduction system in the major UK-based manufacturing company (Coyle, 2012). This case study includes quantitative data related to the new product introduction system time-related performance and is defined in a way that is suitable for use in future research.

Rework and uncertainties were reported in previous literature. Wynn discussed one type of uncertainty: that associated with design assumptions or lack of information (Wynn et al, 2011). The need to eliminate uncertainties and their consequences requires rework that leads to design iteration within the whole system (Wynn et al, 2007). Considering different levels of design uncertainties and rework caused, design iteration occurs either inside one work team or across work teams. Design iteration within particular work teams is considered as a typical and beneficial characteristic of product development processes (Ulrich and Eppinger, 2012), while design iteration across different work teams increases the system complexity and results in rework. For these reasons and without management interventions that can be used to mitigate the consequences of vicious circles, iteration across work teams has more negative effect than positive on the system performance. This case study focused on understanding rework across different functional work teams and its impact on the time-related aspects of the new product introduction system performance.

The case study new product introduction system was defined as a four-stage process, including preliminary design, detail design, manufacturing, and service teams. Through discussion with the case study owner and practitioners, the vicious circles phenomenon within the case study new product introduction system is described as follows. The work team who undertakes a design project often needs design information that is not available at current stage, but might be available in other work teams, they therefore request information to the downstream colleague work teams. For example, the preliminary design team requests design information to the detail design team, and the detail design team then responds to the preliminary design team. Both information requests and the responses form closed information loops that help improving both system performance and product quality. While, not all information requests get responded to in a timely manner in the real world due to various reasons. Under predetermined deadlines style, the work team has to make assumptions for the requests that are not responded to. As a consequence, design uncertainties are involved into the new product introduction system. At manufacturing stage, the design uncertainties are eventually identified and defined as rework tasks, in order to complete the design project. The reworks are returned to detail design stage, where they are considered as priorities.

Rework consumes a significant amount of detail design team resources, i.e. time resource, in this case study. The detail design team tries to complete all rework tasks by using additional time resources, which would otherwise be dedicated to responding to new information requests from the preliminary design team that might produce more reworks needed in the future. At the extreme condition, detail design could not provide sufficient time for completing necessary rework and, the new product introduction system breaks down in a conceptual model of the case study new product introduction system. This kind of operational phenomenon was defined as vicious circles phenomenon in this case study new product introduction system. The conceptual model was developed to demonstrate time-related aspects of the vicious circles phenomenon in the case study and is reported in Chapter 4.

3) *To develop a simulation model to represent time-related aspects of the vicious circles and provide insights into how and why vicious circles arise in the new product introduction system.*

Agent-based simulation is an emerging simulation method compared with traditional discrete-event simulation method (Macal and North, 2010), especially applying it to understand operational system performance. A simulation mapping was developed to specify relationships between key characteristics of the new product introduction system and key concepts of agent-based simulation method in this research. The simulation mapping was built up based on the discussion of advantages and disadvantages regarding the two simulation methods. Such discussion was reported in previous literature (Siebers et al, 2010), and further improved in this research, with respect to the research purpose on the case study new production introduction system.

A thirteen-step procedure for carrying out the research was proposed. The procedure incorporates the simulation steps in extant literature with focus on simulating the case study new product introduction system. The research procedure was developed with potential use in further research of this topic or other applicable research projects.

A simulation model was developed to represent time-related aspects of the vicious circles defined in the case study new product introduction system, based on the simulation mapping. In this simulation model, the functional work teams in new product introduction system are represented by individual agents in the model, the information communication within system is implemented by agents' communication with each other under simulation rule specifications, and the model also provides a simulation world where actions and interactions amongst agents are graphically demonstrated.

The simulation model graphically demonstrated relationships amongst information communication, design uncertainties, rework, and system performance. The system uncertainties level increases with increasing numbers of information requests that are not responded to by the downstream work teams. The need for rework rises since the uncertainties must be eliminated at a later design stage, in order to complete the design project. Excessive rework tasks greatly influence the system performance, and results in vicious circles problems in the case study new product introduction system.

In addition, the agent-based simulation model addressed concerns form previous simulation researches where discrete-event simulation was applied, for example, how the system performance varies with changed uncertainties level within a system? (Wynn et al, 2011) The simulation model developed through this research substantiates Wynn’s viewpoint that agent-based simulation is good for negotiation/rework in simulating new product development process (Wynn et al, 2007).

4) *To verify and validate the simulation model by applying verification and validation strategies and methods.*

The Sargent Circle (Sargent, 2011) was used as a framework for the verification and validation of the simulation model. In this context, following established verification and validation strategies, methods were used: sensitivity analysis method for simulation model verification, animation validation method for simulation model validation. The research approved a primary model validation principle, i.e. applying distinct validation strategies to different model validation stages considering the research purpose. In this research, both simulation model verification and validation used self-validation strategy. Considering identified research purpose, the simulation model verification was focused on checking whether the model is arithmetically right, and the simulation model validation was focusing on checking whether operational process of the simulation model is right. Seven experiments were carried out to implement the verification and validation strategies and methods.

The results of model verification showed that the simulation model is logically correct model to represent relationships amongst key impacting factors of time-related system performance, like information requests, responses, and uncertainties. Both system-level performance and team-level performance in the model are reasonable to represent the vicious circles in the case study new product introduction system. By employing strong animation function enabled by the NetLogo software, the simulation model was validated by using animation validation method. Both system-level and team-level performance displayed in the performance plots were compared with the system operation process that was graphically demonstrated in the simulation world. The model validation results showed that the simulation model is able to represent the case study new product introduction system vicious circles with sufficient accuracy. The model operational process in the simulation world demonstrated how vicious circles arise in the new product introduction systems.

What the author learned from the model verification and validation include: the general verification and validation model provided by Sargent was applicable in simulating the case study new product introduction system. The primary principle of model verification and validation is efficient in this research, i.e. applying distinct validation strategies and methods at different model development stages. Sargent identified animation as a validation method; this research used NetLogo animation function to validate the simulation model. One significant finding was that the build-in animation function of NetLogo provided an effective way to validate the new product introduction model.

5) *To apply the simulation model to the case study new product introduction system, and recommend interventions for managers to mitigate time-related aspects of vicious circles and their consequences on the system performance.*

Four simulation experiments were carried out to answer the four research questions identified in Chapter 4. Results from the simulation experiments are reported in Chapter 7.

The first two experiments explored the impact of different prioritisations of responding to information requests on new product introductions system performance. The experiments considered two extreme operational scenarios: all requests were answered or no requests were answered. Results from the experiments highlighted the importance of prioritising responses to information requests, which significantly reduced the rework volumes in the system. Failure to respond to the information requests caused the simulation system collapse.

The third experiment explored a flexible deadline style of management for particular work teams in the new product introduction system. In this experiment, the detail design deadline was relaxed, with a view to providing sufficient time for completing outstanding rework generated within the design project. Applying this management intervention, a new product was eventually developed with the development cycle extended by 50 weeks. The experimental results showed that managers could apply flexible deadlines with particular work teams in order to mitigate vicious circles influence on time-related system performance. However, managers should balance estimated time scale, increased budget, and business opportunity, when applying this management strategy.

The fourth experiment explored the potential for shortening the whole product development cycle. Two management strategies were applied in this experiment: flexible deadlines and reducing time taken to respond to information requests. In the real world, many strategies could be applied to speed up the responding process, for example, improving work team’s design capability or adopting lean manufacturing techniques. These are beyond of the scope of the simulation model and this research. The results showed that reducing responding time to requests with particular work teams improved time-related aspects of system performance. In addition, making more time available maintained by detail design work team ensures not only reworks could be entirely completed but also it is possible to shorten the whole development cycle. The experiment results suggested that managers could mitigate vicious circles by shortening responding time to requests with particular work teams. Applying this management intervention, managers need to keep balance of time resource allocated to complete current design project and support future projects, in order to avoid vicious circles problems in the future.

8.2 Broader Contribution

In addition to the contributions reported in Section 8.1, there are two wider contributions.

A research procedure for the development and use of modelling and simulation techniques in understanding new product introduction systems is provided in Chapter 3. This research procedure incorporates extant research results on general research with specified research purpose on this case study new product introduction system vicious circles problems. This research procedure brought together two aspects of a simulation model development: model development process and model verification & validation process. This research procedure could also be used for further research on this subject or other simulation researches.

This research developed a simulation mapping demonstrating relationships between key elements of new product introduction system and key concepts that underpin agent-based simulation methods. This simulation mapping was found to be a very effective way to establish a mirror relationship of new product introduction system with agent-based simulation method in this research. Applying this simulation mapping, the functional work teams in new product introduction systems are presented by individual agents in agent based simulation, the engineering communication system in new product introduction systems is implemented by the information communication amongst agents, the real world operational environment is displayed in a simulation world.

Applying the simulation mapping, an agent-based simulation model was built up to represent the vicious circles in the case study new product introduction system in this research. The simulation mapping provides a research foundation for relevant research areas, e.g. supply chain management, new product introduction system performance analysis, and so forth.

8.3 Limitations of the Research

There is no clear definition of uncertainties in new product introduction systems (Thunnissen, 2005), although they are discussed in many literatures with different views of problem-solving. For example, uncertainties with lack of information, uncertainties with system complexity, and so forth (Wynn et al, 2011). In this research, the uncertainties are referring to those associated with design assumptions resulted by lack of design information. That is, the uncertainties are generated within the new product introduction system, because information requests do not get responded to within a satisfactory timeframe.

For those responses provided by the downstream work teams, the required effort and quality of responses may vary in the real world. For example, some responses are clear and efficient, but others need further negotiation. This simulation model assumed that all responses to the information requests used an equal amount of effort, and gave responses at an acceptable quality.

The rework is referring to those across functional work teams in this research and the simulation model, and all rework tasks are identified by the manufacturing team and then returned to detail design work team. In the real world, rework could happen between other teams as well, e.g. between detail design team and preliminary design team. In addition, the time resource used to complete these rework tasks may vary in the real world, considering different levels of uncertainties involved. The simulation model assumed all rework tasks have the same complexity level and consume the same quantity of effort.

Vicious circles problems in new product introduction systems may occur due to various reasons in the real world, e.g. time pressure, lack of financial support, inappropriate procedures, supply chain management problems, and so forth. This research focused on time-related performance of new product introduction system, and therefore explored a view of the vicious circles problems that associate with information communication, time pressure, assumption, uncertainties, and rework.

The simulation model used in this research considered time-related performance of the new product introduction system. The other two measurements, i.e. cost and quality, were not included in this simulation model. In the real world, the management interventions often associate with time-cost trade-offs in new product introduction system operation environment, therefore the discussion of time-cost management interventions needs descriptive context. For example, the fourth simulation experiment results were analysed by using large volumes of description.

New product introduction system performance is closely associated with work teams' design capability. However the simulation model does not reflect the changes of the design capability within each work team. Due to this limitation, the fourth simulation experiment included a set of four independent experiments, in order to reflect the changes of design capability with particular work teams in the new product introduction system.

The simulation model cannot distinguish between product development lead time and product development cycle time. Due to this limitation, the third simulation experiment used a figure to explain development lead time extension and product development cycle extension.

8.4 Recommendations for Further Research

This research developed a simulation mapping, upon which a simulation model was built to understand the vicious circles problems in a case study new product introduction system. Four simulation experiments were conducted to address the research questions identified for this research. Results from the research are promising, and potential further researches are outlined as followings.

This research recommended two management strategies to mitigate the consequences of the vicious circles: answering all information requests and answering the information requests quicker. An alternative strategy could be to focus on reducing the volume of information requests within the product development cycle. One way in which this strategy could be implemented is through integrated project teams (IPTs). By applying this strategy, the whole product development cycle may be shortened with different management solutions. In order to achieve this goal, the conceptual model of the case study new product introduction would need to be modified, and more information needs to be collected from the case study organisation.

The simulation model could be further extended to cover full scale of vicious circles, i.e. preliminary design, detail design, manufacturing, and service. The extended research architecture needs more information and data collected from the case study organisation. By involving the service section, the performance of new product introduction system and its impacting factors will be understood with full views, e.g. product development cycle, product lead time, time-to-market, product competitiveness, and so forth. With respect to the socio-technical hexagon, the simulation model could further involve more key performance indicators, e.g. how much the people will reply the information requests from a particular work team. This simulation model considered one product design project. In the future, the simulation model could be modified to involve two or more product design projects in parallel, where the impacts of rework from a design project affects not only the current project itself but also the future projects.

This research demonstrated an application of modelling and simulation techniques to understand vicious circles in a case study new product introduction system as wicked problems. An agent-based simulation model was developed to represent the new product introduction system, applied to insight of vicious circles problems in the system, and explored potential management interventions to mitigate the consequence of vicious circles.

The long term vision is how to use the simulation model for assisting managers' daily practice.

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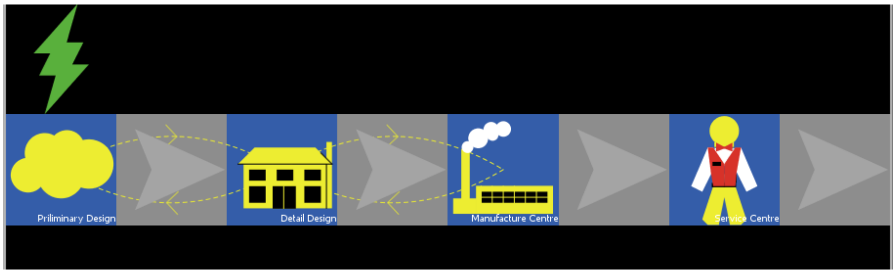
List of Abbreviations

NPIP	New Product Introduction System
NPDP	New Product Development Process
PD	Preliminary Design
DD	Detail Design
ABS	Agent-Based Simulation
DES	Discrete-Event Simulation
MVV	Model Verification and Validation

Appendix A: Simulation Model User Manual 1.0



Vicious Circles Simulation Model User Manual 1.0

This software package was developed at the University of Leeds, Socio-Technical Centre (http://lubswww.leeds.ac.uk/stc/), as part of the Vicious Circles Project, funded by LUBS HEIF. Please cite as: C.-G. Yin, S.I. Coyle, A. McKay and C.W. Clegg, Vicious Circles NetLogo Simulation Model 1.0, Socio-Technical Centre, University of Leeds, Leeds, UK, 2012. Technical support: mncyi@leeds.ac.uk

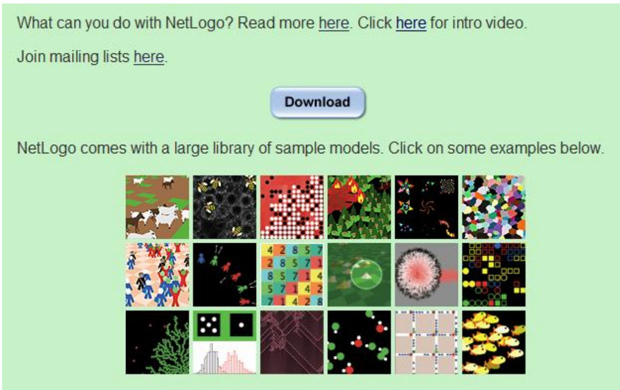
Vicious Circles Simulation Model User Manual 1.0

1. Download NetLogo 5.0.1 version, with respect to Uri Wilensky at CCL, Northwestern University

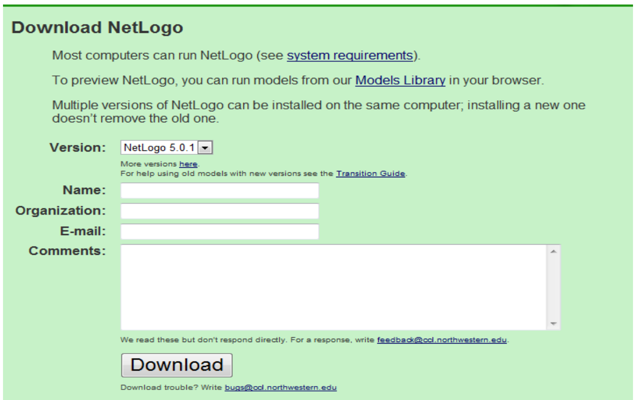
**Please skip to step 2, if NetLogo has already been installed in your computer. If you are experienced with software installation, then please feel free to follow your own preference.*

A. Log onto NetLogo home page, ***http://ccl.northwestern.edu/netlogo/index.shtml***

B. Click ‘***Download***’.

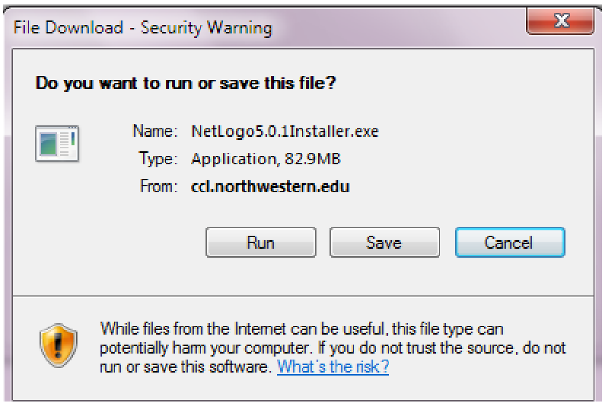


C. Select ***NetLogo 5.0.1*** version, complete the required information, and click the ***Download*** button at the bottom of the page.

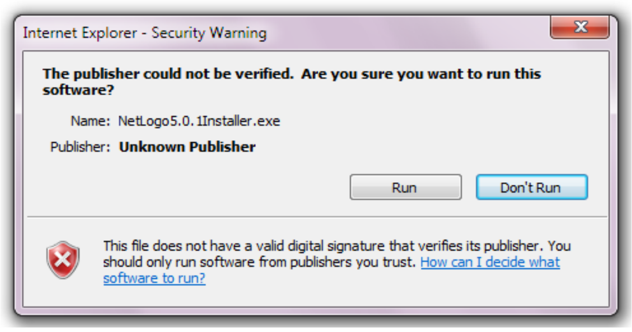


D. Select ***Windows Download (83M)*** option.

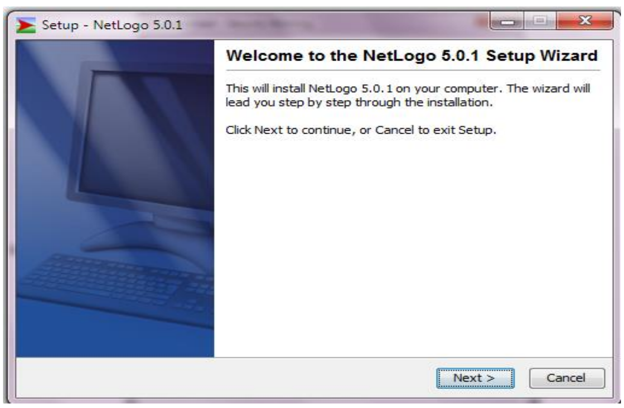
E. Click ***Run***, the software will now be stored in your computers' temporary folder.



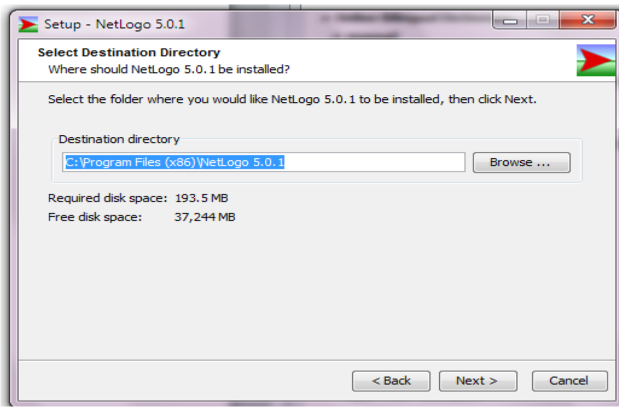
F. Click ***Run***, if your computer reports a security warning.



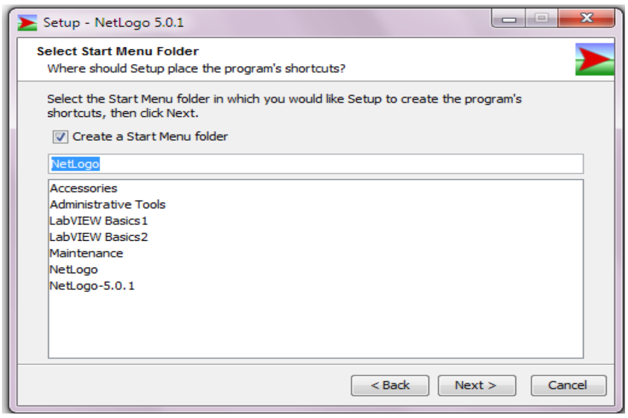
G. Click ***Next***, on the Setup Wizard dialogue.



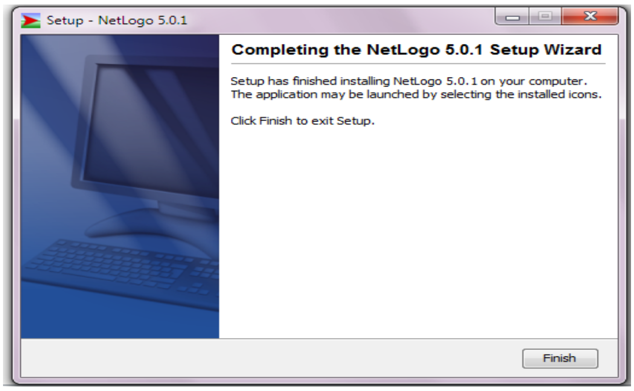
H. Select favorite install destination directory (193.5MB space needed), then click ***Next***.



I. Using default options, click ***Next*** again.

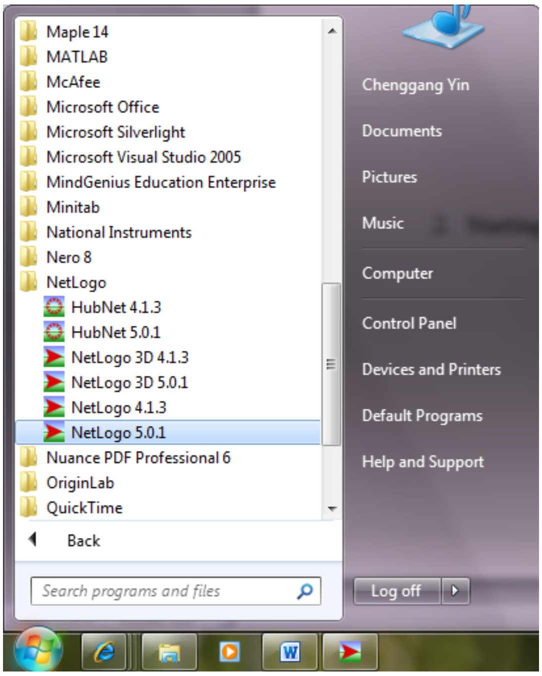


J. Click ***Finish***, thus completing the NetLogo installation on your computer.

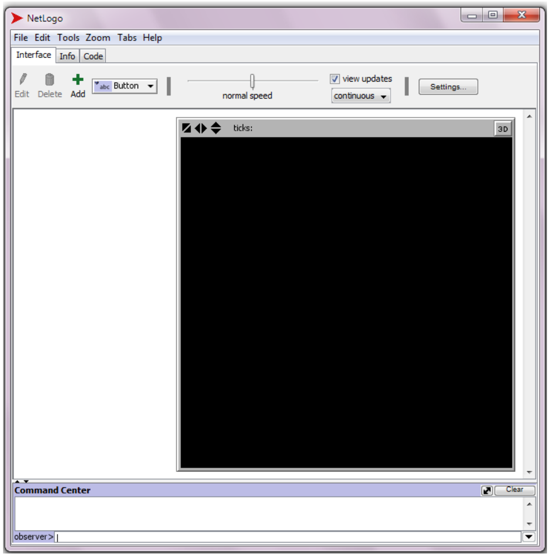


2. Start NetLogo environment

A. Find ***NetLogo 5.0.1*** in the program list of your computer, click it.

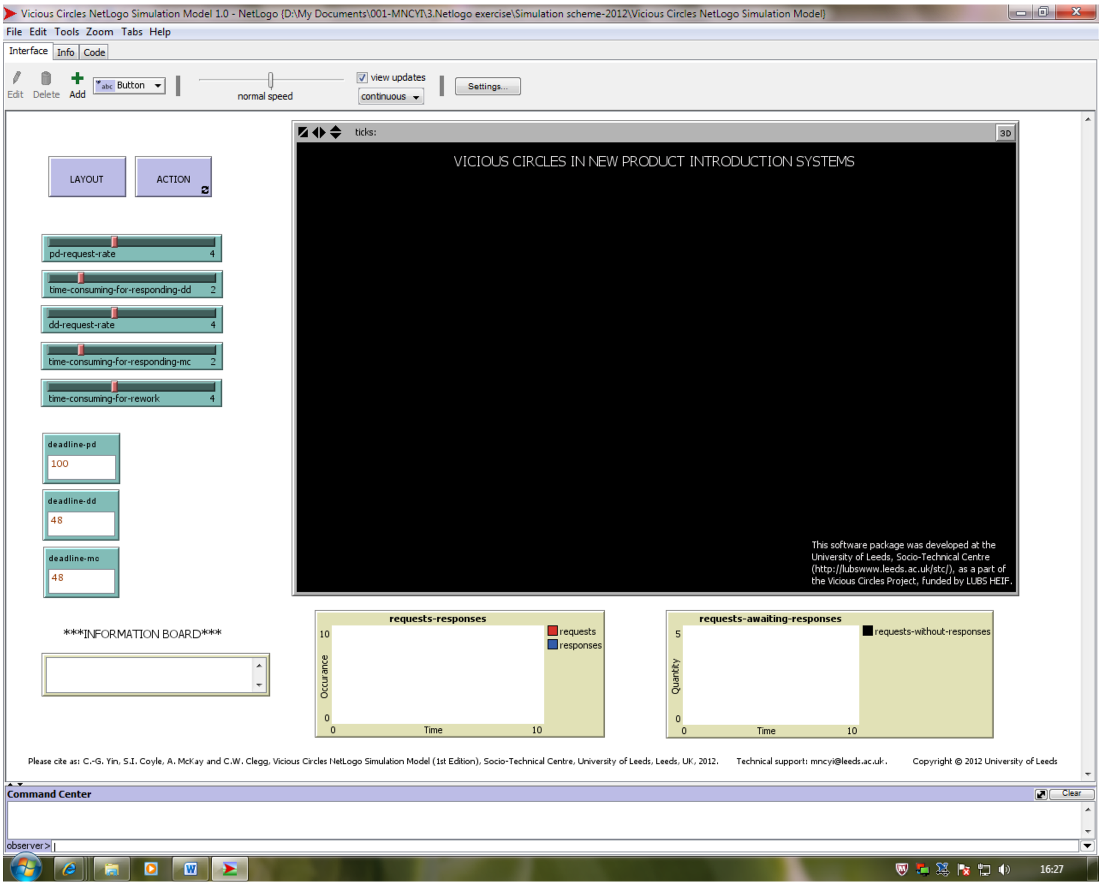


B. A new model will be opened; you can either build this new model or open an existing model.



3. ***Experiment*** - Vicious Circles Simulation Model 1.0

A. Open Vicious Circles Simulation Model 1.0 package and maximize the window: You will get the model interface below. (This model will be perfectly suitable for a 17 inch screen.)



B. Introduction of the simulation interface:

Left: input variables

Right: simulation world

Bottom: output plotting and information board

Left up: function buttons

C. ***Initializing*** input variables

An explanation of each input variable can be found below.

Variables	Explanation
pd-request-rate	How often would preliminary design team request information from detail design team? E.g. if pd-request-rate = 4, then preliminary design team, on average, makes one request to detail design team every 4 weeks.
time-consumed-for-responding-dd	Amount of time detail design team will cost to make a response to preliminary design team. The unit is week(s).
dd-request-rate	How often would detail design team request information from manufacturing team? E.g. if dd-request-rate = 4, then detail

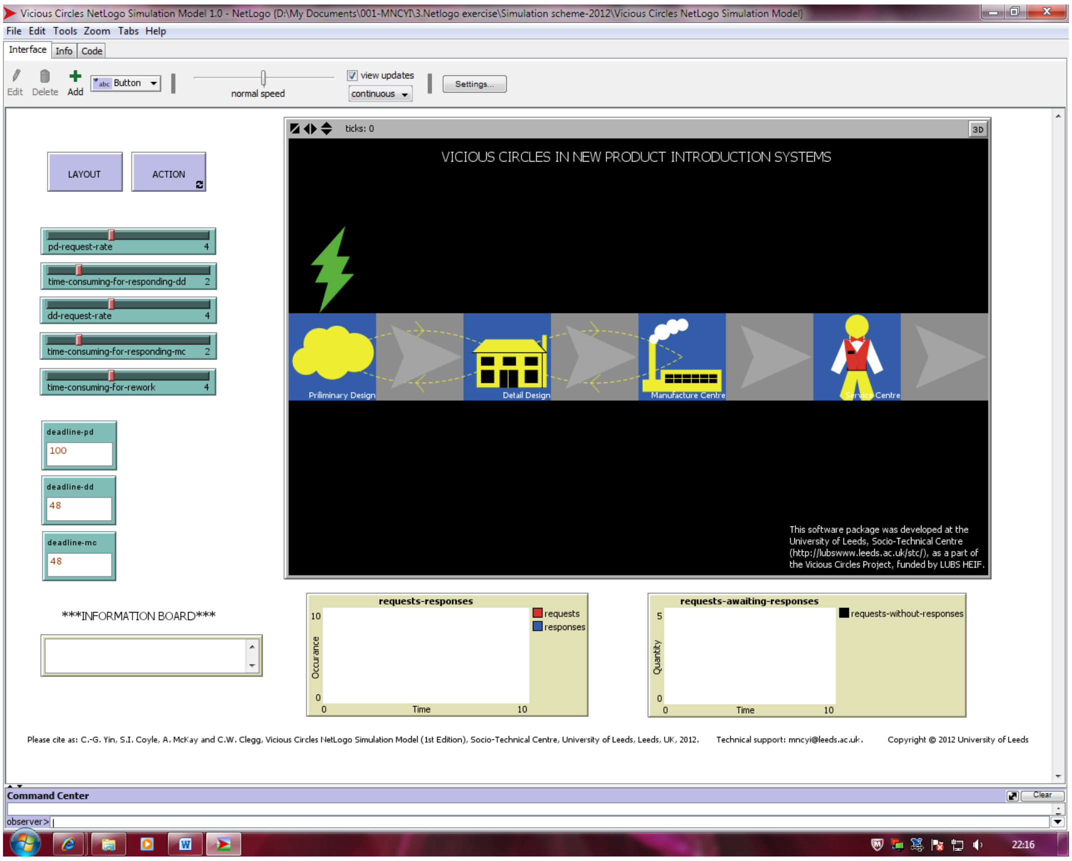
	design team, on average, makes one request to manufacturing team every 4 weeks.
time-consumed-for-responding-mc	Amount of time manufacturing team will cost to make a response to detail design team. The unit is week(s).
time-consumed-for-rework	Amount of time detail design team will cost for rework returned from manufacturing team, as a result of requests that were not appropriately responded to when the product was in previous stages. The unit is week(s).
deadline-pd	Total amount of time for preliminary design team to complete their job. The unit is week(s).
deadline-dd	Total amount of time for detail design team to complete their job. The unit is week(s).
deadline-mc	Total amount of time for manufacturing team to complete their job. The unit is week(s).

The value of these variables can be changed by dragging the sliders or typing values into the input boxes.

D. ***Setting up*** simulation world

When the variables are initialized, click the **LAYOUT** button to set up the simulation world.

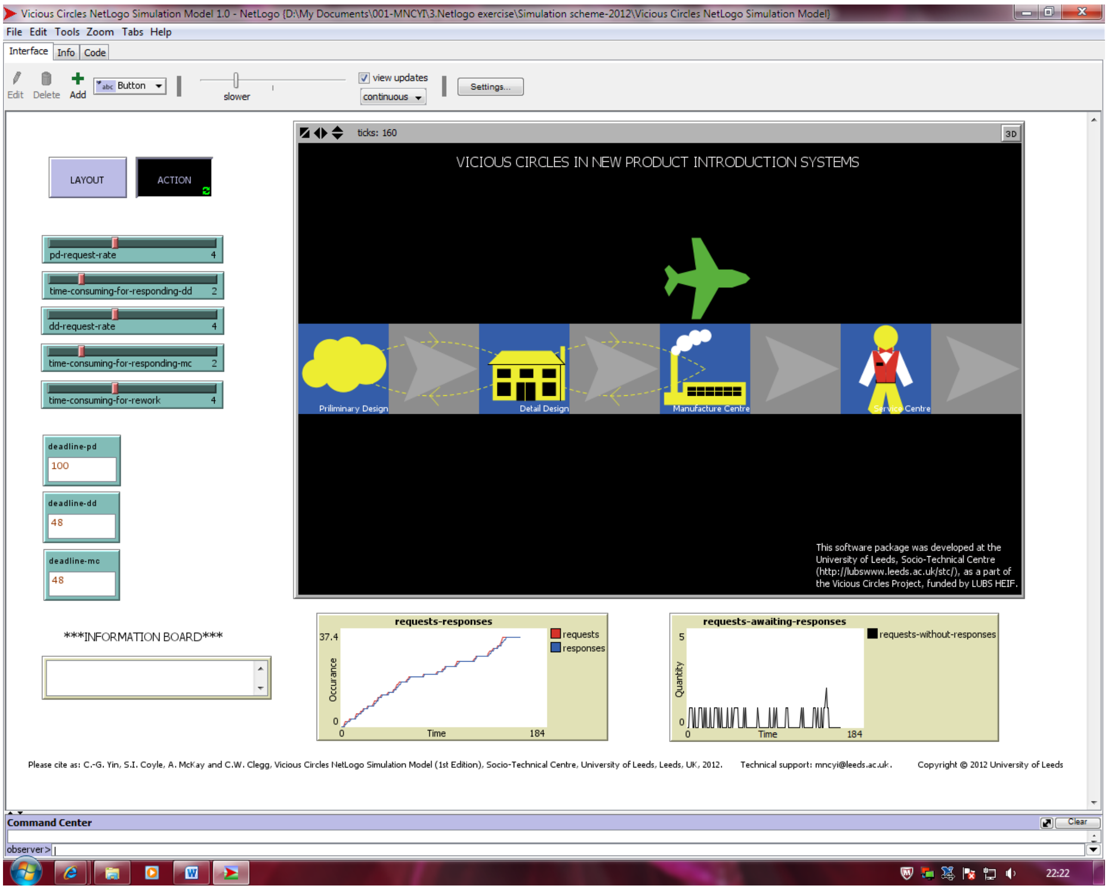
In order to clearly observe the model setting up process, the time can be controlled by dragging the ***speed slider*** on the top of the screen.



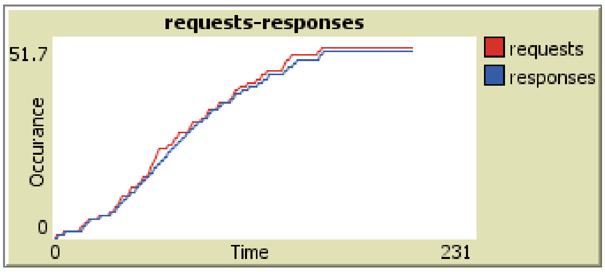
E. ***Running*** simulation model

When the simulation model is set up, click the ACTION button to start running the model.

In order to clearly observe the model simulation process, the time can be controlled by dragging the ***speed slider*** on the top of the screen.

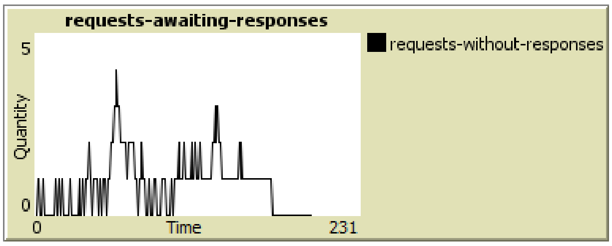


F. Observing simulation results



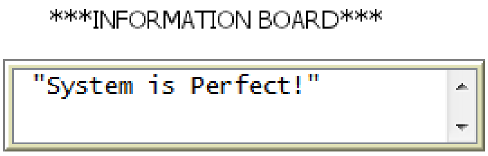
Within the **requests-responses** figure, the red **requests** curve records the requests issued both from the preliminary design team to the detail design team, and from the detail design team to the manufacturing team. The blue **responses** curve records the responses isued to the preliminary design team and the detail design team, from both the detail design team and the manufacturing team respectively.

At any time, the gap between the two curves means the system contains unanswered requests at that point in time.



In the **requests-awaiting-responses** figure, the curve records those requests which were not responded to in a timely fashion or directly missed because of limited resource. These unanswered requests may be responded to later, otherwise they will remain within the product development system as system unknowns and therefore hidden system risks.

When the product is delivered to the manufacturing team, most system unknowns or risk factors would be discovered, resulting in the returning of product to the detail design team for rework. This rework consumes huge time resource within the product development process.



In **INFORMATION BOARD**, the system general performance will be reported. If there are no risks contained within the system when the product is delivered to the final team in the chain – the Service Centre- the system is perfect. Otherwise, the actual situation willl be displayed.

--------THE END-------

Appendix B: Simulation Model Procedure

```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

;;;;;;;;;;;;;;;;Variables Definition;;;;;;;;;;;;;;;;;;;;;

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

globals [universal-time pd-energy-count dd-energy-count mc-energy-count pd-requests pd-requests-number pd-respondings dd-requests dd-requests-number dd-respondings assumption rework judgepoint-1 yachts-a  yachts-a1 yachts-a2 yachts-a3 yachts-a4 yachts-b yachts-b1 yachts-b2 yachts-b3 yachts-b4 yachts-c  yachts-c1 yachts-c2 yachts-c3 yachts-c4 yachts-d yachts-d1 yachts-d2 yachts-d3 yachts-d4 deadline-dd-extension deadline-dd-extension-number addition-rework-period]



;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

;;;;;;;;;;;;;Initialize Simulation Environment;;;;;;;;;;;

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

to setup

  __clear-all-and-reset-ticks
  initial-variables
  ask patch 0 2 [set pcolor blue]
  ask patch 1 2 [set pcolor gray]
  ask patch 2 2 [set pcolor blue]
  ask patch 3 2 [set pcolor gray]
  ask patch 4 2 [set pcolor blue]
  ask patch 5 2 [set pcolor gray]
  ask patch 6 2 [set pcolor blue]
  ask patch 7 2 [set pcolor gray]
```

```
  create-layout
  create-link
  product-produce
end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;
to initial-variables

  set universal-time 0

  set pd-requests 0
  set pd-respondings 0
  set pd-requests-number 0

  set dd-requests 0
  set dd-respondings 0
  set dd-requests-number 0

  set pd-energy-count 0
  set dd-energy-count 0
  set mc-energy-count 0

  set rework 0
  set judgepoint-1 0
  set deadline-dd-extension 0
  set deadline-dd-extension-number 0
  set addition-rework-period 0

  set yachts-a 0
```

```
  set yachts-b 0
  set yachts-c 0
  set yachts-d 0

  set yachts-a1 0
  set yachts-a2 0
  set yachts-a3 0
  set yachts-a4 0

  set yachts-b1 0
  set yachts-b2 0
  set yachts-b3 0
  set yachts-b4 0

  set yachts-c1 0
  set yachts-c2 0
  set yachts-c3 0
  set yachts-c4 0

  set yachts-d1 0
  set yachts-d2 0
  set yachts-d3 0
  set yachts-d4 0

end

;;;;;;;;;;;;;;;;;;;;;;;;;;
to create-layout
  create-turtles 9
```

```
  ask turtle 0 [setxy 0 2 set color yellow set shape "cloud" set label "Priliminary Design"]
  ask turtle 1 [setxy 2 2 set color yellow set shape "house" set label "Detail Design"]
  ask turtle 2 [setxy 4 2 set color yellow set shape "factory" set label "Manufacturing"]
  ask turtle 3 [setxy 6 2 set color yellow set shape "service" set label "Service"]
  ask turtle 4 [setxy 1 2 set color gray + 1 set heading towards patch 2 2]
  ask turtle 5 [setxy 3 2 set color gray + 1 set heading towards patch 4 2]
  ask turtle 6 [setxy 5 2 set color gray + 1 set heading towards patch 6 2]
  ask turtle 7 [setxy 7 2 set color gray + 1 set heading towards patch 8 2]
end

;;;;;;;;;;;;;;;;;;;;;;;;;;
to create-link
  ask turtle 0 [create-link-to turtle 1]
  ask link 0 1 [set color yellow set thickness 0.005]
  ask turtle 0 [create-link-from turtle 1]
  ask link 1 0 [set color yellow set thickness 0.005]
  ask turtle 1 [create-link-to turtle 2]
  ask link 1 2 [set color yellow set thickness 0.005]
  ask turtle 1 [create-link-from turtle 2]
  ask link 2 1 [set color yellow set thickness 0.005]
end

;;;;;;;;;;;;;;;;;;;;;;;;;;
to product-produce
  ask turtle 8 [setxy 0 3 set color green set heading towards patch 1 3 set shape "lightning"]
end
```

```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;MAIN PROGRAM;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

to go

 initial-color-set
 set universal-time universal-time + 1

 ifelse universal-time > 0 and universal-time <= deadline-pd
   [
    stage-1

    ifelse universal-time = deadline-pd
      [ask turtle 4 [set color green]
       ask turtle 4 [set color green]
       ask turtle 4 [set color green]
       ask turtle 4 [set color green]
       ask turtle 4 [set color green]
       ask turtle 4 [set color green]
       ask turtle 4 [set color green]
       ask turtle 4 [set color green]
       ask turtle 4 [set color green]
       ask turtle 4 [set color green]
       ask turtle 4 [set color green]
       ask turtle 4 [set color green]
       ask turtle 4 [set color green]
       ask turtle 4 [set color green]
```

```
      ask turtle 4 [set color gray + 1]
      ask turtle 8 [fd 2]
      ask turtle 8 [set shape "ufo"]
      ]
     []

    ]
    []

  ifelse universal-time > deadline-pd and universal-time <= deadline-pd +
deadline-dd
    [

    stage-2

    ifelse universal-time = deadline-pd + deadline-dd
     [ask turtle 5 [set color green]
      ask turtle 5 [set color green]
      ask turtle 5 [set color green]
      ask turtle 5 [set color green]
      ask turtle 5 [set color green]
      ask turtle 5 [set color green]
      ask turtle 5 [set color green]
      ask turtle 5 [set color green]
      ask turtle 5 [set color green]
      ask turtle 5 [set color green]
      ask turtle 5 [set color green]
      ask turtle 5 [set color green]
      ask turtle 5 [set color green]
      ask turtle 5 [set color green]
```

```
        ask turtle 5 [set color gray + 1]
        ask turtle 8 [fd 2]
        ask turtle 8 [set shape "airplane"]
       ]
     []
     ]
     []

  ifelse  universal-time > deadline-pd + deadline-dd and universal-time <=
deadline-pd + deadline-dd + deadline-mc
    [

      stage-3

      ifelse universal-time = deadline-pd + deadline-dd + deadline-mc and
assumption = 0
       [
        ask turtle 6 [set color green]
        ask turtle 6 [set color green]
        ask turtle 6 [set color green]
        ask turtle 6 [set color green]
        ask turtle 6 [set color green]
        ask turtle 6 [set color green]
        ask turtle 6 [set color green]
        ask turtle 6 [set color green]
        ask turtle 6 [set color green]
        ask turtle 6 [set color green]
        ask turtle 6 [set color green]
        ask turtle 6 [set color green]
        ask turtle 6 [set color green]
```

```
  ask turtle 6 [set color green]
  ask turtle 6 [set color gray + 1]
  ask turtle 8 [setxy 6 3]
  ask turtle 8 [set shape "orbit"]

 ifelse pd-requests-number + dd-requests-number = 0
  [
    output-write "System Perfect!"
    stop
   ]
  [
    output-write "System Smooth!"
    stop
    ]

  stop
 ]
 []

set deadline-dd-extension assumption * time-consumed-for-rework

]
[]

   ifelse universal-time > deadline-pd + deadline-dd + deadline-mc and
deadline-dd-extension > 0
    [
```

```
ask turtle 8 [setxy 2 3]

ifelse random time-amount-to-make-a-sideproduct = 0 [set yachts-a4 yachts-a4 + 1] []
ifelse random time-amount-to-make-a-sideproduct = 0 [set yachts-c4 yachts-c4 + 1] []
ifelse random time-amount-to-make-a-sideproduct = 0 [set yachts-d4 yachts-d4 + 1] []

set deadline-dd-extension deadline-dd-extension - 1
set addition-rework-period addition-rework-period + 1

ifelse random 9 = 0
[
 set assumption assumption - 1
]
[]

ifelse deadline-dd-extension = 0 or assumption = 0
[
 ask turtle 8 [setxy 6 3]
 ask turtle 8 [set shape "orbit"]
 output-write "Product Develop Delayed!"
 stop
 ]
[]

 ]
[]
```

```
    do_drawing_time_period
    show date-and-time

  yachts-producing-PD
  yachts-producing-DD
  yachts-producing-MC
  yachts-producing-SC
  do_plot_1
  do_plot_2
  do_plot_3
  do_plot_4
  do_plot_5
  do_plot_6
  tick

end



          ;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
          ;;;;;;;;;;;;;;;;;SUB PROGRAMS;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
          ;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

;;;;;;;;;;;;;;;;;;;;;;;;;
to initial-color-set
  ask link 0 1 [set color yellow]
  ask link 1 0 [set color yellow]
  ask link 1 2 [set color yellow]
  ask link 2 1 [set color yellow]
```

```
  ask turtle 4 [set color gray + 1]
  ask turtle 5 [set color gray + 1]
  ask turtle 6 [set color gray + 1]
  ask turtle 7 [set color gray + 1]
end

;;;;;;;;;;;;;;;;;;;;;;;;
to stage-1
    ask turtle 0 [set color blue]
    ifelse random 100 < 25 * 4 / pd-request-rate
        [ask link 0 1 [set color red]
         set pd-requests pd-requests + 1
         set pd-requests-number pd-requests-number + 1
         ]
        []
     ifelse pd-requests-number > 0
        [set dd-energy-count dd-energy-count + 1
         ifelse dd-energy-count >= time-consumed-for-responding-pd
            [set pd-respondings pd-respondings + 1 set pd-requests-number pd-requests-number - 1 set dd-energy-count dd-energy-count - time-consumed-for-responding-pd ask link 1 0 [set color red]]
            []
         ]
         []
     ask turtle 0 [set color yellow]
    set assumption pd-requests-number + dd-requests-number
end

;;;;;;;;;;;;;;;;;;;;;;;
to stage-2
```

```
   ask turtle 1 [set color blue]
    ifelse random 100 < 25 * 4 / dd-request-rate
    [ask link 1 2 [set color red]
     set dd-requests dd-requests + 1
     set dd-requests-number dd-requests-number + 1
     ]
    []
    ifelse dd-requests-number > 0
      [set mc-energy-count mc-energy-count + 1
       ifelse mc-energy-count >= time-consumed-for-responding-dd
         [set dd-respondings dd-respondings + 1 set dd-requests-number dd-requests-number - 1 set mc-energy-count mc-energy-count - time-consumed-for-responding-dd ask link 2 1 [set color red]]
         []
       ]
       []
    ask turtle 1 [set color yellow]
   set assumption pd-requests-number + dd-requests-number
end

;;;;;;;;;;;;;;;;;;;;;;;;;
to stage-3
   ask turtle 2 [set color blue]
   set rework assumption * time-consumed-for-rework

   ifelse rework > 0
      [ifelse judgepoint-1 = 0
        [ask turtle 8 [back 2 set shape "ufo" ask turtle 1 [set color blue]]
         set judgepoint-1 judgepoint-1 + 1
         ]
```

```
      [ifelse judgepoint-1 > 0
        [set judgepoint-1 judgepoint-1 + 1 ask turtle 1 [set color blue]]
        []
       ]
      ]
    []

  ifelse rework > 0 and judgepoint-1 >= time-consumed-for-rework
    [ask turtle 8 [fd 2 set shape "airplane"] set assumption assumption - 1
set judgepoint-1 0]
    []

  ifelse judgepoint-1 > 0 and judgepoint-1 < time-consumed-for-rework and
universal-time = deadline-pd + deadline-dd + deadline-mc
    [ask turtle 8 [fd 2 set shape "airplane"]]
    []

  set rework assumption * time-consumed-for-rework
  ask turtle 1 [set color yellow]
  ask turtle 2 [set color yellow]
end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;
to yachts-producing-PD
 ifelse universal-time > 0 and universal-time <= deadline-pd
  [ifelse random 100 > HR-distribution-for-current-project and random time-
amount-to-make-a-sideproduct = 0
    [set yachts-a yachts-a + 1 set yachts-a1 yachts-a1 + 1]
    []
   ]
```

```
    []
  ifelse universal-time > deadline-pd and universal-time <= deadline-pd +
deadline-dd
    [ifelse random time-amount-to-make-a-sideproduct = 0
      [set yachts-a yachts-a + 1 set yachts-a2 yachts-a2 + 1]
      []
     ]
    []
  ifelse  universal-time > deadline-pd + deadline-dd and universal-time <=
deadline-pd + deadline-dd + deadline-mc
    [ifelse random time-amount-to-make-a-sideproduct = 0
      [set yachts-a yachts-a + 1 set yachts-a3 yachts-a3 + 1]
      []
     ]
    []
end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;

to yachts-producing-DD
   ifelse universal-time > 0 and universal-time <= deadline-pd
    [ifelse dd-energy-count = 0
      [ifelse random time-amount-to-make-a-sideproduct = 0
        [set yachts-b yachts-b + 1 set yachts-b1 yachts-b1 + 1]
        []
       ]
      []
     ]
    []
   ifelse universal-time > deadline-pd and universal-time <= deadline-pd +
deadline-dd
```

```
    [ifelse random 100 > HR-distribution-for-current-project and random time-amount-to-make-a-sideproduct = 0
      [set yachts-b yachts-b + 1 set yachts-b2 yachts-b2 + 1]
      []
     ]
    []
  ifelse  universal-time > deadline-pd + deadline-dd and universal-time <= deadline-pd + deadline-dd + deadline-mc
    [ifelse judgepoint-1 = 0
      [ifelse random time-amount-to-make-a-sideproduct = 0
        [set yachts-b yachts-b + 1 set yachts-b3 yachts-b3 + 1]
        []
       ]
      []
     ]
    []
end

;;;;;;;;;;;;;;;;;;;;;;;;;;
to yachts-producing-MC
  ifelse universal-time > 0 and universal-time <= deadline-pd
    [ifelse random time-amount-to-make-a-sideproduct = 0
      [set yachts-c yachts-c + 1 set yachts-c1 yachts-c1 + 1]
      []
      ]
    []
  ifelse universal-time > deadline-pd and universal-time <= deadline-pd + deadline-dd
    [ifelse mc-energy-count > 0
      []
```

```
      [ifelse random time-amount-to-make-a-sideproduct = 0
        [set yachts-c yachts-c + 1 set yachts-c2 yachts-c2 + 1]
        []
       ]
     ]
    []
   ifelse  universal-time > deadline-pd + deadline-dd and universal-time <= deadline-pd + deadline-dd + deadline-mc
    [ifelse random 100 > HR-distribution-for-current-project and random time-amount-to-make-a-sideproduct = 0
      [set yachts-c yachts-c + 1 set yachts-c3 yachts-c3 + 1]
      []
     ]
    []
end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;
to yachts-producing-SC
   ifelse universal-time <= deadline-pd
     [ifelse random time-amount-to-make-a-sideproduct = 0
       [set yachts-d yachts-d + 1 set yachts-d1 yachts-d1 + 1]
       []
      ]
     []
   ifelse universal-time > deadline-pd and universal-time <= deadline-pd + deadline-dd
     [ifelse random time-amount-to-make-a-sideproduct = 0
       [set yachts-d yachts-d + 1 set yachts-d2 yachts-d2 + 1]
       []
      ]
```

```
    []
  ifelse universal-time > deadline-pd + deadline-dd and universal-time <=
deadline-pd + deadline-dd + deadline-mc
    [ifelse random time-amount-to-make-a-sideproduct = 0
      [set yachts-d yachts-d + 1 set yachts-d3 yachts-d3 + 1]
      []
     ]
    []
end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;
to do_plot_1

  set-current-plot "requests-responses"
  set-current-plot-pen "requests"
  plotxy universal-time pd-requests + dd-requests
  set-current-plot-pen "responses"
  plotxy universal-time pd-respondings + dd-respondings

end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
to do_plot_2

  set-current-plot "requests-awaiting-responses"
  set-current-plot-pen "requests-awaiting-responses"
  plotxy universal-time assumption

end
```

```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;
to do_plot_3

    set-current-plot "Preliminary Design Performance"
    set-current-plot-pen "time units"
    plotxy universal-time yachts-a1 + yachts-a2 + yachts-a3 + yachts-a4

end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;
to do_plot_4

    set-current-plot "Detail Design Performance"
    set-current-plot-pen "time units"
    plotxy universal-time yachts-b1 + yachts-b2 + yachts-b3

end

to do_plot_5

    set-current-plot "Manufacturing Performance"
    set-current-plot-pen "time units"
    plotxy universal-time yachts-c1 + yachts-c2 + yachts-c3 + yachts-c4

end

;;;;;;;;;;;;;;;;;;;;;;;;;;;
to do_plot_6
```

```
    set-current-plot "Performance Measurement"
    set-current-plot-pen "time units"
    plotxy universal-time yachts-d1 + yachts-d2 + yachts-d3 + yachts-d4

end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
to do_drawing_time_period

  set-current-plot "requests-responses"
  set-current-plot-pen "npip stages"
  plotxy deadline-pd 0
  set-current-plot "requests-responses"
  set-current-plot-pen "npip stages"
  plotxy deadline-pd pd-requests + dd-requests + 2

  set-current-plot "requests-awaiting-responses"
  set-current-plot-pen "npip stages"
  plotxy deadline-pd 0
  set-current-plot "requests-awaiting-responses"
  set-current-plot-pen "npip stages"
  plotxy deadline-pd 5

  set-current-plot "Preliminary Design Performance"
  set-current-plot-pen "npip stages"
  plotxy deadline-pd 0
  set-current-plot "Preliminary Design Performance"
  set-current-plot-pen "npip stages"
  plotxy deadline-pd 100
```

```
set-current-plot "Detail Design Performance"
set-current-plot-pen "npip stages"
plotxy deadline-pd 0
set-current-plot "Detail Design Performance"
set-current-plot-pen "npip stages"
plotxy deadline-pd 100

set-current-plot "Manufacturing Performance"
set-current-plot-pen "npip stages"
plotxy deadline-pd 0
set-current-plot "Manufacturing Performance"
set-current-plot-pen "npip stages"
plotxy deadline-pd 100

set-current-plot "Performance Measurement"
set-current-plot-pen "npip stages"
plotxy deadline-pd 0
set-current-plot "Performance Measurement"
set-current-plot-pen "npip stages"
plotxy deadline-pd 100

;;;;;;;;;;;;;;;;;;;;
set-current-plot "requests-responses"
set-current-plot-pen "design time"
plotxy deadline-pd + deadline-dd 0
set-current-plot "requests-responses"
set-current-plot-pen "design time"
plotxy deadline-pd + deadline-dd pd-requests + dd-requests + 2
```

```
set-current-plot "requests-awaiting-responses"
set-current-plot-pen "design time"
plotxy deadline-pd + deadline-dd 0
set-current-plot "requests-awaiting-responses"
set-current-plot-pen "design time"
plotxy deadline-pd + deadline-dd 5

set-current-plot "Preliminary Design Performance"
set-current-plot-pen "design time"
plotxy deadline-pd + deadline-dd 0
set-current-plot "Preliminary Design Performance"
set-current-plot-pen "design time"
plotxy deadline-pd + deadline-dd 100

set-current-plot "Detail Design Performance"
set-current-plot-pen "design time"
plotxy deadline-pd + deadline-dd 0
set-current-plot "Detail Design Performance"
set-current-plot-pen "design time"
plotxy deadline-pd + deadline-dd 100

set-current-plot "Manufacturing Performance"
set-current-plot-pen "design time"
plotxy deadline-pd + deadline-dd 0
set-current-plot "Manufacturing Performance"
set-current-plot-pen "design time"
plotxy deadline-pd + deadline-dd 100
```

```
set-current-plot "Performance Measurement"
set-current-plot-pen "design time"
plotxy deadline-pd + deadline-dd 0
set-current-plot "Performance Measurement"
set-current-plot-pen "design time"
plotxy deadline-pd + deadline-dd 100
```

END