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A Generic Framework for Hybrid Simulation in Healthcare

A thesis submitted for the degree of Doctor of Philosophy

by

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Abstract

Healthcare problems are complex; they exhibit both detail and dynamic complexity. It has been argued that Discrete Event Simulation (DES), with its ability to capture detail, is ideal for problems exhibiting this type of complexity. On the other hand, System Dynamics (SD) with its focus on feedback and nonlinear relationships lends itself naturally to comprehend dynamic complexity. Although these modelling paradigms provide valuable insights, neither of them are proficient in capturing both detail and dynamic complexity to the same extent. It has been argued in literature that a hybrid approach, wherein SD and DES are integrated symbiotically, will provide more realistic picture of complex systems with fewer assumptions and less complexity.

In spite of wide recognition of healthcare as a complex multi- dimensional system, there has not been any reported study which utilises hybrid simulation. This could be attributed to the fact that due to fundamental differences, the mixing of methodologies is quite challenging. In order to overcome these challenges a generic theoretical framework for hybrid simulation is required. However, there is presently no such generic framework which provides guidance about integration of SD and DES to form hybrid models. This research has attempted to provide such a framework for hybrid simulation which can be utilised in healthcare domain.

On the basis of knowledge induced from literature, three requirements for the generic framework have been established. It is argued that the framework for hybrid simulation should be able to provide answers to Why (why hybrid simulation is required), What (what information is exchanged between SD and DES models) and How (how SD and DES models are going to interact with each other over the time to exchange information) within the context of implementation of hybrid simulation to different problem scenarios. In order to meet these requirements, a three-phase generic framework for hybrid simulation has been proposed. Each phase of the framework is mapped to an established requirement and provides guidelines for addressing that requirement.

The proposed framework is then evaluated theoretically based on its ability to meet these requirements by using multiple cases, and accordingly modified. It is further evaluated empirically with a single case study comprising of Accident and Emergency department of a London district general hospital. The purpose of this empirical evaluation is to identify the limitations of the framework with regard to the implementation of hybrid models. It is realised during implementation that the modified framework has certain limitations pertaining to the exchange of information between SD and DES models. These limitations are reflected upon and addressed in the final framework.

The main contribution of this thesis is the generic framework for hybrid simulation which has been applied within healthcare context. Through an extensive review of existing literature in hybrid simulation, the thesis has also contributed to knowledge in multi-method approaches. A further contribution is that this research has attempted to quantify the impact of intangible benefits of information systems into tangible business process improvements. It is expected that this work will encourage those engaged in simulation (e.g., researchers, practitioners, decision makers) to realise the potential of cross-fertilisation of the two simulation paradigms.

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This thesis is dedicated to my dear brother

Late Lt. Kanavdeep Singh Khakh

whose memories are the most precious possessions I have.

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Publications arising from the Dissertations

Journals

Chahal, K. and Eldabi, T. A Multi–Perspective Comparison between System Dynamics and Discrete Event Simulation. *Journal of Business Information Systems* (accepted).

Journals under review

Chahal, K. and Eldabi, T. System Dynamics and Discrete e Event Simulation : A Meta–Comparison. *Journal of Simulation*.

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Chapter 1: Introduction

1.1 Introduction

Changing demographic trends, increased customer expectation and reactive government policies are all aggravating the crisis in the National Health Services (NHS). Healthcare providers are experiencing enormous pressure from public and government to improve provision of healthcare. In response to these pressures healthcare is undergoing a radical transformation. Due to the large number and diversity of the constituting organisations, complexity of the healthcare system is overwhelming and beyond the comprehending capacity of human minds (Begun et al, 2003). As healthcare is highly intolerant to failures, healthcare providers require tools to foresee the consequences of their decisions. The need to evaluate these decisions prior to implementation is well recognised (Sobolev, 2005; Walshe and Rundall, 2001; Watt et al 2005). One way to explore different consequences of alternative decision scenarios effectively is simulation and modelling. Although there is considerable literature reported on the use of simulation modelling in healthcare, its impact on healthcare decision making has not been deployed to its full potential (Lowery et al, 1994; Lowery, 1993; Lowery, 1996; Proudlove et al 2007, Brailsford, 2005). Eldabi et al (2007) have argued that both simulation and healthcare can benefit from each other symbiotically.

Healthcare problems exhibit both detail and dynamic complexity. The ability of simulation methods to comprehend this complexity and their use for healthcare issues has received a great deal of attention recently. Eldabi et al (2007) have reported a dramatic increase in healthcare studies since 2000. Discrete Event Simulation (DES) and System Dynamics (SD) are two simulation approaches which are being widely used in healthcare (Brailsford and Hilton, 2001). Both DES and SD model the behaviour of the system over the time. DES as a methodology is based on the philosophy that the behaviour of the system over time is caused by its endogenous structure and variation (Morecroft and Robinson, 2006). DES effectively captures detail complexity, however it struggles when the problems exhibit a high degree of dynamic complexity. SD on the other hand is based on the philosophy that the structure of the system is responsible for its behaviour over the time (Morecroft and Robinson, 2006). SD due to its wider perspective and emphasis on non-linear relations lends itself to smoothly comprehend dynamic complexity (Lane, 2000). Due to its holistic perspective and distant aggregated stance, it struggles to capture detail complexity. Both SD and DES offer advantages in modelling certain aspects of a system, both have their limitations. It is argued that integrated healthcare poses challenges to the use of SD and DES in isolation (Brailsford et al, 2003; Chahal and Eldabi, 2008c). In the appreciation of healthcare as an integrated system, the deployment of hybrid simulation has been proposed (Chahal and Eldabi, 2008c). Hybrid simulation is the deployment of SD and DES in an integrated way, where both paradigms symbiotically enhance each other's capabilities and mitigate limitations by sharing information.

1.2 Simulation Modelling in Healthcare (Background)

Healthcare systems are complex and adaptive systems with multiple stakeholders, where numerous strategic, tactical and operational decisions are made on routine bases. To achieve viable decisions, it is important for all the stakeholders to understand the complexity and have a shared vision of processes. Modelling in general is one of the most widely used tools to support decision making. There are many modelling techniques used in healthcare modelling, such as, Decision trees, Markov modelling, simulation modelling and other statistical methods. Where as Decision trees and Markov modelling deals only with aggregate solutions, simulation modelling deals with both, individual as well as aggregated entities.

Use of simulation modelling in healthcare around the world is gaining momentum. Several different factors are cumulatively contributing towards making healthcare modelling increasingly attractive. Davies and Bensley (2005) cite new challenges for healthcare providers driven by changing demographic and social trends. Young et al (2004) suggested that high expectations of services might be cause for generating the interest of healthcare providers in established modelling approaches. Brigg et al (2006) cites that health care bodies in Australia and Canada require systematic evaluation of all new devices, procedures and pharmaceuticals prior to their approval and adoption. Increasingly institutional factors and advances and availability in computing capacity also favour increasing use of modelling in healthcare.

Eldabi et al (2007) describe a dramatic increase in healthcare simulation since 2000. Two categories of simulation modelling that have gained prominence in the past decade are DES and SD. Another emerging form of simulation, Agent Based modelling, less widespread due to its relative immaturity has also been used in healthcare (Kanagarajah et al, (2006)). The following subsections provide a brief discussion about use and limitations of DES and SD modelling with respect to healthcare systems.

1.2.1 Use of DES in Healthcare

DES modelling is a technique well established in disciplines such as manufacturing and scheduling. Some key texts include Banks et al. (2001) and Law and Kelton (2000). DES models attempt to imitate the observed behaviour of the problem, typically by using stochastic distributions to generate events and quantities typical for the system. Problems are typically conceptualised as networks of queues and servers. Consider the example of a clinic with regular patient entry. Patients wait for registration, after registration, they wait for treatment in the queue until they are given treatment and after the treatment, they leave the clinic. The registration requires a registration nurse and the treatment requires a doctor and a nurse in order to proceed. A simple DES model of this problem may be described by Figure 1.1. It shows the path followed by patient from entry to exit. It also demonstrates activities the patient has undergone and the time and resources required for those activities.

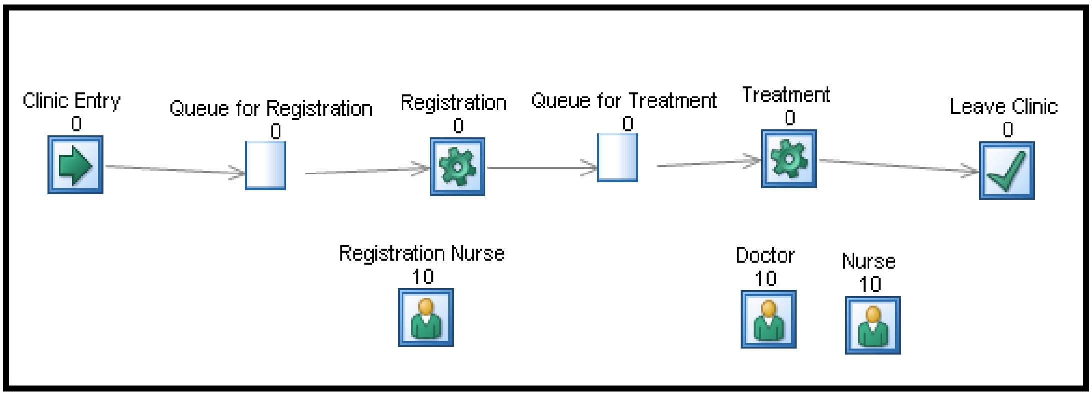

Figure 1.1 Simple DES model of a healthcare problem

DES describes the flow of patients through the treatment system (Davies and Davies, 1994; Karnon and Brown 1998, Caro, 2005). DES has also been used for operational modelling of hospital resources (Harper, 2002). Fone et al (2003) conducted a review of DES in healthcare and reported that DES models had been used to evaluate many healthcare areas, including hospital scheduling and organisation, communicable diseases and screening. Jun et al (1999) conducted a survey on application of DES to understand the operations in healthcare. They have identified that most of the research has been conducted in the area of patient flow and resource allocation. Their survey has also revealed that in most of the scenarios DES has been applied to detailed microscopic analysis of individual units within the multi-facility integrated clinics. They reported lack of literature on application of DES to model the holistic view and argued that this could be due to the increase in complexity associated with modelling integrated systems and due to increase in required resources in terms of time and cost. Lowery (1992, 1993) in his study of hospital critical care has also highlighted the fact that most DES models do not fully consider the inter-relationship between different hospital units. Jacobson et al (2006) have provided a comprehensive review of the use and limitations of DES in the context of healthcare.

Although DES has become increasingly popular in recent years, and is an ideal tool for micro level analysis, they are not well suited to represent the macroscopic view of system taking into account the complex effects produced by interacting processes. This is where SD has advantages over DES. The following section will provide an overview of SD and its use.

1.2.2 Use of SD in Healthcare

SD is based on the philosophy that behaviour of the system over time is determined by its structure. SD is an analytical technique developed by Forrester (1961; 1968) in his work on industrial dynamics. SD models attempt to reproduce the causal structure of the problem, identifying components and feedback loops that are the cause of the dynamic behaviour observed in the system. Models attempt to focus on the systemic properties of the problem caused by the interaction of flows, inter-dependencies and delays. They may also include “soft variables”, qualities that are not measured directly yet are proposed to influence behaviour.

There are two common forms of notation, Causal Loop Diagrams (CLDs), which capture the conceptual relationships in the problem, and Stock-Flow diagrams which describe the structure of the system in more detail. Only Stock-Flow diagrams are implemented as simulations. Both are described in detail by Sterman (2000).Consider the simple example of a hospital operating on a fixed level of external funding. Patients may choose the hospital due to its reputation based on a combination of the treatment outcomes and waiting times reported. Treatment outcomes are influenced by the level of the population. Stock and flow models of this problem may be described by Figure 1.2.

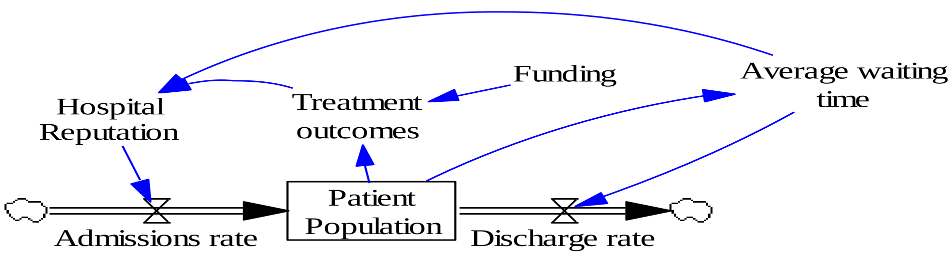

Figure 1.2: Simple SD model of a healthcare problem

The description shows how quantities flow through the system in feedback loops and the active mechanisms that may produce interesting dynamic behaviour. It captures the effect of hospital reputation, which is influenced by treatment outcome and average waiting time, on admission rate. The model also represents the effect of patient population on average waiting times, which further influences discharge rate. The model captures the non-linear relationship between different variables. The SD model is intended to provide an impression of the dynamic trends resulting from the system structure rather than reproduce observed behaviour exactly.

As compared to DES, there have been relatively few applications of SD in healthcare. Dangerfield (1999) presented a survey of SD applications in European healthcare and reported that most of the SD models were either used for persuasion purposes or for providing a framework for evaluation of tactical studies. SD models are more appropriate for studying the inter-relationship between healthcare components. Lane et al's (2000) model of A and E clearly shows the connection of A and E with other parts of the healthcare system. SD models unlike DES models do not produce detailed results at the individual level. Their purpose is to generate insight into the system rather providing accurate predictions. The next section will present the limitation of these modelling approaches and the need for hybrid modelling.

1.3 Need for Hybrid Simulation Modeling

Healthcare systems are complex adaptive systems (Begun et al, 2003). Healthcare complexity comprises of both details as well dynamic complexity. DES captures detail complexity; it is not well suited to represent dynamic complexity. Although DES models are excellent for individual tracking and detailed analysis they are not well suited to model the cross boundary interactions outside the unit for which the analysis is being carried out. These models lack global vision, which can represent interaction between system components. The common objective of large number of reported discrete event studies in literature is to find a correlation between various inputs to healthcare delivery systems (patient scheduling, patient admission rules, patient routing , resource allocation) and various output measures (patient waiting time, resource utilization, patient throughput etc). Most of these studies have been confined to single departments or sections. Since many issues span multiple departments and sectors, decision making for single department results in poor balance of resources across the healthcare system as whole. The few attempts to make

DES models of whole systems have been prone to criticism either for being too simple to represent the reality or too complex to aid in understanding. Due to increasing appreciation of healthcare as an integrated system, another simulation approach SD, which is able to model complex, large, messy integrated systems is gaining a lot of popularity.

SD which has not been as extensively used in healthcare in the past as DES is appropriate for representing the interactions between system's components from a global perspective. Due to their stance on non-linearity and feedback, SD models efficiently capture the dynamic complexity (Lane, 2000; Sterman, 2000). SD does not focus on individual details but on aggregates. In healthcare both interactions between various components as well as detailed individual tracking are equally important. SD models cannot differentiate between individuals on the basis of their attributes. This differentiation is crucial in healthcare systems as many decisions are based on patient attributes (e.g. .maximum waiting time is different for patients with different severity levels). This highlights the importance/need of a modeling approach which is capable of capturing detail up to individual level. This could be the reason for the popularity of DES in healthcare.

From the above discussion, it is quite obvious that where as SD and DES has much to offer in the healthcare field, both have limitations as well. Both their capabilities and limitations appear to complement each other. This research is based on the belief that an integrative hybrid simulation (SD+DES) approach which deploys the capabilities and mitigates limitations of both will provide the decision maker with an invaluable tool to capture both dynamic as well detail complexity. Hybrid simulation is a form of mixing methods and it has been argued that mixing methods can also aid towards stakeholder acceptance (Sachdeva et al, 2007).

Although there has been extensive use of SD and DES in healthcare, the author has not been able to find any reported study which deploys both methods in an integrated way in the healthcare sector. This could be due to the fact that both communities tend to have little appreciation for each other (Moorcroft & Stewart 2006; Lane 2000; Brailsford and Hilton 2001). There is no denial in the fact that there is current awareness and focus of future research in combining these two methods (Eldabi et al 2007; Brailsford et al 2003).

Eldabi et al (2007) have reported in their paper that there is a clear gap in terms of having a holistic view of the system where impact of changes can be viewed outside the departmental boundaries. From the survey they conducted with experts, it has emerged that there is a desire for whole system approach both from the delivery and modelling perspective. They have argued that the overall desire among modellers is to seek a holistic view by mixing methodologies rather than seeking to expand any single methodology to cope with whole system.

Brailsford et al (2003) have also demonstrated the potential benefits of an integrated approach between SD and DES with the example of emergency department. She has emphasised that as both these approaches are complementary, their integration into a unified framework will offer a great insight into the issues confined within the boundaries as well as those system wide factors which are outside those boundaries.

The only study which has used both SD and DES in healthcare (Rohleder et al 2007) has reported that use of SD will be beneficial to explore possible implications of the newly re-designed system. Rohleder et al (2007) have emphasised that it will be beneficial to understand the causal feedback effects of restructuring operations. They have asserted that rather than isolated discrete projects, modelling in healthcare should be viewed as an ongoing process. However like Greasley (2005), Rohleder et al (2007) did not plan the use of SD from the beginning. They used DES to assist healthcare authorities in improving the waiting times at a medical diagnostic laboratory. The initial performance of redesigned facilities was positive, however dynamic feedback within the system of service centres resulted in unanticipated performance problems. They have reported that the use of SD could have helped in predicting these unanticipated implementation problems and suggested some ways to improve.

Coming back to the deployment of hybrid simulation in healthcare context, although there has been a lot of interest, there has not been any study reported so far in the healthcare sector. Hybrid simulation is a form of mixing methods. *In the context of this research it can be defined as integrated deployment of both SD and DES, where both paradigms symbiotically enhance each others capabilities and mitigate limitations by sharing information.* It has been argued that due to different philosophical stance, mixing of methods poses challenges (Mingers 2003; Mingers and Brocklesby, 1997). For effective deployment of hybrid simulation, a theoretical framework for providing guidance for mixing SD and DES is required. This research has not been able to identify any generic framework for hybrid simulation which can be deployed in healthcare.

1.4 Research Aim and Objectives

The aim of this research is to develop a generic framework for hybrid (SD + DES) simulation which can be applied in the healthcare domain. It has been argued in literature that the use of hybrid simulation is justified if there are strong interactions between elements represented by SD and DES (Farhland, 1970). Therefore along with the ability to provide guidelines for integration of SD and DES to form a hybrid simulation model, the framework should also be capable for providing guidelines to identify that problem actually requires hybrid simulation. To achieve this aim five objectives have been outlined. These objectives are summarised as follows:

Objective 1: Develop in-depth understanding of comparisons and selection between SD and DES

For the development of a hybrid framework, thorough understanding of appropriateness of SD, DES and hybrid simulation to different problem scenarios is required. In-depth understanding of differences and similarities between SD and DES is prerequisite for appropriate selection. For this reason meta-analysis of literature on comparison between SD and DES will be conducted followed by a review of literature on selection between SD and DES.

Objective 2: Gain thorough knowledge of existing hybrid (SD+DES) models

In- depth knowledge about the way hybrid simulation has been deployed in the past will serve as a foundation for development of the hybrid simulation framework. In order to gain this understanding, literature on existing hybrid simulation will be reviewed.

Objective 3: Propose Generic Framework for Hybrid Simulation

The research problem represents the gap that there is a need for a generic framework which provides guidelines for integration of SD and DES in the form of hybrid simulation. This objective is about identifying the means to close this gap. On the basis of understanding and knowledge gained from literature reviews, a basic generic framework capable of providing guidance with regards to implementation of hybrid simulation will be proposed.

Objective 4: Evaluation and Refinement of Proposed Framework

In order to assess effectiveness and limitations of the framework within the healthcare context, the framework will be evaluated theoretically by using multiple cases from the healthcare domain. Reflections from this evaluation will provide the basis for refinement. The modified framework will be evaluated empirically using a case study. The empirical evaluation will also be extended to include manual implementation of hybrid simulation. The purpose of implementation is to highlight the limitation of the framework which cannot be identified from theoretical evaluation alone.

Objective 5: Development of Final Framework

The purpose of the previous objective is to identify limitations of the framework. After identifying the weaknesses, the next objective is to reflect upon and address these limitations leading towards the development of the final framework.

It is hoped that by achieving these objectives, the aim of this research will be realised.

1.5 Research Methodology

Irani et al (1999) emphasises on the importance of having relevant research methodology based on the research problem in hand, either related to natural sciences or social sciences both with their corresponding features. However, a research methodology, must not, regardless of all other conditions, dominate the research procedure. The research methodologies must be regarded as mere intellectual frameworks and should not be overused (Quinn et al, 1988).

There are two types of research approaches used by the researchers' Inductive approach and Deductive approach. In a deductive approach reasoning is funnel like; it narrows down from broader more general to specific. It is also informally known as top down approach. In the deductive approach, hypothesis is developed from the research and theory and research method is applied to test hypothesis (Bryman and Bell, 2007). The deductive approach normally works with quantitative research.

The inductive approach is informally known as bottom up approach. As compared to deductive it works in the opposite direction of funnel from specifications to broader generalisations. In inductive we start with specific observations, identify patterns and formulate hypothesis that we can evaluate and finally come up with developing some general conclusions and theories.

There are mainly two research strategies in the field of Information Systems research that are known as Quantitative or Qualitative. The quantitative strategy was originally developed within natural sciences to study natural phenomena. Examples of quantitative methods that are now well accepted include survey methods, laboratory experiments, formal methods (e.g. econometrics) and numerical methods such as mathematical modelling (Myers and Avison, 2002). The quantitative research is based on the meaning derived from numbers and collection result in numerical and standardised data and analysis is conducted through use of diagrams and statistics. The quantitative research entails a deductive approach to the relationship between theory and research i.e. testing theories. The inductive approach is based on qualitative data i.e. non-numerical data and from the analysis of the data, theory is generated i.e. the theory is the outcome of research. Qualitative research emphasizes an inductive approach to the relationship between theories and research and the emphasis is placed on the generation of theories. (Saunders, and Thornhill, 2007; Bryman & Bell, 2007).

Both research approaches equally contribute to research outcome but the emphasis on which research approach should be chosen depends on researchers. The topic which is new and there is scarcity of literature will lend itself into induction by generating and analysing data and developing the theoretical themes the data will suggest (Saunders and Thornhill, 2007).

1.5.1 Research methodology adopted in this research

In this research, as hybrid simulation in an organisational context is a new topic with limited available data on deployment of hybrid simulation in organisational context, an inductive approach has been applied. On the basis of literary observations of existing studies on hybrid simulation, a generic framework is proposed. Figure 1.3 provides diagrammatic sketch of the methodology applied in this research. From the literature on healthcare problem and available simulation methods, the gap in this research was identified. The gap identified is absence of generic framework which can provide guidance for deployment of hybrid simulation in a healthcare context. This research aimed to fulfil this gap by providing a generic theoretical framework for hybrid simulation which can be deployed in healthcare. As discussed in Section 1.4, the aim has been divided into five objectives. In order to achieve the first two objectives, a review of literature was conducted. On the basis of knowledge induced (inductive approach) from the literature, a framework for hybrid simulation is proposed in chapter three.

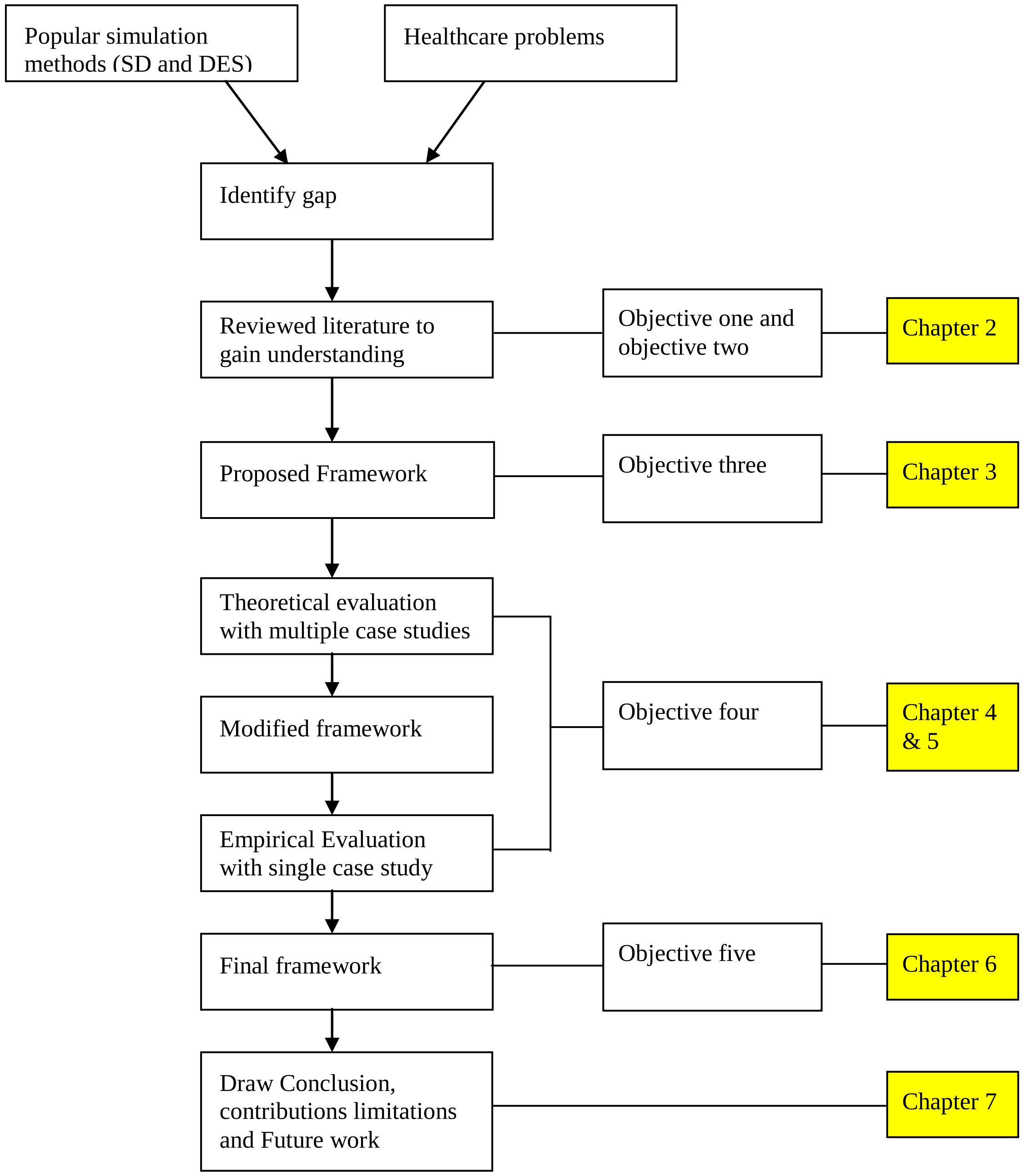

Figure 1.3: overview of research methodology and dissertation map

For further refinement and development, case study method has been deployed. A case study strategy is one that uses the case study method as a systemised way of observing (Weick, 1984). This strategy is characterised by the following two features, which, we think, are valid features for conducting this research: firstly, its ability not to explicitly control or manipulate variables, secondly, the ability to study a phenomena in its natural context. These two features are quite suitable for research into identifying a modelling framework where the aim is to study within realistic settings.

Case study as strategy could be employed in this research for three main scenarios: for development, evaluation and refinement. Case study method can be divided into single case study approach or multiple case approaches. Both approaches will be deployed in this research. For the purpose of theoretical evaluation, the framework will be applied to multiple cases from different settings. The framework will be refined on the basis of reflections from these cases studies. One of the criticisms of the case study method is that the results cannot be generalised, because they relate to specific situations and localities. In response, Yin (2008) and Woods (1997) argue that multiple-case studies can provide analytical generalisations. In the context of the current study, due to the diverse nature of healthcare problems, multiple cases exhibiting different problem contexts have been deployed for theoretical evaluation. It is believed that they will contribute towards increased confidence in the transferability of findings to a broad range of healthcare settings. However the modified framework will be applied empirically to single case study for further evaluation. As the empirical evaluation can be quiet strenuous, due to time constraint, only a single case study will be used for empirical evaluation. On the basis of reflection from empirical evaluation, limitations of the framework will be highlighted. These limitations will be addressed in the final framework.

1.6 Outline of the Dissertation

This section presents an outline of the dissertation. Along with sketch of methodology deployed, Figure 1.3 also provides map of dissertation. The structure of this dissertation is as follows:

Chapter 1 provides a discussion on the use and limitations of SD and DES in the healthcare context and the need of hybrid simulation. It highlights the need for a generic framework for the provision of guidance for hybrid simulation. It also provides a description of the overall aim, its decomposition into five objectives and the research methodology deployed to achieve those objectives.

Chapter 2 provides meta-analysis of literature on comparisons between SD and DES which is a prerequisite for selection between SD and DES followed by review of literature on selection between SD and DES. In order to understand the way hybrid simulation has been deployed in past in organisational context, a review of existing hybrid models has been conducted. It is hoped that by end of Chapter 2, the first two objectives "in-depth understanding of comparisons and selection between SD and DES" and "thorough knowledge of existing hybrids" will be achieved.

Literature reviewed in Chapter 2 provides the foundation for the development of the framework for hybrid simulation. On the basis of knowledge induced from literature review, Chapter 3 proposes a generic framework for hybrid simulation. With the proposition of framework, the third objective of this research will be met.

Chapter 4 is focussed on theoretical evaluation of the proposed framework by using multiple cases. The requirements for the evaluation are set and the framework will be evaluated against its ability to meet those requirements. Reflections from the evaluation will provide basis for refinement of framework.

Chapter 5 will empirically evaluate the framework by deploying a single case study. The purpose of empirical evaluation is to identify the limitations which could not be identified without implementation.

Chapter 6 reflects on the limitation encountered during empirical evaluation and after the modifications describes the final framework which is the main output of this dissertation.

Finally, Chapter 7 summarises dissertation, highlights its contributions, limitations and future work,

1.7 Summary

Chapter 1 provides an introduction to the problem context of this thesis, which is the highly complex nature of healthcare problems exhibiting both detail and dynamic complexity and limitations of widely used simulation methods with regards to comprehension of these complexities. An overview of the use of DES and SD in the context of healthcare is provided. This chapter highlights the need of hybrid simulation in healthcare and the lack of suitable generic framework of hybrid simulation for providing guidance with regards to its deployment. The aim "development of generic framework for hybrid simulation and its deployment in healthcare context" and objectives of the research to realise this aim are discussed in this chapter. It also provides a description of methodology used and outline of the dissertation. In order to achieve the first two objectives, the next chapter will focus on review of literature.

Chapter 2: Literature Review

2.1 Introduction

In the previous chapter the development of a generic hybrid simulation framework and its deployment in the healthcare sector has been proposed as the main aim of this research. The main objective of this chapter is to provide literature to support the main objectives and establish a literary link between the previous chapter and the next chapter which is about the development of a hybrid framework. Prior to application of hybrid simulation it is important to justify that the problem actually requires hybrid simulation (Farhland, 1970). An effective hybrid simulation framework cannot be developed without thorough understanding of the appropriateness of SD and DES to different problem scenarios. For appropriate selection between SD and DES, in-depth understanding of differences and similarities between SD and DES is required (Brailsford and Hilton, 2001). In order to fulfil that need, this chapter provides meta-analysis of literature on comparison between SD and DES followed by review of literature on selection between SD and DES. Literature on hybrid simulation in healthcare and outside healthcare domain has been reviewed. It is hoped that by end of this chapter objective one (in-depth understanding of comparisons and selection between SD and DES) and objective two (gain thorough knowledge of existing hybrids) of this research will be achieved. The following paragraph presents a brief outline of the chapter.

This chapter starts with Section 2.1 which provides brief introduction to the chapter. As mentioned in the previous paragraph, understanding of comparisons between SD and DES is required for appropriate selection between the two. Section 2.2 provides meta- comparison between SD and DES. It has been argued that hybrid simulation is only justified if both SD and DES are required for analysis of different aspects of the system and there are interactions between elements represented by SD and DES (Farhland, 1970; Lee et al, 2002). For this purpose it is important that analysts are able to make appropriate selection between SD and DES prior to hybrid simulation. In order to achieve this purpose Section 2.3 reviews literature with respect to selection between SD and DES. Thorough understanding of the different types of hybrids and the way hybrid simulation has been deployed in the past will provide a foundation for development of generic framework for hybrid simulation. In order to achieve this understanding Section 2.4 and Section 2.5 provide a discussion on hybrid simulation. Section 2.4 provides definition of hybrid simulation and various approaches for its deployment. Section 2.5 reviews the literature on existing hybrid simulation. Section 2.6 provides a description of different hybrid format based on morphology of hybrid models. Section 2.7 discussed different modes of interaction between SD and DES models. Section 2.8 discusses limitations of existing hybrid frameworks followed by Section 2.9 which establishes the main research gaps: no reported literature on use of hybrid simulation in healthcare and the absence of a generic framework for hybrid simulation. Finally Section 2.10 provides a brief summary of the chapter.

2.2 Comparison between SD and DES

The aim of this research is to develop a generic framework for hybrid simulation. It has been argued in literature that hybrid simulation is only justified if the problem actually requires both SD and DES for modelling different elements of the system and there is close coupling between those elements (Farhland, 1970). The prerequisite for that is ability to select between SD and DES according to the requirements of different problem scenarios which further depend upon in-depth understanding of comparisons between SD and DES. It has been found that literature available on comparison of two techniques is very limited. This could be due to the fact that proponents of two fields have very little appreciation of each other (Sweester, 1999; Lane, 2000). This section compares DES and SD modelling approaches on the basis of the existing literature.

SD and DES models have been compared on the basis of technical and philosophical difference in methods, difference in the way they represent and interpret problems and systems and the difference in the way they have been used (Brailsford and Hilton, 2001; Morecroft and Robinson, 2006; Tako and Robinson, 2006; Tako and Robinson, 2008; Lane 2000). There is lack of comprehensive comparison which combined all these separate views. The need to fulfil this gap has been further aggravated with the growing interest in mixing methodologies and finding an answer to the question when to apply which methodology (Brailsford and Hilton, 2001; Lorenz and Jost, 2006; Morecroft and Robinson, 2006).

In an attempt to fill this gap this research has taken a combined approach and classified existing comparisons under *modelling methodology perspective, systems perspective* and *problem perspective*. *Here methodology perspective refers to philosophical assumptions, technical capabilities, limitations and inherent characteristics of modelling method. Problem perspective refers to "Why" the reason behind the modelling exercise and the system perspective refers to real world context under investigation.* There are two reasons behind choosing system, problem and methodology as criteria for comparisons. First is that all the existing comparisons can be classified under these three parameters providing a comprehensive comparison. The second reason is that system, problem and methodology have significant influence in answering the major question, which is better for what? It has been previously argued that what (object of simulation study), why (purpose of study) and how (simulation method) are the main criteria for deciding between methodologies (Lorenz and Jost, 2006).

Pidd (2004) argues that modellers should think about nature of the system and nature of the problem prior to modelling, as some models are better suited for certain problems than others. From his argument it is evident that there needs to be close fit between modelling methodology, system and problem. There are other factors which are related to a successful modelling practice and hence have impact on deciding between modelling techniques, but the systems, problem and capabilities of modelling methodology have come across as primary factors for the purpose of more realistic representation of problem contexts. It is important to note that the boundaries between these perspectives are much diffused with many overlapping features. The following subsections will provide discussion on identified meta–comparisons. These comparisons will not only provides a comprehensive contrast but will also lead a way forward for answering the question which is better in which situation, which is the focus of next section.

2.2.1 Methodology perspective

Methodology perspective refers to philosophical assumptions, technical capabilities, limitations and inherent characteristics of the modelling method. Quite a few comparisons in literature have been found on the basis of capabilities and inherent aspects of both modelling methods such as how the models represent and interpret, what are the modelling elements of the models etc. Dominance of comparisons on the basis of inherent capabilities of methods could be attributed to the fact that most of the comparisons are carried out by academics and academics tend to concentrate more on methodological perspective.

Coyle (1985) identified that SD models represent closed, nonlinear processes whereas DES models represent open linear processes. However Morecroft and Robinson (2006) argued that DES can model nonlinear closed processes as well. It has been stated that SD and DES differ in the way they represent and interpret problems and systems (Morecroft and Robinson, 2006). Differences have been found in their modelling philosophy and underlying mathematics (Coyle, 1985; Mak, 1992; Sweester, 1999; Lane, 2000). Lane (2000) argued that clients find SD models more transparent and easy to understand, whereas though they find DES models convincing, they do not understand the underlying mechanics of the model. Author agrees with Brailsford and Hilton's (2001) argument that Lane's (2000) stance might be applicable to qualitative SD models, however quantitative SD models with their differential equations and mathematical formulae lack this transparency. Models have been compared on the basis of their capabilities (Randers, 1997; Randers, 1980; Sweester, 1999; Lane, 2000; Ruiz et al., 1996) such as ability to capture randomness, resolutions, parameter estimation and predictions. They have been also compared on the basis of their output, validity and the way they handle data and time (Randers, 1997; Coyle, 1985; Sweester, 1999; Lane, 2002; Tako and Robinson 2006; Tako and Robinson 2008; Randers, 1980).Lane (2000) has argued that both methodologies differ in the way they pursue complexity, "dynamic complexity" in case of SD and "detailed complexity" in case of DES. Detailed comparisons between SD and DES with respect to methodological perspective are shown in Table 2.1.

MODELLING METHODOLOGY PERSPECTIVE		
CRITERIA	**SD**	**DES**
Modelling Philosophy	Causal structure of the system causes behaviour and model building reveals this	Randomness associated with interconnected variables leads to system behaviour.
Representation	System represented as stocks and flows	System represented as queues and activities, processes
Feedback	Feedback explicit	Feedback Implicit
Relationship	Interested in identification of nonlinear relationships	Relationships can be nonlinear but mostly are linear
Randomness	Randomness is not of direct interest and hence is subsumed into delays	Randomness explicitly modelled
Recurring modelling structures	Standard recurring modelling structures exist e.g. Asset stock management process	Standard modelling structures generally do not exist
Interpretation	Feedbacks and delays are vital to system performance over time	Feedback is not that important, randomness leads to system behaviour.
Interpretation of results	Results are easy to interpret, it does not require in-depth knowledge of statistics	Interpretation of results require statistical knowledge
Data	SD Models are not heavily dependent on numerical data	DES models are highly data dependent
Data Sources	Broadly drawn: Subjective , judgemental data held in the form of mental maps is also crucial	Primarily numerical, tangible data with some informational element
Complexity	Complexity increases linearly with size of the model.	Complexity increases exponentially with size of the model.
Type of Model	Qualitative Model/Quantitative	Quantitative Model
Resolution of Models	Homogenised entities, continuous policy pressures and emerging behaviour	Individual entities, attributes, decisions and events
Parameters	SD model's parameters are affected feedbacks loops with in the system	In DES parameters are set after intensive research on historical data but once they are entered in the model they remain unchanged.
Parameter estimation	SD score higher then DES on parameter estimation.	One of the drawbacks of DES is it's weakness in parameter estimation.
Accuracy of the model	System Dynamists are not interested in acute accuracy, As stated that SD models are never more than 40% accurate. They are more interested in the outcome of model as learning laboratories.	DES due to its heavy reliance on data produces accurate, statistically valid models.
Point Predictive ability	SD scores less	DES scores high

Transparency	client find the model transparent/ fuzzy glass box, nevertheless compelling	Client find the model Opaque/dark grey box, nevertheless convincing.
Client confidence	SD models generate confidence in clients by engaging with mental models	DES model generate confidence by engaging with data provided by the client
Validity	Validation increases plausibility of the model as a theory for the causal mechanism generating behaviour	Validity proves the model to be true representation of system.
Scope of Validation	Concerned more with model usefulness. SD proponents shy away from holding their model to strict standards of predictive validity.	DES due to its reliability on data have stronger empirical basis
Validation approach	Emphasis on Internal structure approach - white box approach	Emphasis on model outputs - Black box approach
Underlying Mathematics	SD models the behaviour of system using differential equations	DES use statistical distributions to model the increments of simulation clock.
Computer Animation	computer animation is limited to graphs and equations	DES , with its computer animation capabilities where entities can be shown moving across the system help more in visual understanding of process flow

Table 2.1: Comparisons between SD and DES on basis of modelling methodology perspective

2.2.2 Systems Perspective

Systems perspective refers to real world context under investigation. Upon reviewing literature, System's perspective has also been identified as one of the main criteria which was used as the basis for comparisons. The nature of the system being simulated is an important consideration before deciding between the models because "the model needs to be a close fit, a good representation of the system" (Morecroft and Robinson, 2006; Pidd, 2004). SD and DES have been compared on the basis of the nature, representation and view of the systems Morecroft and Robinson, 2006; Sweester, 1999; Mak, 1992). It has been argued that SD provides a broader holistic view of the system whereas DES provides narrow, microscopic view focusing on precision and detail (Mak, 1992; Lane, 2000). Sweester (1999) has argued that System Dynamicists are interested in fuzzy ambiguous systems whereas DES modeller focuses on clearly defined system. MacDonald (1996) argued that DES is more appropriate for modelling systems where behaviour of the system changes significantly when a specific variable reaches a threshold level, whereas SD is better where the system reacts in a specific way in response to the gradual building up of pressure. Detailed comparisons between SD and DES with respect to systems perspective are shown in Table 2.2.

SYSTEM'S PERSPECTIVE		
CRITERIA	**SD**	**DES**
System focus	Holistic view, wider focus	Analytic view, narrow focus
Clarity of the system	Fuzzy, ambiguous	Clearly defined
Organisational Level	Strategic Level	Operational Tactical Level
Relationships	Nonlinear relations and feedback are under consideration	Mostly linear relations where output has no impact on input
Relation to Outside world	Un-isolated continuous system with cross boundary interactions	Isolated discrete system with no interactions with the outside world.
System processes	Focus is on continuous nonlinear processes.	Focus is on discrete linear processes.
System Orientation	SD focus more on modelling systems	DES focuses more on modelling processes.

Table 2.2: Comparisons between SD and DES on basis of system perspective

2.2.3 Problem Perspective

The third main perspective which has been identified as criteria for comparison is the Problem Perspective. Again this has been influenced by the relevant literature suggesting that nature, scope and different aspects of the problem has influence on deciding between SD and DES, as both SD and DES are more capable of modelling certain aspects of the problem. It has been argued in literature that SD is more suitable for modelling strategic problems and DES for operational and tactical (Brailsford and Hilton, 2001; Lane, 2000). Problems which are caused by the internal structure of the system are better analyzed by SD and problems which are caused due to the randomness are better modelled by DES (Sweester, 1999; Morecroft and Robinson, 2006). DES is more suitable for problems which require detailed analytical analysis and SD is more suitable for problems in need of holistic understanding (Sweester, 1999). Detailed comparisons between SD and DES with respect to problem perspective are shown in Table 2.3.

CRITERIA	SD	DES
Problem scope	Strategic level	Operational Level
Problem Purpose	Gaining understanding, parameter estimation	Precise prediction
Problem perspective	The understanding of the problem lies in analysis of causal feedback effects	Understanding of the problem lies in analysis of randomness associated with interconnected processes and events.
Problem studied	Strategic Level	Operational & tactical Level
Importance of randomness	Low	High
Complexity of importance	Dynamic complexity	Detail complexity
Required resolution	Aggregate, Holistic	Detailed

Table 2.3: Comparisons between SD and DES on basis of problem perspective

From the above discussion on comparisons between SD and DES it is obvious that where as both techniques have distinct advantages at modelling some aspects of systems, both have limitations as well. DES is capable of describing the dynamic behaviour of complex systems with a high quotient of detail complexity and stochastic nature. However it does have major drawbacks. It can only establish estimates of correlation among variables and performance measures using statistics. Without being complicated, it cannot be used to understand the difference between correlation and causality, especially when modelling large integrated systems. DES gives credible models at operational and tactical level, when it comes to modelling strategic level SD scores higher. A major advantage of SD in modelling integrated organisations is its ability to trace relationships among the constituent parts and variables of such systems. Along with that ability of SD to model holistic view of the integrated systems, SD focus on policies rather than individual decisions, dynamic representation of causal relationships and minimum dependency on data makes it ideal for modelling large integrated systems. However, when it comes to modelling high resolution systems, where individual tracking, point prediction, and optimisation are required, DES scores high. Due to the complementary nature of SD and DES, and ever increasing complexity of organisations, hybrid simulation (continuous - discrete approach) has been proposed as potential solution. It has been argued that hybrid simulation should only be deployed in situations where some aspects of the problem require SD and some require DES, and both aspects have strong interactions between them (Farhland, 1970; Lee 2002). Hence it can be implied that selection between SD and DES depending upon their suitability to different problem scenarios is a prerequisite for hybrid simulation. The purpose of meta–analysis was to gain in-depth understanding of overlapping and contrasting features of SD and DES, so that effective and informed decisions are made while selecting the method. The next section will provide a review of literature focussing on selection between SD and DES.

2.3 Selection between SD and DES

As previously mentioned in Section 2.1, selection between SD and DES is a prerequisite for effective hybrid simulation. Harper and Pitt (2004) have argued that selection of an appropriate tool contributes towards successful implementation. Apart from this, due to increasing emphasis on the use of multi-methods, there is a growing concern in the research in understanding which method is better or more suited for a particular problem. It has been argued that the choice of modelling methodology is dictated by the modeller's expertise (Brailsford and Hilton, 2001; Morecroft and Robinson, 2006). This is a typical example of forcing a screw with a hammer. Rather than adopting a tool to the problem, analysts try to adapt problem to available tools. However it should be the other way around because modification of problem according to available tool deviates from real problem context. This mismatch between problem context and methodology could be attributed to the lack of a comprehensive framework helping decision makers to decide upon methodology. Quite a few articles are available on good modelling practices, but very few have attempted to describe how to choose from the many types of available methods. The decision about which methodology is more appropriate in a given situation is very scarcely addressed in published studies (Naseer et al, 2010). Policy recommendations based on different methods depend upon the assumptions of the model (Brennan et al 2006). Different methods are based on different philosophical assumptions and provide differing insights in to the problem situation. Use of inappropriate model in a given situation can lead to flawed results and serious repercussions. Several authors have attempted to provide some guidelines for the selection process. As the aim of this research is to develop a framework for hybrid simulation between SD and DES, only those papers have been selected for discussion, which have included both SD and DES.

Brailsford and Hilton (2001) in their paper on comparisons between SD and DES focussed on the technical difference and suggested that the choice between the two methods is determined by the purpose of the problem.

Barton et al (2004) provided a flowchart for selection of method among SD, DES, decision trees, cohort Markov models or individual level models. The answer to the first question (whether interaction is important) narrows down the options from five to two (SD and DES) and three (decision trees, cohort Markov and individual sampling models). The framework suggests that selection between decision trees, cohort Markov models and individual models depends upon: whether pathways can be adequately represented by decision trees, whether a Markov model will require excessive number of states, and whether interaction between patients is important. Interactions are suggested by Barton et al (2004) as the main criteria for distinguishing SD and DES from rest of the methods discussed in framework. Aggregate interactions and individual interactions distinguish between SD and DES.

It has been argued that although several methods are used for interventions in practice, their selection is made in a very ad-hoc and unsystematic way (Mingers 2000). Mingers (2003) provided a two dimensional framework based on the assumption that different dimensions of the problem such as personal, social and material are captured accurately by different models and depending upon the phase of intervention different method are required. He has mapped the different OR methods to that grid. It is a good attempt in terms of framework as it does not limit its applicability to set number of solo methods but also allow for use of combination of methods. He has advocated using purpose of the problem as the differentiating criteria for selection purposes. Like Brailsford and Hilton (2001), Mingers (2003) also has not provided due importance to system's perspective.

Cooper et al (2007) have argued that choice of modelling technique depends upon the acceptance of modelling technique, model “error”, model appropriateness, dimensionality and ease and speed of model development. They have emphasised on the importance of these stakeholder, time and resources on the selection of model. Like Brailsford and Hilton (2001) their framework also lacks the distinction between selection criteria based on the core features of the problem situation and other organisational constrains (stakeholder acceptance, resources, time). In their framework organisational constraints such as acceptance of model, model “error” (stakeholder preferences), ease and speed of model development (time and expertise) share the platform with “appropriateness of model” (fit of model with system and problem context).

Brennan et al (2006) described the underlying theory linking each approach and selection criteria. They developed a taxonomy grid in which the horizontal axis describes the assumptions about the expected values, randomness, heterogeneity of entities and the degree of non Markovian structure and the vertical axis describes potential interactions between the actors and their evolution over the time. He then mapped the different methods on this grid depending upon their ability to incorporate different elements. The limitation of this taxonomy grid is that it is incomplete as it does not involve the combination of approaches which is widely used on an ad-hoc basis.

Owen et al (2008) suggested a framework for selection between SD, DES and Agent based simulation (ABS) in supply chain context. The core of their suggested framework also based on matching ability of various techniques to capture the problem attributes.

In all these frameworks, authors have provided some of the problem attributes and selection has been guided by the ability of the methods to represent those attributes. Most of these frameworks have focussed on the problem attributes and suggested the models should be selected on the basis of their ability to represent these attributes accurately. It has been argued in the literature that there should be alignment between what (system or problem context), Why (purpose) and How (Method) (Lorenz and Jost (2006); Pidd 2004). Most of the above discussed frameworks have neglected the system perspective. In order to select an appropriate method according to problem situation, it is important that the method is weighed against both system and problem perspective. The author has not been able to find any reported framework which has covered both dimensions. In order to fill this gap, the author has extended the framework proposed by Brailsford and Hilton to incorporate this combined view. Brailsford and Hilton (2001) have provided exhaustive list of criteria for selection between SD and DES. The detail discussion on this adaptation will be provided in the next chapter. From now onwards the emphasis of this chapter will be on hybrid simulation. The following sections will provide detailed discussion on different aspects of hybrid simulation.

2.4 Hybrid Simulation Approaches

Quite a few literatures reported on use of DES to capture detail complexity and SD to analyse dynamic complexity of the healthcare systems (Lane, 2000). However, although healthcare systems exhibit coupled dynamic and detail complexity, no reported work has attempted to capture these interactions between dynamic and detail complexity (Chahal and Eldabi, 2008c). As health care organisations have become more complex and integrated, decision making has been facing challenges. This could be attributed to the lack of available tools. As mentioned previously, the aim of this research is to develop a generic framework for hybrid simulation which will assist management in analysing problems exhibiting interactions between dynamic and detail complexity. Hybrid simulation can be deployed in different ways. The purpose of this section is to provide a description of various approaches to hybrid simulation and provide justification for the approach adopted for development of framework in this research.

There are different approaches to modelling, analysis, and synthesis of hybrid systems. They can be characterized and described along several dimensions. As shown in Figure 2.1, on the one end of the spectrum there are hybrid approaches that represent the extension of continuous systems to model discrete events (Coyle 1985; Wolstenholme and Coyle, 1980) and on the other end there are discrete models extended to represent the behaviour of continuous models (Antsaklis, and Koutsoukos,1998). Apart from these two extremes there are composite approaches that combine the complementary aspects from discrete and continuous.

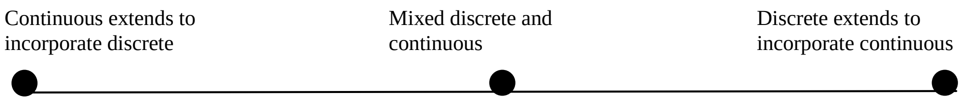

Figure 2.1: Hybrid simulation approaches

Both extreme cases (extension of continuous to model discrete and vice versa) have been excluded from the discussions. The reason behind this exclusion is that the resulting models from these approaches can represent the hybrid behaviour but they do not involve cross breeding of different methodologies. One of the main reasons behind using hybrid models is to reduce complexity (Antsaklis and Koutsoukos, 1998). The extensions of a paradigm to include the behaviour of another paradigm increases complexity.

This thesis focuses on hybrid simulation which is a result of the marriage between SD and DES. Although one of the incentives behind the use of hybrid simulation is reduction in complexity but developing a hybrid model can be quite challenging (Farhland ,1970 ; Helal et al, 2007; Martin, 2000). As stated by Mingers (2003) mixing of methods poses challenges to the developers. He argued that a theoretical framework which can provide step by step guidelines will assist the modellers in the development of hybrid models. As no reported study has been found in healthcare domain, the author reviewed existing hybrids outside the healthcare domain. The following section provides an overview of previous work in the development hybrid simulation.

2.5 Existing Hybrid simulation and Frameworks

The purpose of this comprehensive review is to understand the way hybrid simulation has been deployed in the past so that this understanding serves as a foundation for the development of a hybrid simulation framework. Hybrid models are not a new concept; the first attempts to simulate combined models go back to the days of analogue and hybrid computers. Farhland (1970) is generally credited with the initial work on modelling hybrid systems. Realisation that systems are hybrid and their analysis required hybrid models has been present for some time. The focuses of previous studies have been more on physical control systems. However, interest in use of hybrid models as a tool for decision making in the organisational context is fairly recent. This research focuses on the use of hybrid simulation in the context of organisational decision making. In this section hybrid models which have been deployed or proposed in organisational context will be reviewed.

An intensive literature survey using different combinations of keywords has been carried out in order to find reported existing hybrid models. Only those studies have been reviewed which deployed the integration of SD and DES in the organisational context. It has been identified that majority of the reported hybrid (SD+DES) studies have been found in software industry, followed by manufacturing, supply chain and construction sector. Table 2.4 enlists the industries in which hybrid simulation (SD+DES) has been reported. It also highlights the absence of reported studies in the healthcare domain. The following subsections will provide a description of reported hybrid studies in different industries and the purpose/context for which they have been used or proposed.

Industry	References
Software	Choi et al. (2006); Martin and Raffo, 2000; Martin and Raffo, 2001; Donzelli and Iazeolla, 2001; Wakeland et al, 2004; AbouRizk, et al, 1997; Wakeland et al. (2004).
Manufacturing	Venkateswaran, and Son, (2004); Venkateswaran and Son, (2005) Rabelo, et al, (2003). Rabelo et al, (2005); Helal, et al, (2007) Rabelo,
Construction	Peña-Mora, F., Han, S., Lee, S.H. and Park, M. (2008); Lee et al (2009).
Supply Chain	Lee et al 2002 Lee et al 2002b; Venkateswaran et al, 2006; Reiner, 2005; Umeda and Zhang, 2008; Rabelo et al, 2007; Lee and Kim, 2002
Healthcare	***Nothing reported so far***

Table 2.4: Showing literature search indicating gap

2.5.1 Software Industry

Software processes consist of both event driven dynamics and time driven dynamics. DES captures these event driven dynamics, details of process and randomness associated with process activities. On the other hand SD captures the time driven dynamics of software process and interactions between project factors (Choi et al, 2006; Martin and Raffo, 2000). Quite a few studies have tried to capture these both simultaneously using hybrid simulation (Martin and raffo, 2000; Martin and raffo, 2001; Donzelli and Iazeolla, 2001; Choi et al, 2006; Wakeland et al, 2004; Lakey,2003 ;Raffo et al, 2007; Raffo and Harrison 2000; Setamint et al, 2007;

Setamint and Raffo, 2008). Donizelli and Iazeolla (1996) presents a hybrid model that uses DES for representing activities of work breakdown structure (WBS) and continuous equations to express the resource utilisation and effort as functions of time for each activity of WBS. Their model although categorised under hybrid is more of an extension of DES which uses equations to calculate effort and duration of an activity. Unlike SD models the model doest not incorporate changes in environment due to interaction between various factors constituting the environment.

Christie and Staley, (2000) developed a hybrid model with EXTEND for both DES and SD modelling. The DES captures the activities for requirement process and SD captures the technical capability and social interactions such as influence and interactions of project participants. He faced challenges during the integration of two models. As the model cannot support two separate clock systems, he created pseudo events at the time intervals required for SD model. This technique can support small models, as Christies model was only analysing the requirement gathering process, his approach can become quite complicated for large hybrid models.

Martin and Raffo (2000) used hybrid simulation which represents software development process as a series of discrete activities which are executed in a continuously changing project environment. They used DES to model activities and resources required for the software development process and SD for modelling interactions between project factors and process. They argued that the combined model would allow analysing the effect of discrete variables such as resource change on continuous variables such as productivity. They developed the hybrid using EXTEND. They overcame the problem faced by Christy of having a single clock for SD and DES by creating an executive that can drive the continuous block at the required time increment while preserving the discrete scheduling.

Setamanit et al (2007) further extended and applied Martin and Raffo’s (2000) work for Global Software development (GSD) projects. In which along with environmental factors defined by Martin and Raffo(2001), it also include fundamental GSD factors such as communication, coordination, cultural differences, language difference and time difference etc. the analysed the interaction between these factors and process performance. They applied their model for task allocation strategy and analysed how different task allocation strategies influence these factors and the overall project duration.

Most of the hybrid work in software industry has focussed on understanding and evaluation of interactions between different environmental factors and their overall impact on process. In all hybrids described above the SD is used for representation of environment and DES is applied for detailed representation of activities of the development process. Hence in nutshell it can be implied that the majority of the work in software has been targeted towards capturing the coupling between software development process and the environment surrounding it. On the basis of representation of different aspects of the problem context by SD and DES i.e. representation of environment by SD and representation of process by DES, this type of hybrid combination is named as ***"process- environment"*** format. As the environment and process are coupled in time and space, simultaneous runs of SD and DES models have captured these interactions. Both SD and DES models interact and exchange information during simulation runs. With regards to framework, as exchange between models was happening during run time, the focus has been on the technical side to achieve interaction and synchronisation between SD and DES.

2.5.2 Manufacturing and production Planning

After software the other industry where utility of hybrid simulations has been proposed or deployed is manufacturing industry. Historically DES has been used widely in manufacturing industry. Increased emphasis on globalisation and increasing level of integration in manufacturing poses challenges to the microscopic stance of DES. Responding to those challenges Rabelo *et al*. (2003) proposed hybrid simulation (integrated use of SD and DES) for modelling manufacturing organisations. They presented potential merit of integrating SD and DES models to evaluate the impact of local production decision on the holistic enterprise level. They used the term "Enterprise simulation" for hybrid simulation. They argued that in a modern enterprise that is dominated by different layers of management, an enterprise wide hierarchical simulation will aid in alignment of objectives and tasks of different management levels. They suggested that integration of SD and DES can provide a good framework for hybrid simulation. However, integration of the simulations in terms of time and information coordination was not addressed.

Rabelo et al. (2005) combined DES with SD to develop hybrid models. These models are simple and yet comprehensive enough to model large integrated systems while being able to address different needs of different management levels. In this hybrid model SD is used to build a model for the entire organisation providing the holistic view of organisation and DES used for providing detailed microscopic view of manufacturing and other operational level activities.

Helal and Rabello (2004) further demonstrated the potentials of using hybrid simulation for developing balanced scorecards. They argued that the lack of reliable tool to guide the implementation of balanced scorecard results in numerous failures and hybrid simulation has the potential to fill that gap.

Venkateswaran and Son (2004) highlighted a need for an integrated hybrid SD-DES simulation environment. They suggested that hybrid simulation model comprises of two layers: a lower level DES model representing detail and high level SD model representing aggregate abstraction. An initial feasibility analysis has been carried out in which the inventory management aspects of a facility are modelled using SD and the shop floor operations are modelled using DES. Later, Venkateswaran et al. (2004) described a two level Hierarchical production planning (HPP) architecture consisting of SD components at the higher decision level and DES components at the lower decision level. Venkateswaran and Son (2005) showed the applicability of their approach to a multi-product discrete part manufacturing enterprise and provided formal descriptions of their generic architecture for HPP analysis within a single enterprise. The architecture consists of two levels: The enterprise level planner; and a shop level scheduler. The enterprise level planner is composed of three modules: the plan optimiser, enterprise performance monitor and enterprise level simulator. The enterprise level planner generates the optimal assignment of production capacities to produce over multiple time periods. These are fed forward into schedule level planner. Schedule level planner also consists of three modules: schedule level optimise, schedule level performance monitor and schedule level simulator. In response to input from the enterprise level planner, schedule level planner selects optimal schedule, monitors performance and simulates shop level production activities. The WIP, cycle time and throughput from the detailed model are fed back into the aggregate level SD model. A feedback mechanism is employed so that models are linked in time and space. In their architecture they emphasised more on the information and time synchronisation. The functional description and sequential interactions of different processes of the proposed architecture have been presented using IDEF and IDEF3. The SD and DES model are integrated with HLA/RTI.

Helal et al (2007) proposed a framework for hybrid simulation SDDES for manufacturing which spans across entire enterprise. SDDES offer comprehensive simulation model that encompass all management levels and is capable of providing both holistic as well as microscopic abstraction of the system. Unlike Venkateswaran in their SDDES, single SD model of entire organisation interact with multiple DES models of different departments. DES model representing different units interact and exchange information with SD after different time intervals. It enhances both the utility and reuse of existing DES models and more freedom to the analysts regarding the development of DES for different units.

From the above discussion it is evident that hybrid simulation proposed/deployed in manufacturing focuses on alignment of decision making between different management levels. In this sector Hybrid modelling is deployed in hierarchical manner in which SD represent the holistic view required for strategic decision making and DES represents a microscopic view required for operational decision making, hence this type of combination of hybrid simulation is named as ***"hierarchical format".*** Where as the main focus of HPP (by Venkateswaran, 2005) is more on Top Down evaluating the feasibility of strategic plans before implementation, the focus of Rabelo et al (2007) is more on bottom up alignment looking at the ripple effects from a global point of view.

Simulation in manufacturing is well established and the use of SD for strategic problems and use of DES for operational problems is well accepted. Frameworks discussed above are based on the understanding that there are interactions between strategic and operational decision-making hence in order to make effective decisions regarding problems such as production planning and scheduling, hybrid simulation is required. As these frameworks are based on accepted understanding, they do not provide any guidance with respect to identification of those problems. In healthcare simulation is not that mature and the spectrum of problems is much wider, every problem in healthcare is unique in a way. So in order to apply frameworks to healthcare it is vital that framework guides the modeller about the identification of the problems that require hybrid simulation. The framework proposed by Helal et al (2007) and Venkateswaran et al (2005) do not cover those dimensions, both focuses more on technical integration between SD and DES.

2.5.3 Construction Industry

Quite a few literatures about either use or proposition of hybrid simulation in the management of construction projects have been reported. Unlike other industries the construction industry is more affected by changes in environment such as weather conditions. The need for tools that can predict the weather and their interaction of those with process activities of construction was realised long time ago. AbouRizk et al (1997) used combined simulation modelling for achieving more accurate representation of randomness associated with construction process activities and impact of weather on those activities. They used integration between DES and neural networks.

Recently a couple of reported studies in construction management have focussed on the importance of understanding the importance of coupling between construction process and construction context (Lee et al 2009; Lee et al 2007; Pena Mora et al 2008). Lee et al (2007; 2009) highlighted the significance of interaction between construction context and construction process. The importance of both was known prior to this but they were analysed separately: DES was used widely for analysis of construction process and SD is used for capturing construction context which changes continuously with time. Despite the acknowledgement of a need for analysing both construction operations and context simultaneously, there has not been any reported effort. This could be due to the lack of available tools. Lee et al (2007) proposed a hybrid simulation approach. Environment of construction cannot be represented with DES as it changes continuously. He has further argued that management actions cannot be incorporated in DES accurately. For example if there is a policy that a new resource should be added when resource utilisation reaches 0.9. the action will be triggered only when the event takes place and if there is no event between utilisation values from 8 to 9.9, it won't triggered unless it is too late. For these issues continuous simulation such as SD could be more responsive. Lee used hybrid simulation for simultaneous analysis and representation of interactions between construction process and context. He used Prisker's (1998) principles for mapping between SD and DES. He used Anylogic for the whole hybrid simulation.

The majority of reported studies in construction context have also used the ***"process environment"*** hybrid format, in which DES represents process and SD represents the context or environment in which process operates. The process – environment format found in construction is more like that of the software industry (Martin and Raffo, 2000) in which SD and DES models are coupled in space and time and hence are executed in ***parallel fashion***.

2.5.4 Supply chain

Quite a few studies have been reported on use or proposition of hybrid simulation for tackling the challenges faced by decision makers for the effective management of supply chain (Lee et al, 2002a ; Lee et al, 2002b; Venkateswaran et al, 2006; Reiner, 2005; Umeda and Zhang, 2008; Rabelo et al, 2007). Appreciating the fact that supply chains are neither discrete nor continuous, Lee et al (2002) proposed hybrid simulation methodology in which discrete parts of supply chain are modelled using DES and continuous parts are incorporated in a DES model in the form of differential equations. Umeda and Zhang (2008) argued that the performance of supply chain depends upon external factors such as marketability, traffic congestion and other management environments. He further argued that during analysis DES practitioner condenses these factors into parameters and defines these parameter values in the beginning. They remain constant after definition. Umeda and Zhang (2008) argued that these parameter values keep on changing. He proposed that inclusion of these factors into modelling analysis would provide more realistic outputs. He suggested that SD is more suitable to represent these parameters and DES more suitable for representing internal supply chain processes. He argued that there are dynamic interactions between demand, lead time and customer satisfaction and captured these dynamic interactions with SD and process specific performance indicators such as lead time with DES. With hybrid modelling he demonstrated how these two interact and influence each other. Reiner (2005) has shown how the process improvements can be dynamically evaluated by tandem usage of DES model and SD model. With hybrid simulation modelling he analysed the fluctuation in demand due to improved processes and enhanced customer satisfaction.

In the context of supply chain Venkateswaran et al (2007) distinguished between two types of interaction during the process of decision making: vertical and horizontal interactions. Vertical interactions involve interactions that are spread across different levels of decision making such as strategic and operational levels, horizontal interactions involve interaction among members that occupy same level. In their paper they focussed on production planning and VMI (vendor managed inventory) decision, both represent vertical and horizontal interactions respectively. In hierarchical production planning the decisions are split into levels, such as strategic aggregate planning which determines type and quantity of products, and detailed production scheduling which determine resources required for achieving those targets in set time scales? They used hybrid simulation for analysis of vertical interactions b/w aggregate and detailed decisions in single enterprise (Venkateswaran et al, 2005). In the collaborative supply chain context they extended their previous hybrid framework to incorporate horizontal interactions.

Rabelo et al (2007) integrated AHP (analytic hierarchy process) with their previously proposed hybrid simulation (Rabelo et al 2003) to model the service and manufacturing activities of global supply chain of a multinational construction company. In this project they used SD to model the extended enterprise system, while DES is used to model the manufacturing and service sub- systems. In this hybrid integration SD estimates the demand for products and services, quality levels new product and service development functions, reaction of customers, investment decisions and overhead costs. The results are exported to a DES model to study the performance of manufacturing and service facilities in response to these inputs from SD and estimate the associated cost. Costs and unit produced and the service level provided are outputs of DES and are fed back to SD top re-evaluate the overall performance of the enterprise. SD-DES hybrid is implemented manually in a distributed simulation like approach. The results obtained are provided to decision makers for group decision making using stochastic AHP. Discussion on AHP is out of the scope of this thesis.

Unlike Software and Manufacturing industry, there is a lot of variation with regards to deployment/ proposed deployment of hybrid simulation in a supply chain context. This can be explained on the basis that effective decision making in supply chain requires alignment of different kind of interactions such as horizontal and vertical interactions within the member of supply chain and cross boundary interactions with the environment. As discussed above Venkateswaran et al (2006) have tried to comprehend these interactions by extending their hierarchical hybrid simulation framework for production planning to incorporate horizontal interactions among suppliers, manufactures and retailers in the context of Vendor managed inventory. Vendor managed inventory is a form of collaborative supply chain. In this context hybrid simulation allows both alignment and optimisation of decision-making within the different layers of management in single company (for example alignment between operational and strategic decision making in retailer, supplier or manufacturer) and also optimisation of decision making with respect to other players such as a manufacturer aligning its production planning with respect to supplier capacity and retailers sales. These interactions between SD and DES are similar to the hierarchical interactions discussed in manufacturing context, where SD captures the holistic strategic perspective and DES captured detailed operational perspective

In addition to theses interactions with in the organisation, supply chain also interacts with environment outside the organisational boundaries. Performance of supply chain influences environment and vice-versa. As reported by Reiner (2005) and Umeda and Zhang (2008), in this context SD represents environment and DES represents processes inside the supply chain, this is similar to ***"process-Environment format"*** of the software sector. In this hybrid format SD is used for representing environment and DES for internal processes. Outputs of process affect environment and changes in environment affect input of processes. SD and DES are executed in tandem in cyclic fashion. It is important to note that this "process–environment format" is different than the process environment format discussed in software, both in terms of how the different elements represented by SD and DES interact and the way this integrated hybrid is executed. Unlike supply chain where environment affects the input of process and outputs of process affect environment in cyclic fashion, process and environment in software are tightly intertwined and they affect each other simultaneously during the execution. In order to distinguish between the two, in this research it has been named as ***"process performance – environment"*** as it is the performance of the process which causes ripple effects in environment. Another format which is observed in supply chain is extension of one paradigm to incorporate another. Lee (2002a) in the appreciation of supply chain as both discrete and continuous variables modelled the discrete activities with DES and used differential equations for obtaining the values of continuous parameters. As this is not a case of integration between SD and DES, further discussion of these is out of the scope of this thesis.

From the above reported hybrids it has been identified that depending on problem situation, SD and DES are used for capturing different aspects of the problem context. *On the basis of these differences, hybrid simulation can be categorised in three different formats: Hierarchical format, process – environment format and process performance – environment format. Similarly depending upon the problem situation, information is exchanged between SD and DES either in cyclic (SD and DES models run consecutively and interact with each other to exchange information after* *completing run) or in parallel fashion (SD and DES model run in parallel and interact with each other to exchange information during their run time).* As different hybrid formats and modes of interactions are dictated by problem situation, in order to develop a conceptual framework, understanding of these formats and interactions is vital. The following sections will describe these formats and interactions in more detail.

2.6 Hybrid Simulation Formats

As identified in the previous section, on the basis of distinction between applicability of SD and DES to model different elements of organisational problems in the context of hybrid models, it has been identified that existing or potential hybrid models can be classified in three categories as shown in Table 2.5. It has been observed from existing hybrids that there has been a relationship between hybrid format and the information exchanged between SD and DES models for example in hierarchical format SD passes down targets to DES and DES in return provides SD with the actual status of operations.

Hybrid Format	**Description**
Hierarchical format	SD is used for strategic level and DES for operational level decisions. Used for analysing vertical interactions between different levels. Depending upon the problems situation, can have both cyclic as well as parallel interactions.
Process – Environment	Process is represented with DES and environment factors with SD. They are tightly coupled; environment affects activities and resources of process and vice versa.
Process performance - environment	Process in represented with DES and environment with SD. They interact in cyclic way through inputs and outputs.

Table 2.5: Hybrid (SD + DES) Formats

As Formats provide the context of what is exchanged between SD and DES, it is believed that they can be deployed for setting the context for identification of variables which are exchanged between SD and DES. Further description on the relationship between hybrid format and what is exchanged between SD and DES will be provided in the next chapter. As mentioned in Section 2.4, it is worth noting that the author has only considered the hybrid models in the organisational context only. The author is aware that this list can be extended to include many other formats such as discrete at higher level and SD at lower level if we remove the restriction of decision making in organisational context

2.6.1 Hierarchical Hybrid Format

In this format SD models are used for higher level strategic decision making and DES models are deployed for operational level (Rabelo et al, 2004; Helal et al, 2007; Rabelo et al, 2007; Venkateswaran et al, 2005). This format is used for analysing vertical interactions between different management levels (as shown in Figure 2.2). Venkateswaran et al (2007) has also applied this format to collaborative supply chain, in which SD model is used for modelling the horizontal interactions between different players in supply chain and DES for capturing the detail operational logistics of each player. This format can be used for the evaluation of impact of strategic decisions on operational level (Top –down approach) and can also be used for understanding the global impact of local decisions (bottom up approach).

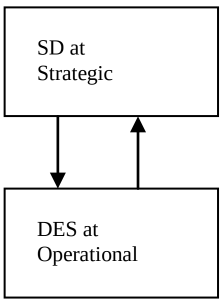

Figure 2.2: Hierarchical format

This format of hybrid simulation maintains the integrity of both SD and DES paradigms and can use existing models without requiring learning new simulation skills. Most of the recent work on hybrid simulation in the production planning within the manufacturing sector has deployed this format.

2.6.2 Process – Environment format

In this format DES, due to its process stance is used for representing the process and SD can be deployed for representing environmental factors surrounding the process (as shown in Figure 2.3). This format is based on the realisation that processes are part of the environment in which they occur and the activities of the process are affected by surrounding environmental factors and the environment is affected by the process.

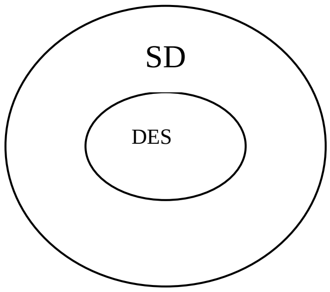

Figure 2.3: Process- environment format

Martin and Raffo's (2000) study in software project management can be categorised under this format. Martin and Raffo (2000) argued that SD models represent interactions between project factors but are unable to represent queues and discrete process steps. Discrete models are capable of representing process steps but are unable to capture causal relationships between project factors. In order to overcome the above limitations Martin and Raffo (2000) proposed a combined model that represents the software development process as a series of activities executed in a continuously varying project environment. In the Hybrid model, they used DES to model the sequence of activities and resources of software development process and SD to represent continuously varying environment. In this process and environment are coupled with each other in time and space. They showed the feasibility of this approach by combining two separately developed SD and DES model.

2.6.3 Process performance– Environment format

In supply chain a variation of “process – environment” format has been observed. In this process and environment interact with each other but are not coupled in terms of time and space. There is delay between cause and effect. Fig 2.4 has attempted to represent this by thick boundaries between process represented by DES and environment represented by SD.

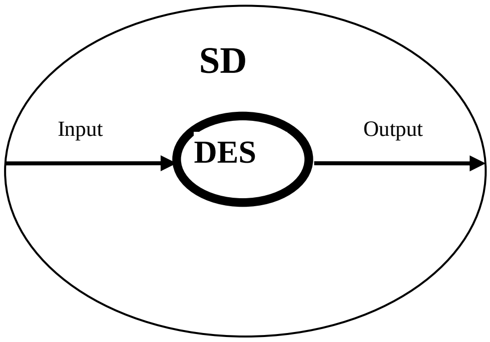

Figure 2.4: Process performance - environment format

In this format SD and DES models interact with each other via inputs and outputs. Environment is affected by output of process and consequently changes the inputs of supply chain. Supply chain hybrid simulation carried out by Reiner (2005) and Umeda and Zhang (2008) can be categorised under this. This format is used for analysing the ripple effects of local operations from a global perspective. Ripple effects are normally far in space and time and hence are not analysed by traditional methods. This format in literature has been used for analysing the sustainability of operational interventions in long run and evaluation of local actions from a global perspective (Umeda and Zhang 2008; Lee et al., 2002). Unlike hierarchical mode, the leading model in this hybrid union is DES, as it is the operational interventions which are analysed from a global environmental perspective. The central idea for this mode is to analyse the impact of improved performance measures such as waiting time, throughput etc. on environmental dynamics. The dynamic interaction between operational outputs and environmental variables affect the demand for operational services. With traditional methods this fluctuation in demand which is the result of operational interventions is not analysed. Due to this reason, literature is abundant with case studies where initial results of improvement interventions were positive but could not be sustained for long. With this hybrid mode these fluctuations in demand can be captured with SD and operational performance can be evaluated in response to this fluctuation demand. This mode provides decision makers to visualise the long term effect of their decisions from global perspectives.

The other important aspect of hybrid simulation is how SD and DES models interact with each other over the time to exchange information. The next section will provide a discussion on interactions between SD and DES.

2.7 Interaction and Synchronisation between SD and DES

Where as the previous section focussed on different aspects/perspectives of the problem modelled by SD and DES such as strategic level by SD and operational level by DES in hierarchical format, this section provides discussion on the way information is exchanged between SD and DES over time. On the basis of the way SD and DES interact with each other over the time to exchange information, two modes of interactions have been identified from existing hybrids:

- Cyclic Interaction
- Parallel Interactions

2.7.1 Cyclic Interactions

In this mode SD and DES are run separately and the information is exchanged between consecutive runs in a cyclic fashion as shown in Figure 2.5.

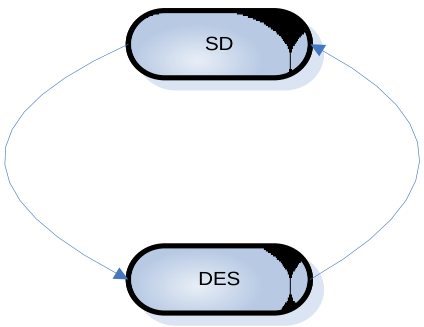

Figure 2.5: Cyclic Interactions

There are no interactions between SD and DES during run time. They interact with each other only after completion of their individual run. In this, SD model completes its run and outputs are fed into DES as inputs. Then DES model runs and after completion its output is fed back into the SD model. This cycle continues till SD and DES align with each other. Umeda and Zhang (2008) deployed hybrid model in which SD and DES exchange information in cyclic way for the evaluation of long term impact of process improvements in a wider context. Chatha and Weston (2006) argued that DES and SD provide concepts that complement one another and can be used together in interventions to support management decision making. They deployed SD and DES models in cyclic fashion for evaluating different alternatives. They used DES for identifying the bottlenecks in a furniture manufacturing company. The management suggested various alternatives for removing bottlenecks. After analysing the impact of these alternatives on process performance, Chatha and Weston (2006) evaluated the longer term and wider impact of suggested initiatives with SD. The selection of appropriate initiatives was based on both narrower short term simulation analysis as well as wider long term system thinking analysis. Similarly Reiner (2005) deployed cyclic interaction for evaluating the economic impact of process improvement.

2.7.2 Parallel Interactions

In this mode, SD and DES models are run simultaneously for some time and the information is exchanged during run time**.** SD and DES run in parallel. Continuously changing elements represented by SD, causes changes in the discrete events and discrete events cause changes in continuous elements as shown in Figure 2.6. The hybrid model developed by Martin and Raffo (2000) for managing development of software projects provides an example of this type of interaction. In their model continuously changing qualitative factors such as experience and motivation influenced the discrete process activities such as production and inspection etc.

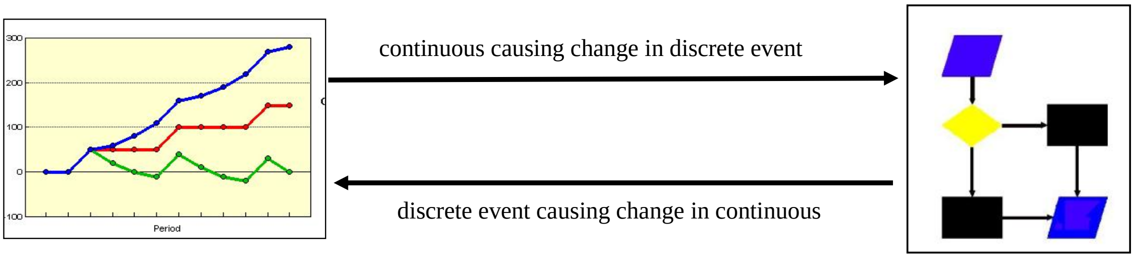

Figure 2.6: Parallel Interactions

Similarly discrete elements represented by DES such as completion of production activity influences continuous parameters such as experience and motivation. Lee et al (2007, 2009) have also deployed parallel interactions in their hybrid model for capturing the interactions between construction process and construction context.

2.8 Limitations of existing Framework for Hybrid simulation

From the above section it is clear that on the basis of the way they represent different elements of the problem, hybrid simulation exist in different formats and depending upon the problem context SD and DES models in hybrid can exchange information either in cyclic mode or in parallel mode. As mentioned in the section on existing hybrids different industries have different problems and have used SD and DES in different combinations. Although the authors of the previous studies on hybrids have demonstrated and justified their choice to use SD or DES for their problem context, due to the narrow focus they are limited in their ability to be extended beyond their problem contexts.

Existing hybrid frameworks do not provide generic guidance regarding identification of SD and DES elements which are exchanged or influenced during hybrid simulation. Venkateswaran et al (2005) in their framework focussed actually on what is actually being exchanged between two models in production planning and scheduling context rather than the generic guidance with wider scope. This narrow focus limited the applicability of their framework to other problem situations. Venkateswaran et al (2005) for example stated that aggregate production release order from SD is passed down to DES and operational performance indicators such as WIP, lead time, throughput etc are passed from DES to SD. As the terminology is very specific to production planning, it cannot be applied to other problem situations.

From the literature it has been identified that two primary ways SD and DES interact with each other: parallel interactions and cyclic interactions. Similarly with respect to interactions, they have simply stated that whether they have used parallel or cyclic, why they used that has not been justified. Their frameworks do not provide any guidelines for making selection between parallel and cyclic mode. It could be due to the reasons that all the existing hybrids are developed for solving specific problems for example Venkateswaran et al (2005) and Helal et al (2007) used hybrid simulation for alignment between strategic production planning and operational schedule planning, similarly Martin and Raffo (2000) used hybrid to represent the interactions between discrete process activities and qualitative environmental factors.

Another limitation of all previous studies is that their frameworks are build upon the assumption that their problem requires hybrid simulation. There is no methodology or guidance to identify that whether the problem require hybrid simulation or not. It is well documented in literature that effort and investment in hybrid is only justified if there is strong coupling between elements represented by SD and DES (Farhland, 1970 Lee et al 2002a; Helal, 2008). From the above discussion, it can be concluded that a generic framework for hybrid simulation should be able to provide guidance on following aspects:

- Identification and justification of problems requiring hybrid simulation
- Information exchanged between SD and DES in hybrid simulation model
- The way information is exchanged

Previous work on hybrid simulation has been motivated by the author's own myopic problems which they try to resolve by focusing on the technical aspects of methodology perspective rather than conceptual. The most promising frameworks for hybrid frameworks have been provided recently by Venkateswaran et al (2005) and Helal et al (2007). Both of these frameworks (Helal et al, 2007; Venkateswaran, 2005) adopted tight problem centric approach, this approach compromised on the generalisation and application of this framework to other problems. They have started their approach from a defined problem which they believed required a hybrid solution. Their hybrid frameworks focus more around the guidance for technical aspects of interactions between SD and DES rather than generic guidance with respect to identification of problems in need of hybrid simulation, what is exchanged between SD and DES and how this information is exchanged over time. Mingers and Brocklesby (1997) stated that theoretical framework should be established before investigating the logical possibilities for combining methods technically. However in Venkateswaran et al (2005) and Helal et al (2007) the focus has been more on technical exchange and synchronisation of SD and DES models rather than generic guidance for different problem situation. As hybrid is still a novel concept, frameworks need to take a backward stance to provide generic guidelines for the identification of problems seeking hybrid simulation, identification of what is exchanged between SD and DES models and the way information is exchanged. None of the previous frameworks have attempted to provide guidance on these aspects.

2.9 Research Gap

The appetite for mixing methods in the healthcare domain has been documented (Sachdeva et al, 2006; Eldabi et al, 2007; Brailsford et al, 2003). Healthcare is complex and there is a plethora of problems which cannot be analysed using a single method. There are problems which exhibit elements which require both SD and DES, and there are interactions between them. In those scenarios accurate analysis demands to capture those interactions. It has been argued in literature that a hybrid approach, where SD and DES are integrated symbiotically, will provide more insight and accurate analysis of such problems with fewer assumptions. As proposed by Chahal and Eldabi (2008c) there are various contexts in healthcare where hybrid simulation will be more applicable. Despite the appetite for mixing SD and DES in healthcare, there is an absence of reported study (as highlighted in Table 2.4) which has applied these methods in an integrated way. It could be due to the challenges associated with mixing methods and the absence of a generic framework which provide guidance with regards to implementation of hybrid simulation.

It has been argued that mixing methodology has the potential to provide a more complete way of dealing with the complexity of the real world, however mixing methods in practice presents challenges due to their different philosophical stance (Mingers, 2003). Theoretical frameworks are required to provide practical guidance for mixing methodologies. Mingers and Brocklesby (1997) stated that task of investigating the logical possibilities for combining methods, putting them to work and then reflecting upon the results needs to be preceded after establishment of frameworks. However from the reported literature it has been observed that it has followed a reverse order. No reported theoretical framework has been identified which provides guidance about mixing SD and DES to form hybrid models. On the other hand a handful of frameworks, which have attempted to address the technical interoperability between SD and DES have been identified (Martin and Raffo, 2000; Venkateswaran et al, 2005; Helal et al, 2007). As discussed in the previous sections, frameworks developed in the past have emphasised more on technical automation of exchange of information between SD and DES rather than providing generic guidance for implementation of hybrid simulation. Another limitation of previous frameworks is their problem-centric approach. They explain which information is exchanged between SD and DES within their problem context however they have not provided generic guidance on how they made those selections. This limits their generalisation to wider problem contexts. Due to this tight problem specific approach it is difficult to apply those frameworks to the healthcare context. This research attempts to fill that gap by providing a generic theoretical framework for hybrid simulation. As both the need and absence of hybrid simulation in the healthcare context has been highlighted in the previous sections, this dissertation aims to further contribute by applying the proposed hybrid simulation framework to healthcare problems.

2.10 Summary

Chapter 2 starts with Section 2.1, which provides the purpose of the chapter and introduction to the various sections. As stated before, the aim of the research is the development of a generic framework for hybrid simulation for which selection of SD and DES according to their suitability to problem context is a prerequisite, which further requires thorough understanding of contrasting and overlapping features of SD and DES. Section 2.2 and Section 2.3 provides this understanding by reviewing the literature on comparison and selection between SD and DES. In Section 2.2 the author used problem perspective, systems perspective and methodology perspective as parameters for meta- comparisons between SD and DES. It has been argued that the alignment between these three provides provide recipe for accurate representation of problem scenarios. These three parameters are used for making selection between SD and DES. Section 2.3 provides review of literature on selection between SD and DES. Sections 2.2 and 2.3 have cumulatively contributed towards achieving the first objective (in depth understanding of comparisons and selection between SD and DES) of this research. This is followed by Section 2.4 which describes hybrid simulation and various approaches to it. This section provides a description of different ways hybrid simulation can be deployed and also provide justification for the hybrid approach adopted in this literature. Section 2.5 provides extensive review of existing hybrid studies focussing on their purpose and the way they have been deployed in different industries. The knowledge gained from Section 2.4 and Section 2.5 provides foundation for development of framework. Section 2.6 and 2.7 describes the way SD and DES have been deployed in different hybrid formats and the way the interactions between SD and DES models have been realised. Section 2.8 summarises the limitation of existing hybrid frameworks followed by Section 2.9 which provides description of research gap: absence of framework which provides guidance to its perspective users with regards to identification of the problem in need of hybrid simulation followed by guidance on identification of what is exchanged between SD and DES and how. Finally Section 2.10 provided a brief summary of the chapter. On the basis of literature reviewed and discussed in this chapter, the next chapter will propose a generic framework for hybrid simulation to fulfil the research gap.

Chapter 3: Hybrid Simulation Framework

3.1 Introduction

Chapter 2 has established that there is an absence of a generic conceptual framework which can provide guidance with respect to exploitation of hybrid simulation in healthcare. This chapter attempts to fill that gap by proposing a framework for hybrid simulation. The purpose of the extensive literature review on existing hybrid simulation models in the previous chapter was to gain a thorough understanding regarding the way hybrid simulation has been deployed in the past. In this chapter, the knowledge gained from the literature provides the basis for establishing requirements for hybrid simulation framework. By the end of this chapter it is hoped to provide a workable version of a generic conceptual framework which is capable of addressing those requirements. The proposed framework will be evaluated in the following chapters. The next paragraph describes the structure of the rest of the chapter.

Section 3.2 provides a discussion on the requirements of the framework followed by the sections focussing on the detail discussion on each of these requirements. Section 3.3 addresses the first requirement "identification of problems in need of hybrid simulation" in detail. As discussed in the previous chapter, selection between SD and DES is a prerequisite for hybrid simulation this section also provides discussion on the criteria for selection between SD and DES. The next section provides discussion on the way SD and DES are linked in different formats and the way this information can assist in identifying interaction points (variables which participate during exchange of information between SD and DES) between SD and DES. Section 3.5 explores different ways of interactions and synchronisation between SD and DES models. Section 3.6 provides a description of generic conceptual framework for hybrid simulation. The proposed framework consists of three phases; as there are three requirements established in Section 3.2, each phase of the framework has attempted to fulfil one requirement established in the beginning of the chapter. Finally Section 3.7 summarises the whole chapter.

3.2 Requirements of the Framework

As suggested by Robinson (2008a), it is useful to establish requirements for generic conceptual frameworks. The descriptive nature of the model at this stage poses a challenge to set measurable criteria for evaluation. These requirements provide the basis for evaluation of conceptual frameworks. It has been discussed in the previous chapter that there has been emphasis on justification for the need of hybrid simulation prior to integrated deployment of SD and DES (Frahland, 1969; Lee 2002). It implies that problems requiring hybrid simulation should be identified prior to any further analysis.

Once the problem is identified as one which requires hybrid simulation, the next challenge is establish linkage between SD and DES models. Due to different philosophical stance, establishment of linkage between SD and DES has been quite challenging (Lee et al, 2009). In order to link SD and DES models in hybrid simulation, the following information is required:

- Which information is exchanged between SD and DES?
- How do SD and DES models interact with each other to exchange this information?

From the literature on existing hybrid simulation models, it has been observed that there are different ways SD and DES represent the problem context (hybrid simulation formats) and there is a relationship between information (variables) exchanged between SD and DES and different formats, for example in the "process environment" format SD passes productivity value, experience level etc to DES and DES provides SD with status of process. Similarly in "process performance – environment" format DES provides information about waiting time which affects satisfaction level which result in fluctuation in demand, SD passes on this demand to DES where it is disintegrated and used in form of inter-arrival frequency at entry point. *Variables whose values are changed or influenced by variables of the other model and variables which replace or influence the values of variables of other* *models during hybrid simulation will be named as* ***"interaction points"*** *through out the rest of the dissertation.* They are named interaction points because all the interactions between SD and DES model occur through these variables. The detailed discussion on hybrid formats and relationship between what is exchanged between SD and DES models will be provided in the following sections. *Similarly, depending upon the problem situation, different modes of interaction (the way SD and DES interact with each other over the time for exchanging information) have been identified.* As mentioned in Section 2.7, it has been identified from the literature that SD and DES model interact with each other either in cyclic or in parallel fashion. From the above discussion it can be deduced that the generic conceptual framework should be able to provide answers to the following questions:

- Why the problem in hand requires hybrid simulation? Justify the need for it.
- What is exchanged between SD and DES?
- How do SD and DES models interact with each other over time to exchange information?

These questions establish requirements for the framework and are discussed in detail in the following sections.

3.3 Why the problem in hand requires hybrid Simulation?

As discussed in Chapter 2 most of the previous frameworks for hybrid simulation are problem domain specific and based on implicit understanding of the authors that the problem requires hybrid simulation. However few studies have explicitly highlighted the need to identify continuous and discrete elements and the need for justification that the problem actually requires a hybrid simulation (Farhland, 1970; Lee et al 2002). Farhland (1970) mentioned that investment and effort in hybrid is only justified if some aspects of the problem require SD for analysis and some require DES and there is strong coupling between elements represented by SD and DES models. Lee's (2002a) framework for supply chain is based on the understanding that supply chains are a mix of both continuous and discrete elements hence using a single method for their abstraction will result in a mismatch between problem reality and model. He advised that the selection of method should be followed by identification of continuous and discrete elements of the supply chain. As the focus of this dissertation is on hybrid simulation between SD and DES, the need for it is only justified if there are interactions between elements represented by SD and elements represented by DES. Hence the hybrid framework should be able to provide distinction between situations in need of SD, DES or Hybrid models. Identification of elements which can be represented by SD and DES is a precursor for Hybrid simulation. In order to identify which aspects of the problem require SD and which require DES, criteria for selection between SD and DES are required. The following subsection provides discussion on these criteria.

3.3.1Criteria for SD and DES (revisit Section 2.2 and Section 2.3)

Section 2.3 has provided a review of existing frameworks for selection between different methods. In all of these frameworks, selection has been guided by the ability of the methods to represent problem attributes. Upon deciding between SD and DES, it has been argued in the literature that the answer to the question of deciding between SD and DES depends more on the purpose of the model rather than the system being modelled (Brailsford and Hilton, 2001). Contrary to that, this research argues that the system is an integral aspect when it comes to deciding between SD and DES (Chahal and Eldabi, 2008a). Pidd (2004) advises that modellers should think about the nature of the system and nature of the problem prior to modelling, as some models are better suited for certain problems than others. From his argument it is evident that there needs to be close fit between modelling methodology, system and problem. Lorenz and Jost (2006) argued that what (object of simulation study), why (purpose of study) and how (simulation method) are the main criteria for deciding between methodologies (Lorenz and Jost, 2006). The common limitation of previous frameworks for selection is the absence of the system or **WHAT** perspective. As shown in Figure 3.1, this research argues that in order to select an appropriate model for a given situation, there needs to be strong fit between system, problem and methodology; therefore the selection process should be based on the consideration of the combined view of system, problem and methodology.

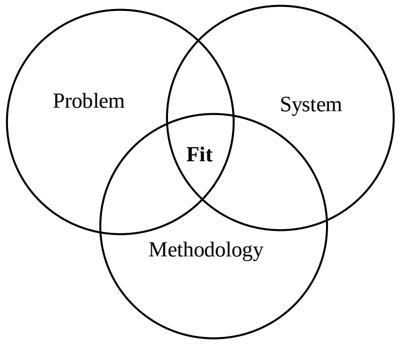

Figure 3.1: Fit between problem, system and methodology

Out of all the previous frameworks on selection, Brailsford and Hilton (2001) provided most the comprehensive criteria for selection between SD and DES. In the rest of the selection frameworks SD and DES merely form a fraction of various methods addressed. Due to this it was decided to use criteria established by Brailsford and Hilton (2001) for selection between SD and DES. The limitation of their approach like many others is that their selection criteria are explicitly based only on the alignment of problem purpose with appropriate method. On the basis of the argument that there should be alignment between problem, system (problem context) and methodology, selection criteria provided by Brailsford and Hilton (2001) has been modified to incorporate "system perspective" as shown in Table 3.1. The purpose of this table is to provide guidance with regards to selection between SD and DES. As argued by Chahal and Eldabi (2008b), the decision to select SD and DES for analysing a particular problem context is further subjected to the feasibility constraints such as resources, time and client expectation etc.

Criteria	**DES**	**SD**
Problem Perspective		
Purpose	Decision: Optimisation, prediction and comparison	Policy making, overall understanding
Problem Scope	Operational	Strategic
Importance of randomness	high	Low

Importance of interaction between individual entities	High	Low
Required level of Resolution	Detailed individual level	Aggregate, high level
System's Perspective		
System View	Detailed Microscopic view	Holistic Telescopic view
Complexity of importance	Detail Complexity	Dynamic Complexity
Evolution over time	Discontinuous event based	Continuous
Control parameter	Holding (queues)	Rates (flows)

Table 3.1: Criteria for Selection between SD & DES

The selection process will lead to three possible outcomes.

1. Problem requires SD
2. Problem requires DES
3. Problem requires both SD and DES

If the selection process leads to the third option and there are significant interactions among elements represented by SD and DES, then the hybrid simulation will be the method of choice. That is why it has been stated that the selection between SD and DES acts as a prerequisite for identifying the problems which require hybrid simulation. Hence this is the vital component of the framework and will be discussed later during the description of generic framework. The next section will provide discussion on the second requirement of the framework which is about identification of interaction points between SD and DES.

3.4 What is exchanged between SD and DES?

Once it is identified that the problem requires a hybrid solution, the next step would be to identify what is exchanged (interaction points) between SD and DES. As defined in Section 3.2, *variables whose values are changed or influenced by variables of the other model and variables which replace or influence the values of variables of other models during hybrid simulation will be named as **"interaction points"***. It has been deduced from the literature that there is relationship between hybrid format and interaction points. As discussed in the previous chapter, on the basis of morphology, hybrid simulation can have three different formats: "hierarchical format", "process performance – environment format" and "process – environment format". The following subsections provide a brief description of the relationship between different formats and information exchanged between SD and DES.

3.4.1 Hierarchical format and interaction points

Hierarchical format represents two levels: hierarchical management structure in which SD represents the strategic level and evaluates parameter values for operational variables whereas DES represents operational level and provides real time status of operations. This format creates a dialogue between strategic level and operational level management: strategic decisions are not based on averages or estimates about the operational capacity but are evaluated in light of real status of operations which is provided by DES. SD in this format is used for evaluation and estimation of parameters and establishment of criteria for production plan, resource allocation, operational targets and policies for management interventions. The output of SD is passed down to the DES model for the purpose of evaluation of these parameters, targets and policies from operational perspective. DES evaluates operational capacity in response to these parameters and provides SD with state of the art information about operational status such as work in process, lead time, inventory and production rates etc.

3.4.2 Process performance - environment format and interaction points

This format in the past has been used for analysing the ripple effects of local operations from a global perspective. Ripple effects are normally far in space and time and hence are not analysed by traditional methods. This format in literature has been used for analysing the sustainability of operational interventions in the long run and evaluation of local actions from a global perspective. Quite a few articles on this approach have been identified **(**Umeda and Zhang, 2008**;** Lee et al 2002a, Reiner, 2005**)**. Unlike hierarchical mode, the leading model in this hybrid union is DES, as it is the operational interventions which are analysed from global environmental perspective. The central idea for this mode is to analyse the impact of improved performance measures such as waiting time, throughput etc. on environmental dynamics. The dynamic interaction between operational outputs and environmental variables affect the demand for operational services. With traditional methods this fluctuation in demand (which is the affected by output of operations) is not analysed. Literature is abundant with case studies where initial results of improvement interventions were positive but could not be sustained for long. Article by Rohelder et al (2007) on use of simulation for improvement of waiting time and time in system for patients of Calgary Patient Service Centre network, exemplifies it. With the "process performance – environment" format, fluctuations in demand (which results from operational output) can be captured with SD and operational performance can be evaluated in response to this fluctuation in demand. This format provides decision makers to visualise the long term effect of their improvement initiatives from global perspectives. In both hierarchical and process performance - environment, SD models the holistic view of the system and DES provides modeller with the detailed microscopic view.

3.4.3 Process-Environment Format and Interaction points

In this hybrid format process and environment of the problem context are tightly coupled. This type of hybrid format has been used in the domain of project management in construction and software industry to capture the interactions between process activities and qualitative environment factors such as motivation, schedule pressure, experience and fatigue etc. It has always been a challenge to capture the impact of these soft variables on tangible process outcomes. This format of hybrid simulation in the literature has demonstrated ability to capture that. Like the other two, in this hybrid format DES provides SD the model with real status of system or operations, SD however unlike process performance – environment format, instead of influencing the entry gate (demand in terms of inter arrival), influences the internal activities and resources. It affects the activities of process by affecting their duration. Execution of activities in turn changes the values of environment variables.

Hybrid Format	**Description of the format**	**Purpose**	**From SD to DES (interaction points)**	**From DES to SD (interaction points)**
Hierarchical format	SD is used for strategic level and DES for operational level decisions. Used for analysing vertical interactions between different levels. Depending upon the problems situation, can have both cyclic as well as parallel interactions.	Setting strategic targets and evaluating their feasibility Simultaneous generation of strategic plan and operational schedules. Evaluation of resource allocation policies from operational perspective	Production plan Allocated resources Targets (performance measures) Policies for management actions	Work in Process (WIP) Throughput Utilisation Lead time
Process performance - environment	Process is represented with DES and environment with SD. They interact in cyclic manner through inputs and outputs.	Re-engineering of process or operations department. Long term consequences of interventions	Change in demand	Waiting time, Lead Time
Process – Environment	Process is represented with DES and Environment factors with SD. They are tightly coupled; environment affect activities and resources of process and process affect environment variables.	Evaluating the interactions between environmental context and process activities; for example evaluating the impact of qualitative factors such as experience, motivation, schedule pressure etc on process performance.	Productivity, resources	Status of process such as WIP, inventory, throughput

Table 3.2: Description of hybrid format, their description, purpose and interaction points

Table 3.2 provides description of different formats, problem contexts in which they have been applied and the interaction points in different hybrid formats. This table has been created on the basis of information deduced from discussions in previous sections and discussion provided in Section 2.6 of Chapter 2.The next section provides a discussion on different modes of interaction between SD and DES models.

3.5 Mode of Interaction between SD and DES models

Once the problem is identified as one which requires hybrid simulation and interaction points between SD and DES model are defined, the next requirement is to identify the mode of interaction between SD and DES. *Mode of interaction implies to the way SD and DES models interact with each other over the time to exchange information during hybrid simulation.* Where as interaction points provide information regarding WHAT is exchanged between SD and DES models, mode of interaction describes the way (HOW) SD and DES interact with each other to exchange that information. It has been identified in the Section 2.7 that interactions between SD and DES can be either parallel or cyclic.

3.5.1 Cyclic Interaction (Revisited Section 2.7.1)

In this mode SD and DES are run separately and the information is exchanged between consecutive runs in a cyclic fashion. There are no interactions between SD and DES during run time. They interact with each other only after completion of their individual run.

3.5.2 Parallel Interactions (Revisited Section 2.7.2)

In this mode, SD and DES models are run simultaneously in parallel and information is exchanged during run time. Continuously changing elements represented by SD, causes changes in the discrete events and discrete events cause changes in continuous elements.

Table 3.3 provides description of the problem contexts in which they can be applied. The problems in which interactions between elements represented by SD and DES are linked with each other in time and space, and these interactions influence overall purpose, those problems will require parallel interactions. However the problems in which elements represented by SD and DES either are not coupled with each other in time and space or if they are coupled, this coupling is not important for overall objective. In those scenarios, problems can be analysed with cyclic interactions.

Mode of interaction	Problem context
Cyclic	The problems in which interactions among elements represented by SD and DES are consequential. Variables represented by SD and DES are mostly not linked in time and space and even if they are linked, their linkage does not influence overall objective.
Parallel	The problems in which elements represented by SD and DES are linked in time and space and this coupling influences overall objective.

Table 3.3: Modes of interaction

The above sections have provided detail discussion on the questions (requirements) the prospective users of the framework will use the framework to seek answers for. A wide breadth of discussion has been provided to address all possible alternative answers for those questions. The next section will provide description of the generic framework.

3.6 Generic Description of Conceptual Framework

In order to meet requirements set in previous section, a three phase conceptual framework as shown in Figure 3.2 is proposed. Each phase attempts to address one requirement, for example Phase 1 assists prospective users in identifying the problems which require a hybrid simulation. Phase 2 provides guidelines for answering the question: what is exchanged between SD and DES during hybrid simulation followed by Phase 3 which provides instructions to select appropriate mode of interaction. As described before the way SD and DES interact with each other over the time to exchange information is referred as “mode of interaction”. All these phases need to be carried out in a sequential way. The following subsections will describe these three phases in detail.

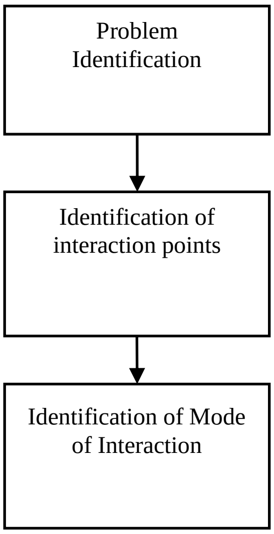

Figure 3.2: Overview of the proposed hybrid simulation framework

Phase 1: Identification of Problem seeking Hybrid Solution

The purpose of this phase is to identify problems which require hybrid simulation. Models have very little intrinsic value unless they aid in decision making and hence the purpose of the modelling is not to develop the model itself but is to develop a model for analysing a problem (Robinson, 2004; Robinson 2008b). The first step of any modelling exercise after understanding the problem is to identify the overall objective problem owners want to achieve. The framework is based on the assumption that the problem is thoroughly understood. The decision to not include problem understanding in the framework is based on the appreciation that problem understanding is a vast area and in order to do justice, it requires a framework on its own rather than embedding it as step in the beginning of frameworks which are designed for other purposes. Quite a few articles are available on problem understanding. Once the problem is understood the next step is to identify the overall objective. As shown in Figure 3.3 Phase 1 consists of the following main steps for identifying problems in need of hybrid simulation:

- Identify overall Objective
- Decompose in to smaller objectives
- Method Selection

Identify overall objective

Here it is emphasised that understanding of overall objective should be carried out in light of both problem as well as system context. The following questions have been designed for understanding the overall objective:

- What causes the problem owners to seek assistance from analysts?
- What is the goal they are seeking?
- What are the internal and external influences on the goal?

The first two questions emphasised more on the problem context, however the last one focuses more on system perspective. These questions aid potential users in acquiring in-depth understanding of the modelling objectives in light of both problem and system perspective. Understanding of internal and external influences, made potential users aware of wider implications and assist the modeller with identification of sustainable objectives.

Decompose in to smaller objectives

Once the overall objective is defined, the next step is to apply the third principle of model building "Divide and Conquer" (Pidd, 2001). Powell (1995) described this as decomposition. Pidd (2001) quoted Raiffa(1982), "Beware of general purpose, grandiose models that try to incorporate practically everything. Such models are difficult to validate, to interpret, to calibrate statistically and most importantly to explain. You may be better off not with one big model but with a set of simpler models".

Decomposition of objective into smaller objectives not only simplifies model building but also aids in selection of appropriate method, especially in problem contexts which demand multi-method analysis. As in those scenarios different aspects of the problem may require different methods and development of a grand single model covering all aspects can restrict the process of selection of the appropriate model.

Method Selection

After decomposing into smaller objectives, the next step is to select an appropriate method for each objective. As mentioned before, decomposition also simplifies the process of selection as well. With larger objectives the probability of having features appropriate to be analysed by different methods increases. This poses challenges in identification of appropriate method. Table 3.1 provides criteria for selection between SD and DES. This step is repeated for each objective. If there are more than one objective, there will be the following three options after the appropriate methods have been selected for each objective:

1. All the objectives require DES
2. All the objectives require SD
3. Both SD and DES are required: some objectives require SD and some DES

As the framework is for hybrid simulation, the first two scenarios are out of the scope of this framework. In case of third option where both SD and DES are required, the next step in the framework is identifying whether there are interactions between objectives met by SD and DES or not. It depends upon the overall purpose. Can the purpose be achieved by separate models or does it require linking of the models? If there are interactions among elements represented by SD and elements represented by DES, then Hybrid simulation is required. Figure 3.3 provides diagrammatic sketch of the process discussed above. Once it is established that problem requires hybrid simulation, only then analyst are advised to apply next phase.

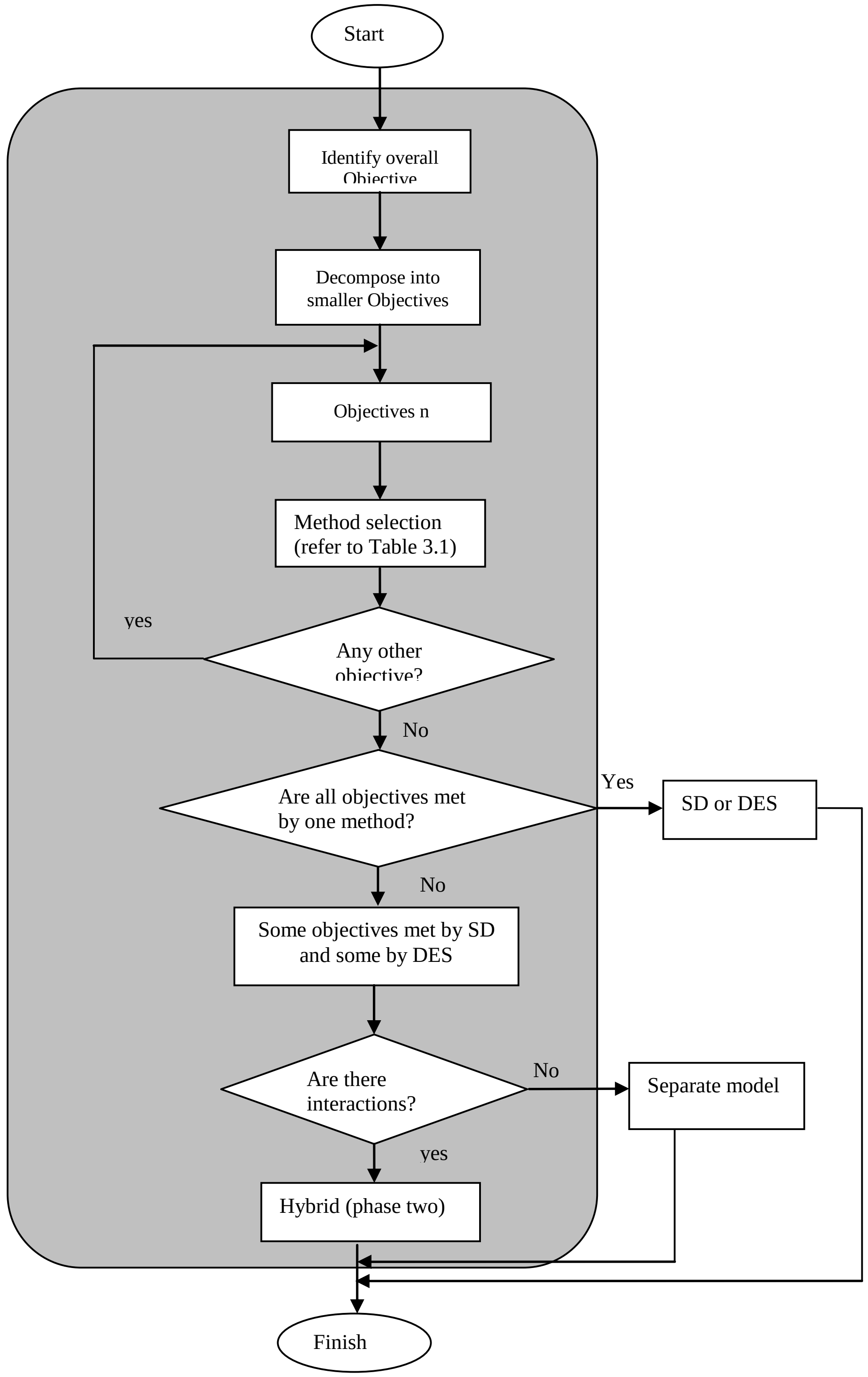

Figure 3.3: Overview of Phase 1 of the proposed framework

Phase 2: Identify interaction points between SD and DES models

The purpose of the second phase is identification of interaction points (what is exchanged between SD and DES). It has been observed in literature that there is a relationship between hybrid format and interaction points as shown in Table 3.2. Hence knowledge of hybrid format provides some contextual idea about the interaction points. It also provides some idea about the lead model in the SD, DES union. As we know in hybrid simulation SD and DES models exchange information, from lead model the author means the model which initiates the process of exchange. In "***hierarchical***" format, there is resonance with top down approach of management, where parameter values for certain DES variables such as desired production release rate, demand, performance targets and allocation of resources are set at strategic level and passed down to DES to evaluate the performance of operations in response to these parameters. Outputs of DES such as WIP, throughput and lead time, inventory etc are passed up to SD for exercising the control.

In "***process performance- environment***" format, the lead model is DES as it is the output of improved operations which causes changes in dynamics of environmental variables. The "process performance –environment" format has resonance with the bottom up approach of management. In both hierarchical and process performance formats, DES models detailed operations and SD captures a holistic view of the system. It has been identified from literature that DES in this format has been used for analysing process re-engineering initiatives and outputs of DES in the form of lead time and throughput are passed to SD and SD has been deployed to capture fluctuation in demand in response to these variables. The third form of hybrid format ***"process environment***" is different from the first two. In this there is coupling between qualitative factors which form the environmental context and discrete activities of the process. From the reported literature it has been identified that in this format it is actually the productivity of human servers which affects the duration of activities. Like hierarchical and process performance mode, DES in this also provides SD with real status of system in terms of WIP, throughput etc but SD (unlike the other formats) does not affect the entrance point of DES model (inter- arrival times) but the internal activities of DES.

From the above discussion it is clear that identification of hybrid format provides the modeller with some contextual understanding about the interaction points. Hence the first step in the Phase 2 is identification of hybrid format. As overall objective and objectives of SD and DES models are already defined at this stage, identification of hybrid format is quite straightforward. Table 3.2 can aid in identification of hybrid format and can also provide some idea about what is exchanged between SD and DES. This table on its own is just to provide some context of interaction points depending upon the historical analysis of hybrid models. *Due to limited number of existing hybrid models from which this relationship is deduced and diffused boundaries between different formats, this research took a conservative stance on applying Table 3.2 on its own for identification of interaction points.* Another reason for not applying this is tightly problem centric approach of previous hybrid studies. Terminology used in previous hybrid models poses challenges to its applicability to wider context. Due to these reasons it was vital to identify generic terms rather than specific terms. As the terminology for different variables can change with different problem contexts but what they represent does not. It was realised that change of focus from face value of variables to their place value will enhance generalisation of the proposed framework. As use of hybrid format for identification of interaction points was limiting the generalness of the framework, they are applied only for providing context for identification.

Keeping in mind the place value of variables, it has been reported in literature that interactions between SD and DES occur via inputs and outputs (Helal et al, 2007). As the main purpose of Phase 2 is identification of interaction points, detailed knowledge of outputs and inputs of SD and DES is required. Objectives of SD and DES models have been already described in Phase 1. From objectives outputs and inputs of SD and DES models can be defined. Robinson (2008b) in his framework for conceptual model development provides guidelines for identification of outputs and inputs. As the guidance provided by Robinson (2008b) is for conceptual modelling, same guidelines can be applied for both SD and DES models. Once the outputs and inputs of SD and DES models are defined the next step is to identify interactions points.

Interaction points provide the link between SD and DES. Establishment of linkage between SD and DES in hybrid model has been a challenge. Pena- Mora et al, (2008) and Helal et al. (2007) have provided some guidance for establishing this link.

- *Pena-Mora et al(2008). and Lee et al. (2009) used Pritsker's principles for linking SD and DES*

Pena- Mora et al, (2008) and Lee et al (2009) have applied Pritsker's (1998) principles to formulate interactions. Pritsker's principles are more suitable in situations where hybrid simulation represents physical control systems. In an organisational context they do not fit well. In physical control hybrid systems SD is used for providing lower level operational representation of continuous variables and DES for higher level control variables. However in organisational context use of SD and DES is mostly the other way around: SD is usually used for representing higher strategic level analysis and DES for analysing lower operational details.

- *Helal et al. (2007) used inputs and outputs of SD and DES models to establish link*

Helal et al. (2007) proposed that linking between SD and DES models in the hybrid model is established through inputs and outputs. All variables defined in a model can be categorised under inputs and outputs. According to the framework proposed by Helal et al. (2007), inputs of one model are identified along with their source model. Then outputs are identified along with their destination model. According to their framework some outputs of DES can be used as inputs of SD and vice-versa. The limitation of their framework is that it does not provide guidance when the value of output variables of one are replaced by value of output variable of another because they are more accurately calculated by the other model. Helal et al's (2007) framework also provide limited guidance in situations where value of SD and DES variables are not directly replaced by values of variables defined in the other model but are influenced, for example experience level defined by Martin and Raffo (2000) in their hybrid model is an SD variable (output) which influences the activity duration (input variable) of the DES model. Influences like this cannot be explained with the framework provided by Helal et al (2007).

In order to overcome these limitations, this framework guides to identify variables of the DES model which are more **accurately captured** or **influenced** by SD and vice versa. Variables "accurately captured" by the other model cover both scenarios:

- where outputs of one model can be input of another (Helal et al, 2007)
- where value of output variable of one model is replaced by value of output variable of another model (because other model compute more accurately)

The command "identify the variables influenced by other model", capture variables where SD and DES variables are not merely replaced but are influenced by each other.

Identification of the above variables will result in identification of interaction points. All the variables identified above along with their corresponding variables in the other model which replaces or influence their values are all classified as interaction points. As per definition, variables *whose values are changed or influenced by variables of other model and variables which replace or influence the values of variables of other models during hybrid simulation will be named as* ***"interaction points***. With this Phase 2 achieves its objective as the purpose of Phase 2 of the framework is to provide potential users with guidance for identification of interaction points. Figure 3.4 provides diagrammatic representation of the various steps carried out in Phase 2 for achieving this purpose. As shown in Figure 3.4 Phase 2 consists of following steps:

- Identification of hybrid format
- Identification of inputs and outputs of both SD and DES models
- Identification of variables which are accurately captured or influenced by variables of other model
- Identification of interaction points

Although an elaborate discussion on these steps have been provided above, the rest of the section will provide brief summary of these steps.

Identification of hybrid format

As objectives of SD and DES models are already established in Phase 1, some implicit knowledge about hybrid format is already there from Phase 1, however Table 3.2 assists in further clarification of this and aids in identification of hybrid format. Table 3.2 also sets some context for identification of interaction points.

Identification of inputs and outputs of both SD and DES models

As discussed above interactions between SD and DES occur via their input and output variables. Robinson (2008b) has provided guidance for identification of inputs and outputs. As argued before as the guidance provided by Robinson (2008b) is for conceptual simulation modelling, same guidance can be applied for identification of inputs and outputs of both SD and DES models. As argued by Robinson, identification of outputs does not pose a challenge as they resonate with objectives of the model. Inputs of the model are the model variables whose values can be altered to achieve modelling objectives. Just like outputs, identification of inputs is also driven by objectives of the model. Inputs can be quantitative like demand over a period of time, number of resources or qualitative like changes to rules, logic or model structure (Robinson, 2008b).

Identification of variables which are accurately captured or influenced by variables of other model

This is achieved by careful analysis of all the variables of both SD and DES models. Variables which are accurately captured by other model can be easily identified for example although SD can calculate work in process (WIP) but WIP is more accurately captured by DES. Identification of variables influenced by other models depends upon the deeper understanding of the problem scenario. In this case values of variables defined in one model are not directly replaced by values of corresponding variables defined in another model but are influenced. The relationship between corresponding variables is more of causal type as exhibited by SD and DES variables of hybrid model developed by Martin and Raffo (2000). In Martin and Raffos' (2000) hybrid model of software project management, productivity and experience level variables of SD model affect duration of software activities represented by DES model.

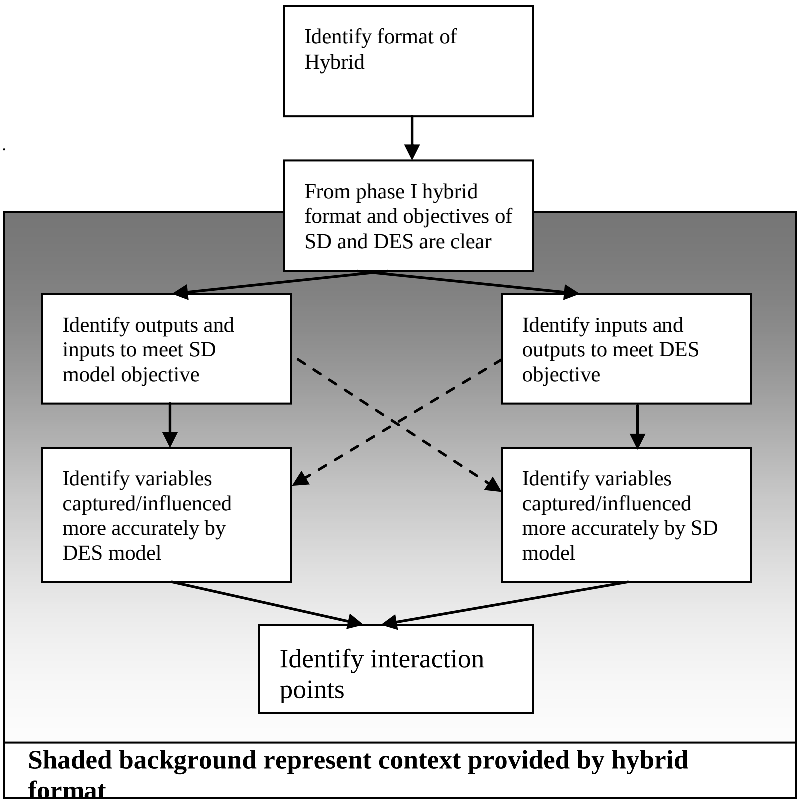

Figure 3.4: Overview of Phase 2 of the proposed framework

Identification of interaction points

Interaction points comprises of both variable being replaced and influenced as well as variables of the other model which are replacing or influencing values. As the variables whose values are more accurately captured by variables defined in other model and variables whose values are influenced by variables defined in other model are already identified, identification of interaction points is straight forward as it only requires the explicit listing of corresponding variables of both models**.** Once the interaction points are defined, the next step is to define the way SD and DES interact with each other over time to exchange data.

Phase 3: Identification of mode of interaction

The purpose of this phase is to provide guidelines for identification of mode of interaction (the way SD and DES interact with each other over time with respect to their run time) between SD and DES components of hybrid model. Figure 3.5 provides a sketch of various steps carried out in this phase. As discussed in Section 2.7 and 3.5, there are two modes of interaction between SD and DES: Cyclic and Parallel. In cyclic interaction mode, both SD and DES models run in tandem, both models exchange outputs and inputs only after completing the entire simulation run. There is no information exchange during the simulation run time. In parallel interaction mode, both SD and DES model run simultaneously and the information is exchanged during run time, models are stopped after equal time intervals during the run to exchange information. Depending upon the overall objective and the way elements represented by SD and DES are coupled with each other in time and space define the way SD and DES models interact with each other. Table 3.3 aids in selection of appropriate interaction mode. If the elements represented by SD and DES are coupled in time and space and this coupling influences overall objective, then parallel interactions are required if they are not coupled in time and space then cyclic interactions can provide the required analysis.

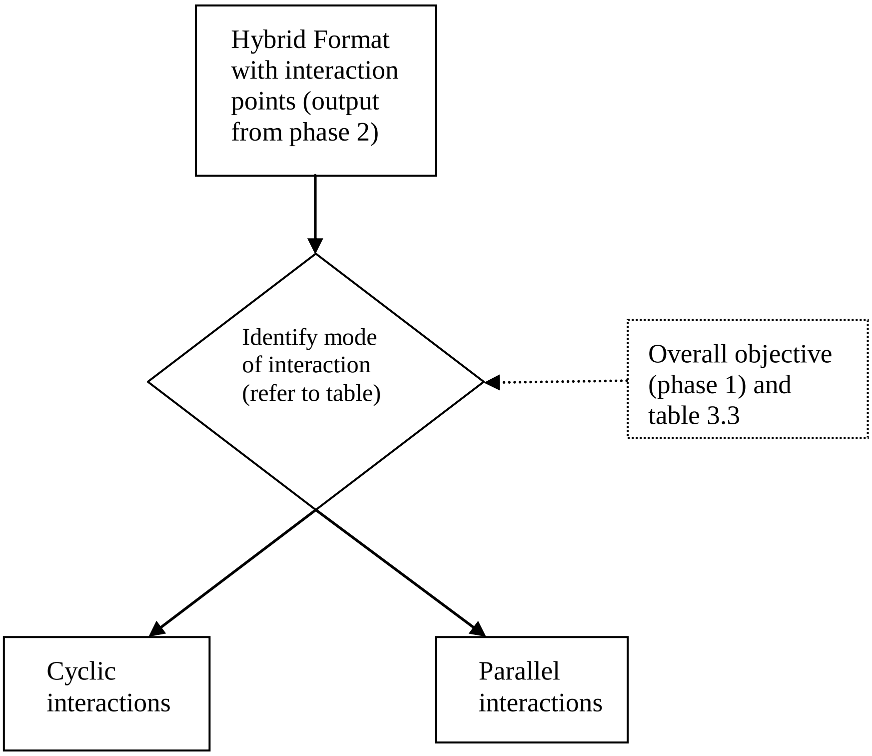

Figure 3.5: Overview of Phase 3 of the proposed framework

It is hoped that the proposed framework will be able to meet the requirements and fill the gap of lack of generic conceptual framework to provide step by step guidance to prospective users of hybrid simulation. The next section will provide a brief summary of the entire chapter.

3.7 Summary

Chapter 3 starts with Section 3.1 which provides introduction and purpose of the chapter. It establishes connection with the previous chapter by reiterating the research question set in the previous chapter and the way different sections of this chapter are going to contribute towards answering that. After introduction Section 3.2 described the requirements of hybrid simulation framework. This section argued that the framework for hybrid simulation should be able to provide answers to Why (Why hybrid simulation), what (what information is exchanged in hybrid simulation) and How (how the information is going to exchange) within the context of problem scenarios and hybrid simulation. Section 3.3 provides discussion regarding identification problems which require hybrid simulation. It highlighted the need and provided discussion on criteria for selection between SD and DES. It has been argued that selection between SD and DES is prerequisite for hybrid simulation. Section 3.4 elaborates on the hybrid simulation formats discussed in the previous chapter and described the relationship identified between hybrid formats and interaction points. The motivation behind this description is to use this as a guideline for identifying interaction points. The next section provided a description of different modes of interaction between SD and DES. Section 3.6 satisfies the objective of this chapter by proposing a three phase framework for hybrid simulation. Each phase of the framework is mapped to a requirement established in Section 3.2 and provides guidelines for meeting those requirements. Finally Section 3.7 summarises chapter. The framework proposed in this chapter will be evaluated theoretically in next chapter.

Chapter 4: Theoretical Evaluation of the Framework

4.1 Introduction

In the previous chapter a generic theoretical framework for providing guidance with respect to hybrid simulation in the organisational context has been proposed. On the basis of the literature reviewed, three requirements for the framework were established: Identification of the problems which require hybrid simulation, identification of variables of SD and DES models which are going to be exchanged and finally selection of the appropriate mode of interaction between SD and DES to exchange information. The purpose of this chapter is to evaluate the proposed framework with respect to its ability to meet established requirements.

In order to evaluate the proposed framework a retrospective multiple cases based analysis is carried out. In the context of the current study, due to the diverse nature of healthcare problems, multiple cases exhibiting different problem contexts have been deployed for theoretical evaluation. As mentioned in the previous chapter, the proposed framework consists of three phases and each phase further consists of several steps. For the purpose of evaluation, all these steps are applied to the different cases. Findings and limitations of the proposed framework encountered during evaluation are used as a basis for its refinement. The following paragraph provides a description of the structure of the rest of the chapter.

Chapter 4 starts with an introduction focussing on the objective and structure of the chapter. Section 4.2 provides a description of the evaluation criteria. Section 4.3 provides a sketch of application of hybrid simulation framework to six different cases from healthcare domains. Section 4.4 provides a detailed account of reflections from theoretical evaluation. Section 4.5 focuses on modification of the framework by addressing the limitations discussed in the previous section. Section 4.6 describes the modified framework. Finally Section 4.7 provides summary of the chapter and its relation to the rest of the next chapter.

4.2 Framework Evaluation Criteria

The theoretical framework is evaluated against its ability to meet requirements set in previous chapter. Due to the descriptive nature of the proposed framework, it is not possible to measure accuracy of theoretical frameworks until a full complete model is available (Robinson, 2008a). However the modeller can assess it theoretically whether it can provide sufficient accuracy for the purpose to which it will be applied. The initial analysis of the proposed framework is based on its ability to fulfil requirements, provision of guidance for identification that the problem in hand requires hybrid simulation followed by guidance with regards to identification of interaction points between SD and DES models and finally conceptualise the way SD and DES models are going to interact and exchange information over the time. In a nutshell the three phases of hybrid framework address Why, What and How aspects of the problem requiring hybrid simulation. The following section provides a discussion on the evaluation criteria and the how the framework performs against these criteria.

4.2.1 Ability to identify whether the problem requires hybrid solution

The framework is assessed with regards to its ability to assist its potential users in identifying whether the problem in hand requires a hybrid solution or not. As discussed in the previous chapter, this can not be achieved without the ability to select between SD and DES. As argued in literature (Farhland, 1970) hybrid simulation is only justified if some aspects of the problem require SD for analysis, and some require DES and there are strong interactions between the elements represented by both. Identification of problems requiring hybrid simulation is the first step of this framework. It will be inappropriate to apply hybrid simulation to problems which can be analysed effectively either with SD or DES or by both SD and DES without the need for integration. Hence it is important for the framework to aid selection between SD, DES, both SD and DES and Hybrid approaches.

4.2.2 Ability to identify interaction points between SD and DES

Once it is identified that problem seeks hybrid simulation, the second requirement for hybrid simulation is to define interaction points. Some understanding about interaction points is already there from Phase 1. The answer to the question that "Are there interactions between SD and DES elements" is vital for identification of problem as hybrid. This not only indicates the need for hybrid simulation but also provides a basis for the interaction points. The framework is evaluated theoretically for its ability to provide guidance for identifying and defining interaction points.

4.2.3 Ability to provide guidance for mode of interaction

Once it is identified that the problem requires hybrid simulation and interaction points between SD and DES are identified and defined, the next question analysts have in mind for carrying out hybrid simulation is "how SD and DES are going to interact with each other over time". The third criteria for evaluation is the ability of the framework to guide modellers in making an appropriate choice with respect to the way SD and DES are going to interact with each other over the time to exchange information.

4.3 Retrospective Application of Framework

For the purpose of evaluation, the proposed framework is applied to multiple cases from the healthcare domain. The cases are selected on the basis of the following three criteria:

- The paper focuses on the healthcare domain
- The work is conducted after 2000
- The paper has either deployed SD, DES or both

On the basis of above criteria, six cases, undertaken in diverse clinical environments, are incorporated in the design for the purpose of retrospective evaluation. In order to illuminate different aspects of research, multiple sources of evidence are used. One of the criticisms of the case study method is that the results cannot be generalised, because they relate to specific situations and localities. In the context of the current study, because cases used are from diverse healthcare environments, confidence is increased in the findings being transferable to a broad range of healthcare settings. The following subsections will describe the application of instructions embedded in the three phases of the proposed framework to multiple case studies.

4.3.1 Case 1

Modelling Health Service Centres with Simulation and System Dynamics (Ying and Zhanming, 2008)

Problem Description

Chengzi Health consultation Corporation Ltd (CHCC) provides diagnostic services to the population of Beijing, Hebei and surrounding areas. Services include standard tests on blood, Urine, ECG and a number of specialised tests. CHCC operates 21 health care centres (HSC), four hospital laboratories, a mobile collection service and specimen pickup service from physician offices and a centralised laboratory. Physicians are supplied with standard test requisition form to give to their patients and the patients can go to any of the 21 HSC centres. CHCC was faced with increasing demand for its services but had limited resources available to meet that demand. Due to that, patients suffered long waiting times. There was pressure to reengineer the HSC network to reduce waiting times as well as their variability. Health service targets require that 80% of patients should not have to wait more than twenty minutes. In order to meet increasing demand within the waiting time targets, one of the interventions management were interested in was to reduce the number of HSC to fewer but larger HSCs, so that resources can be pooled and variation in demand reduced. Simulation expertise was sought for analysing the feasibility of achieving this target and long term consequences of this intervention. The following subsections will provide a description of the way different phases of the proposed framework are applied to problem scenarios.

Phase 1

As described in previous chapter, Phase I start with identification of overall objectives.

Identify overall Objective

In order to consider both problem perspective as well as system perspective, three questions have been designed. The potential users are required to answer these questions for the purpose of identification of overall objectives (see Table 4.1). As this is retrospective evaluation, the answers are provided on the basis of problem description.

Identify overall Objective	
Questions	Answers
What causes problem owners to seek assistance from analysts	Long waiting times
What is the goal they are seeking	PSC management have planned interventions to reduce waiting time. They want the modelling team to analyse the impact of these interventions. Also want them to recommend the optimum number of PSC and resources required to meet performance targets.
What are the internal and external influences on the goal	Internal influences on the goal are internal organisation, resources and flow of patients within the boundaries of PSC network. External influences on goal are fluctuation in demand due to demographic and environmental factors.
Overall Objective: The overall objective is to improve the operations of PSC network to meet performance targets in response to fluctuating demand	

Table 4.1: Identification of overall objective for Case 1

Once the overall objective is defined, the next step is to decompose it into smaller objectives.

Divide it into smaller objectives

As the overall objective is to improve services so that performance targets set by government can be achieved in response to fluctuating demand. For the detailed analysis of this, the model should be capable of representing the operational logistics and individual level tracking for capturing performance measures. As the operation logistics and performance are influenced by demand which is fluctuating, for accurate analysis model is required to capture that fluctuation in demand. Although the temptation would be to develop an all inclusive model, but as suggested by Pidd (2001) it would be a better idea to start with simple models and if required link them. Hence we can split the main objective in to the following two objectives and develop models accordingly:

- Develop a model which is capable of representing the PSC operations and patient flow so that individual level detail such as waiting times and total time spent in the system can be calculated.
- Develop a model which is capable of modelling fluctuation in demand.

Once the overall objective is divided into smaller objectives, the next step is to select the appropriate method for each objective.

Method Selection

For the purpose of method selection criteria provided in Table 3.1 are applied to all objectives (as shown in Table 4.2). Depending upon the objective defined, the appropriate option is selected out of the two options provided against each criterion established in Table 3.1. Table 4.2 shows the options selected for both objectives.

Criteria	**Objective 1** Develop a model which is capable of representing the PSC operations and patient flow so that individual level detail such as waiting times and total time spent in system can be calculated	**Objective 2** Develop a model which is capable of capturing fluctuation in demand
Problem Perspective		
Purpose	Optimisation of operational logistics	Parameter estimation (estimation of fluctuation in demand)
Problem Scope	operational	strategic
Importance of randomness	High (stochastic nature)	Low (deterministic)
Importance of interaction between individual entities	High	Low
Required level of Resolution	Detailed	Aggregate
System's Perspective		
System View	Detailed	Holistic
Complexity of importance	Detail complexity	Dynamic complexity
Evolution over time	Event based discontinuous	Continuous
Control parameter	Queues	Rates
SD/DES	DES	SD

Table 4.2: Selection criteria applied to objectives defined in case 1

In the above table, the purpose of objective one is optimisation of operational logistics of HSC to achieve performance targets. The scope of objective one is operational as it focuses on operational improvement. Achievement of performance targets cannot be analysed without capturing how much time each patient has waited and spent in HSC. Randomness, due to varying process time and inter-arrival time is of high importance. Hence individual level detail and randomness are important for objective one. In order to achieve objective one the model should be capable of comprehending detail complexity. Control parameters for this objective are queues the objective is to reduce queue size and time patients spend waiting in queues. From the Table 4.2, it is clear that objective one requires DES. Similarly by applying these criteria to the second objective (as shown in Table 4.2) it has been decide that SD is the appropriate method for achieving objective two. Demand is an aggregate variable which is affected by dynamic interactions between various environmental and process factors contributing towards dynamic complexity. Evolution of demand over time is continuous as it varies continuously in response to process and environment factors. Control parameter in this objective is rate, as demand is measured in the form of number of patients over time unit. Due to these reasons SD was selected for capturing fluctuation in demand.

Are there interactions?

Yes. Fluctuations in demand affects inter- arrival frequency which in turn influences waiting times and resources required. Similarly waiting times affect the patient satisfaction and demand for services in HSC. As there are interactions between elements represented by DES (Inter- arrival frequency and waiting times) and elements represented by SD such as aggregated demand, hence the problem requires a hybrid simulation.

Phase 2

Identify Format

As the DES is used for representation of as-is and reengineered processes and SD to evaluate the impact of this effort on demand (environment), from Table 3.2 it is clear that this scenario fits well into process performance – environment format. According to the relationship between format and interaction points (as shown in Table 3.2), the interaction points between SD and DES should be waiting time and demand. Identification of hybrid format only provides context for interaction points on the basis of relationship observed between formats and interaction points. Following instructions will provide more objective identification of interaction points.

Identify outputs and inputs of SD model

Once, the objective of the SD which "captures the fluctuation in demand" is clear the next step is to identify outputs and inputs. As mentioned by Robinson (2008b) identification of outputs is quite easy as it resonates with the objective. In this case as the objective is to estimate fluctuation in demand, the output is aggregated demand over time.

The inputs are driven by the outputs and experimental factors (Robinson, 2008b). As the demand is affected by, population demographics waiting times etc. the main inputs of SD are: Waiting times, population density, patient satisfactions etc.

Identify outputs and inputs of DES model

The overall objective of DES is to calculate the waiting time and total time spent by each patient; hence the main output of DES is waiting time and Time in system for patients. Inputs are driven by outputs and experimental factors as they affect output. In this case inter arrival frequency of patients and process logic and logistics are defined as inputs as overall performance (output) of centres depend upon these factors. Considering these factors the inputs of DES are: Patient arrivals, HCS logistics, Number of HCS, HCS process flow logic.

Identify SD variables whose values are more accurately captured or influenced by DES variables.

Patient satisfaction is influenced by waiting times and waiting times are more accurately captured by DES. From this it is obvious that “waiting time” variable of DES influences “patient satisfaction” variable of SD.

Identify DES variables whose values are more accurately captured or influenced by SD variables.

Patient arrivals is disaggregated demand over time (inter- arrival frequency) and is captured more accurately by SD. It implies that “inter-arrival frequency”, which is an input variable of DES and more accurately captured by “demand” which is a SD output variable.

Define Interaction points.

Interaction points are variables whose values are changed or influenced by variables of the other model and variables which replace or influence the values of variables of other models during hybrid simulation.

As per definition of interaction points, demand from SD, Patient inter–arrival frequency of DES, waiting time from DES and patient satisfaction from SD are identified interaction points.

Phase 3

Hybrid problem with identified interaction points is the input to this phase. The interaction between SD and DES depends upon the coupling between SD and DES models. According to Table 3.3 If the elements represented by SD and DES are coupled and linked in time and space and this coupling is important for the overall objective then parallel interactions are required. However if there is coupling but they are not linked in time and space then cyclic mode is suitable. In this scenario elements represented by SD and DES models are not linked in space and time, hence cyclic interactions are required.

What this study could have gained from framework?

The modelling team in this case used DES for this problem and helped problem owners with optimum design and requirement for resources. Initially the problem owners were satisfied with the modelling output as the facility designed on the basis of recommendations by the modelling team worked efficiently without excessive waits. However after 18 months, the efficiency of the new PSC started deteriorating and waiting times started to increase. The modelling team was called in again and they realised that they failed to anticipate the change in demand which is result of improved patient satisfaction along with demographic trends. They realised that they could have anticipated this with a SD model. The author believes that although that would have been better than having DES alone but would not have been the ideal. As demand is affected by efficiency of operations and operations are affected by demand. There is an obvious feedback loop between them and this can only be effectively captured with hybrid simulation.

4.3.2 Case 2

Evaluation of different Prevention Strategies for Coronary Heart Disease (Babad et al, 2002)

<u>Problem Description</u>

Coronary heart disease (CHD) is one of the leading causes of morbidity and mortality in UK. The cause of CHD is progressive narrowing of arteries which supply blood to heart muscle. This narrowing of arteries leads to angina and in worse to a heart attack. According to National Service Framework (NSF) approximately 1.5 million people suffer from angina and about 300,000 people have a heart attack in a year. CHD is one of the major causes of premature deaths in UK. There are socio economic and ethnic differences in mortality rate.

There is emphasis in on devising prevention and treatment strategies. The policy makers need to be able to evaluate these prevention and treatment strategies from the perspective of their effectiveness and affordability. The modelling team was approached to develop a model for evaluation of different prevention strategies. The primary purpose of prevention is to either prevent or delay the onset of disease, once it is developed it would require treatment and that is not part of this study.

Healthcare policy makers are interested in the consequences of different prevention strategies on incidence and prevalence of CHD, Healthcare utilisation, cost and effectiveness of these interventions. In chronic disease it has been proved that instead of one intervention, the cumulative effect of multiple interventions is much more effective. Healthcare authorities approached the modelling team for evaluation of these prevention strategies on prevalence of CHD and associated cost. The following subsections will describe the way different phases of proposed framework are applied to this problem scenario.

Phase 1

The proposed framework consists of three phases: Phase1, Phase2 and Phase3. Phase I start with identification of the overall objective. The following question aids potential users in defining the overall objective in light of both problem perspective as well as system perspective.

Identify overall Objective	
Questions	Answers
What causes problem owners to seek assistance from analysts	The problem owner seek assistance from modelling team to evaluate and compare the impact of different prevention strategies on prevalence of CHD and associated cost
What is the goal they are seeking	They are looking for single or mix of strategies with highest influence on prevention of CHD.
What are the internal and external influences on the goal	Dynamic interactions between various factors such as life style, obesity, diabetes, genetic, cultural preferences etc contributes towards the prevalence of CHD. The external influences are different strategies impact these interactions and overall outcome of these interactions
Overall Objective: The main objective is to evaluate and compare the effect of different prevention strategies on prevalence of CHD and cost either in isolation or collectively.	

Table 4.3: Identification of overall objective for case 2

Decompose in to smaller objectives

This aim can be achieved by capturing the dynamic complexity between variables responsible for prevalence of CHD and analysing the effect of different policies on these variables responsible for CHD prevalence and their associated cost.

- Capture Dynamic interactions between factors contributing towards prevalence of CHD
- Capture effect of different policies on CHD prevalence, pathway and their associated cost effectiveness

Method Selection

Just like case study one, the criteria provided by Table 3.1 are applied to all objectives (as shown in Table 4.4).

Criteria	**Objective 1** Capture Dynamic interactions between factors contributing towards prevalence of CHD	**Objective 2** Capture effect of different policies on CHD prevalence, pathway and their associated cost effectiveness
Problem Perspective		
Purpose	Understanding	Understanding and comparison
Problem Scope	NA	Strategic
Importance of randomness	Low	Low
Importance of interaction between individual entities	Low	Low
Required level of Resolution	Aggregate	Aggregate
System's Perspective		
System View	Holistic	Holistic
Complexity of importance	Dynamic complexity	Dynamic complexity
Evolution over time	Continuous	Continuous
Control parameter	Rates	Rates
SD/DES	SD	SD

Table 4.4: Selection criteria applied to objectives defined in Case 2

Depending upon the options selected for each objective, the appropriate method is selected. It is clear from the table that due to associated dynamic complexity and holistic aggregate stance SD is more appropriate. As both objectives can be achieved by SD, it implies that problem does not require hybrid simulation. Hence the application of framework to problem scenario terminates here. There is no need for applying Phase 2 and Phase 3.

What could have they gained out of this framework?

The study could have been done more effectively by applying SD instead of DES. The framework would have helped them in the selection of right method for analysis. They have aggregated patients in their model, one patient in their model represent a population of thousand patients. One of the main advantages of DES over SD is its ability to capture individual level detail, if that was not required for the purpose then use of DES is not justified. Prevalence of heart diseases is due to dynamic interactions between various factors. As the purpose was to evaluate the impact of policies on prevention of heart diseases, SD would have offered more by capturing these dynamic interactions and how various policies influence these interactions. It could have saved them lots of time as SD model comparatively takes less time as compared to DES.

4.3.3 Case 3

Operational level model for scheduling resources to meet varying demand experienced by NHS direct call centres (Lacey, P., 2005)

Problem Description

Every year approximately nine million people receive out of hour care. It not only provide reassurance and peace of mind that expert care is available outside normal GP hours but also is a vital means of managing demand on other parts of healthcare system. In the absence of this there will be additional demand on hospital A and E departments. One of such initiatives of providing out of hours service is NHS Direct. It provides medical advice over the phone. Patient satisfaction is vital for its utility and efficiency. It is important that callers do not have to wait for long hours. If there are long waits patients will switch to A and E. In order to achieve the efficiency of such call centres, the supply for services needs to match demand for services. Adequate numbers of resources are required so that the patients' calls can be handled within an acceptable time frame. Demand is stochastic and varies depending upon days of week, public holidays and hour of day. The modelling team was approached by the problem owners to provide analysis for scheduling resources to cope with varying level of demands. Variation in demand depending upon population size of different regions and time and day of week is recorded by health authorities. The modelling team was provided with statistics for this demand. The following subsections will describe the way different phases of the proposed framework are applied to this problem scenario.

Phase 1

The purpose of Phase 1 of the proposed framework is to provide guidance for selection of appropriate method for analysis of the problem.

Identify overall objective

Identify overall Objective	
What causes problem owners to seek assistance from analysts	Mismatch between supply and demand (demand varies) which result in long waiting times
What is the goal they are seeking	To schedule resources in response to varying demand in such a way that waiting times can be reduced.
What are the internal and external influences on the goal	Variation in demand and logistics of call centre
Overall Objective: The objective of the model is to capture process logistics and identify the optimum staffing level required to meet the varying demand profile so that the patients do not experience long waits. .	

Table 4.5: Identification of overall objective for case 3

Decompose into smaller objectives

As it is the variation in demand and process logistics which affects overall objective and statistics for variation in demand are already recorded by healthcare, it does not require to be captured with a new model. It can be achieved by capturing process logistics and using historical data for capturing variation in demand. Hence the overall objective does not required to be decomposed into smaller objectives.

Method Selection

Criteria	**Objective**: The objective of the model is to capture process logistics and identify the optimum staffing level required to meet the varying demand profile so that the patients do not experience long waits.
Purpose	Optimisation, scheduling
Problem Scope	operational
Importance of randomness	high
Importance of interaction between individual entities	high
Required level of Resolution	detail
System View	Microscopic, analytic
Complexity of importance	Detail complexity
Evolution over time	discrete
Control parameter	queues
SD/DES	DES

Table 4.6: Selection criteria applied to objectives defined in Case 3

As discussed in previous case study, criteria established in Table 3.1 have been used for selection of appropriate method. According to the objective defined, Table 4.6 shows the options selected for different criteria. Due to high importance of randomness because of variation in demand and stochastic nature of different call centre activities and importance of individual tracking (waiting time for each patient is required to be monitored), DES has been selected as the appropriate method. As there is only one objective which can be achieved with DES, it implies that the problem does not require hybrid simulation. As the problem does not require hybrid simulation, evaluation terminates here.

4.3.4 Case 4

Modelling Patient service centres with simulation and system dynamics (Rohleder et al, 2007)

Problem Description

Calgary Laboratory Services (CLS) is a network of laboratories in Calgary which provide diagnostic services for Calgary's population. Services include standard tests on blood, Urine, ECG and a number of specialised tests. Physicians are supplied with standard test requisition form to give to their patients and the patients can go to any of the PSC centres. CLS was faced with increasing demand for its services but had limited resources available to meet that demand. Due to that patients had to wait long times. There was pressure to reengineer the PSC network to reduce waiting times as well as their variability. Health service targets require that 80% of the patients should not have to wait more than twenty minutes. In order to improve a new Patient service centre (PSC) within CLS was designed. Authorities approached the modelling group for optimising the design and allocation of resources for efficient delivery of services without excessive waiting times. The remainder of the section will provide a discussion with regards to application of the proposed framework to this problem.

Phase 1

Identify overall Objective

Identify overall Objective	
What causes problem owners to seek assistance from analysts	Long waiting times
What is the goal they are seeking	PSC management have planned reengineering of PSC to reduce waiting time. They want modelling team to analyse the long term impact of reengineering
What are the internal and external influences on the goal	Internal influences on the goal are internal organisation, resources and flow of patients with in the boundaries of PSC network. External influences on goal are fluctuation in demand due to demographic and process improvement
Overall Objective: The overall objective is to improve the operations of PSC network to meet performance targets in response to fluctuating demand.	

Table 4.7: Identification of overall objective for case 4

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Divide it into smaller objectives

Like case study one, the overall objective is to improve services so that performance targets set by government can be achieved in response to fluctuating demand. In order to achieve it a model capable of representing the operational logistics and individual level tracking for capturing performance measure is required. As the operation logistics and performance influence demand which is fluctuating, for accurate analysis, model is required to capture that fluctuation in demand. Hence we can split the main objective in to the following two objectives and develop models accordingly:

- Develop a model which is capable of representing the base scenario (as-is) and reengineered PSC operations and patient flow so that individual level detail such as waiting times and total time spent in the system can be calculated.
- Develop a model which is capable of modelling fluctuation in demand.

Method selection

Once the overall objective is dividing into smaller objectives, the next step is to select the appropriate method for each objective. Table 3.1 provides criteria for selection of method. Similar to case study one, the criteria established in the previous chapter have been applied to both objectives. Table 4.8 describes the options selected for different selection criteria.

Criteria	**Objective 1** the operations	**Objective 2** capture the fluctuation in demand
Problem Perspective		
Purpose	optimisation	Parameter estimation
Problem Scope	operational	strategic
Importance of randomness	High (stochastic nature)	Low (deterministic)
Importance of interaction between individual entities	High	Low
Required level of Resolution	detailed	aggregate

System's Perspective		
System View	detailed	holistic
Complexity of importance	Detail complexity	Dynamic complexity
Evolution over time	Event based discontinuous	continuous
Control parameter	queues	rates
SD/DES	DES	SD

Table 4.8: Selection criteria applied to objectives defined in Case 4

From the above table it is clear that objective one due to its operational stance, detailed requirement for resolution (so that attributes such as time in system for individual patients can be captured), high importance of interactions between individuals , high content of detailed complexity and randomness can be achieved more effectively with DES. On the other hand, the output of objective two is aggregated demand which evolves continuously over time in response to dynamic interactions between various environmental and process related factors. Due to the holistic aggregate strategic level stance, there is less emphasis on randomness. Because of the ability of SD to capture the criteria discussed above, SD was selected as the most appropriate method for capturing fluctuation in demand over time.

Are there interactions?

Yes. Fluctuation in demand affects the waiting times and resources required. Similarly waiting times affect the patient satisfaction which further influences people's behaviour and contribute towards fluctuation in demand services in PSC. Hence the problem requires a hybrid simulation.

Phase 2

Identify Format

As DES is used for representation of base and reengineered processes and SD to evaluate the impact of this effort on demand, according to Table 3.2 this scenario fits well into process performance – environment format. According to relationship between format and interaction points (Table 3.2), the interaction points should be waiting time and demand. The following instructions will provide more objective identification of interaction points.

Identify outputs and inputs of SD model

Once, the objective of the SD "capture fluctuation in demand" is clear the next step is to identify outputs and inputs. As mentioned by Robinson (2008b) identification of outputs is quite easy as it resonates with the objective. In this case the output is aggregated demand over time. The inputs are driven by the outputs. Demand for services is affected by: Patient satisfaction, waiting times and demographic factors.

Identify outputs and inputs of DES model

The overall objective of DES is to calculate the waiting time and Time in system for each patient hence the main output of DES is waiting time and Time in system

As inputs are driven by outputs and client intentions, the inputs of DES are: Patient arrivals, Resources, Number of PSC and Process logistics.

Identify SD variables whose values are more accurately captured or influenced by DES variables.

Waiting times are more accurately captured by DES

Identify DES variables whose values are more accurately captured or influenced by SD variables.

Incoming demand is captured more accurately by SD. Hence arrival of patients can be mapped to demand (SD).

Define Interaction points.

Interaction points are variables which are exchanged between two models

Demand from SD, patient arrival of DES, patient satisfaction and waiting time of SD and Waiting time calculated by DES are interaction points for the hybrid model.

Phase 3

Hybrid problem with identified interaction points are the inputs of this phase. The mode of interaction between SD and DES depends upon the interactions between elements of the problem represented by SD and DES models. Table 3.3 aids in the selection of appropriate mode of interaction. According to Table 3.3 if the elements represented by SD and DES are coupled and linked in time and space and this coupling influences the overall objective, then parallel interactions are appropriate, otherwise cyclic interactions can provide the required analysis. In this scenario SD and DES models are not linked in space and time, as impact of waiting time on demand is delayed by time, hence cyclic interactions are required.

What this study could have gained from framework?

The modelling team used DES for this problem and provided recommendations to problem owners on the basis of results and analysis of the DES model. Initially the problem owners were satisfied with the modelling output as the facility designed on the basis of recommendations by modelling team worked efficiently without excessive waits. However after approximately one and half years, the waiting times started to increase. The problem owners contacted the modelling team again and demanded explanation for increasing waiting times. After careful analysis the modelling team realised that increase in waiting times was due to increase in demand for services. It was noted that due to improvement in waiting times the patients from other PSCs switch to the new facilities. The modelling team realised that they did not anticipate this increase in demand which is the result of improved patient satisfaction along with demographic trends. They realised that they could have anticipated this with a SD model. The author believes that although that would have been better than having DES alone but would not have been the ideal. As demand is affected by efficiency of operations and operations are affected by demand. There is an obvious feedback loop between them and this can only be effectively captured with hybrid simulation. The proposed framework would have helped them in the selection of an appropriate method as well as providing guidelines for carrying out hybrid simulation.

4.3.5 Case 5

Understanding the effect of waiting time targets (Gunal and Pidd, 2009)

Problem Description

NHS performance targets have put pressure on healthcare management to reduce waiting times. Waiting time targets are a major element of the current NHS performance assessment framework in England and play a major role in determining the performance rating of NHS Trusts. The latest target set by government originally specified that by 2008 no patient should spend more than 18 weeks from referral to treatment. This is known as referral to treatment (RTT) target. This target was later relaxed and modified so that instead of all, 90% of admitted patients enter inpatient care within 18 weeks and treatment of 95% of non admitted patients start within 18 weeks. This target is ambitious for many hospitals and trusts in England. It is a known fact that along with environmental exogenous factors such as demographic changes, elective admissions are affected by endogenous factors emergency admissions, referral patterns and discharge policies. . Both elective and emergency admissions and referral patterns have stochastic nature. The purpose of this research is to analyse the effect of different policy initiatives on 18 week target for elective admissions. Application of the proposed framework to problem is discussed in rest of the section.

Phase 1

Identify overall objective

Identify overall Objective	
What causes problem owners to seek assistance from analysts	Healthcare management wants to know the operational implications of planned intervention for improving eighteen week target.
What is the goal they are seeking	They want to identify effective policies for meeting 18 week target
What are the internal and external influences on the goal	Internal influences are operational logistics for 18 week pathway. External influences are ripple effects of local optimisation on global aspect for example effect of reducing outpatient wait time on GP referral fractions etc. effect of reduction in LOS on readmission rate.

Overall Objective: The purpose of this research is to develop a conceptual model for analysing the effect of different policy initiatives on 18 week target for elective admissions	

Table 4.9: Identification of overall objective for case 5

Decompose into smaller objectives

In order to achieve impact on the 18 week target, a process map of individual patient flow is required. As healthcare is an interconnected, policies targeted at one sector have ripple effects somewhere else. These ripple effects also contribute towards fluctuation in the demand for various services for example policies at reducing 18 week RTT, contribute towards increased demand for elective services. An increase in GP referral rates and more demand from society (change from private to government treatment) has been observed in response to reduced waiting times. In order to capture the impact of different policies on 18 week RTT performance measure, a holistic analysis for capturing non linear ripple effects (such as change in demand) of different policies is also required. Where as for capturing RTT performance measure a model capable of capturing process logistics and patient pathway up to individual level resolution is required for analysing ripple effects, a dynamic model which can provide a holistic view and dynamic complexity due to nonlinear feedback between different components of healthcare is required. Hence the overall objective is decomposed into the following objectives.

- Develop a model which can accurately represent the patient flow of elective patients to identify the RTT for each patient.
- Develop a model which can provide the holistic view of integrated healthcare and is able to capture ripple effects of policy interventions due to non linear feedback among constituting components.

Method selection

Once the overall objective is dividing into smaller objectives, the next step is to select the appropriate method for each objective. Table 3.1 provides criteria for selection of method.

Criteria	Objective 1 Develop a model which can accurately represent the patient flow of elective patients to identify the RTT for each patient.	Objective 2 Develop a model which can provide the holistic view of integrated healthcare and is able to capture ripple effects of policy interventions due to non linear feedback among constituting components. Such as referral rates, cancellations etc.
Problem Perspective		
Purpose		understanding
Problem Scope	Operational/strategic	Operational/strategic
Importance of randomness	high	low
Importance of interaction between individual entities	high	low
Required level of Resolution	High detailed individual level	Low aggregate
System's Perspective		
System View	detailed	holistic
Complexity of importance	detail	dynamic
Evolution over time	Event based	Continuous with delays
Control parameter	Queues , waiting time	flows
SD/DES	DES	SD

Table 4.10: Selection criteria applied to objectives defined in Case 5

Table 4.10 provide sketch of options selected against different criteria for both objectives. From the above table it is clear that in order to achieve objective one (patient flow and RTT time for each patient), randomness associated with patient flow, interactions among individuals and detailed resolution up to individual level is required for capturing RTT time for each patient. Due to high content of detail complexity and reasons discussed above, DES has been selected as method for further analysis. On the other hand in order to achieve objective two, nonlinear feedbacks and dynamic complexity between constituting parts is required to be captured. Due to these reasons along with holistic stance and less emphasis on randomness, detail resolution and individual interactions, SD has been selected as the appropriate method.

Are there interactions?

Yes there are interactions between two objectives as ripple effects in the form of change in demand for services affects process logistics and process outcome such as waiting times affect these ripple effects, such as enhanced GP referrals.

Phase 2

Identify format

SD represents High-level holistic view and DES represents the operational perspective. SD represents the overall effect of policies from global perspective and DES represents the effect of these policies on operations. According to Table 3.2 this scenario fits in both hierarchical as well as process performance– environment format. Boundaries between these formats are much diffused. The identification of interaction points on the basis of format can be quiet misleading due to overlapping features of formats.

Identify outputs and inputs of SD

Due to large size and complexity of the model, detailed outputs are not obvious, conceptually outputs of SD should be referral rates, readmissions rates, cancellations etc. Inputs to SD are consultation rates, waiting times

Identify outputs and inputs of DES

Outputs of DES are waiting time, waiting list, Throughput (processing rates such as consultation rate etc). Inputs of DES are going to be patient arrivals, processing time, resources, and referral rates.

Identify variables of SD which are captured/ influenced more realistically by DES.

Consultation rate, waiting times

Identify variables of DES which are either captured/ influenced more realistically by SD.

Readmission rate, referral rate, and cancellations

Identify interaction points

Referral rates, readmission rate and cancellation rates from SD and waiting times and consultation rates from DES

Identification of outputs and inputs and interaction points faced challenges as eighteen week pathway consist of many independent sections such as GP outpatients elective admissions and inpatient wards etc. Due to the size and ambiguity of relationship between different sections identification of inputs and outputs is not obvious. It is difficult to comprehend inputs and outputs of such as large problems in the absence of models.

Phase 3

Hybrid problem with identified interaction points is the input of this phase. The mode of interaction between SD and DES depends upon the coupling between SD and DES models. If they are coupled and linked in time and space and this coupling influences overall objective then parallel interactions are required otherwise cyclic mode can provide the required analysis. The system is represented from different perspectives and elements represented by SD and DES are closely linked in space and time and influence the overall objective hence parallel interactions are required.

What this study could have gained from the Framework?

The modelling team in this study has used DES for analysis. As DES model gets over complicated for large systems, the resulting model would have been very complex. In order to avoid that complexity, the authors of the paper have only developed one detailed DES model of A&E. For rest of the departments in the network, such as outpatients and inpatients, only high level less detailed models have been developed. Hence the resulting model has not utilised the DES capabilities to its optimum level.

The model also has not able to capture the nonlinear interactions between different departments within the network. By using hybrid simulation these problems could have been avoided as DES would have provided the required level of detail and SD can capture the ripple effects of different interventions which result due to non linear feedback between different components.

4.3.6 Case 6

Development of Tool Kit for GUM clinic (Viana, 2008)

Problem Description

Chlamydia is a sexually transmitted disease. Government has opened Genito – Urinary Medicine clinics (GUM) for the treatment of patients. The purpose of this study is to develop the toolkit for GUM clinic to forecast the required number of resources so that GUM clinic meets the level of service demanded by patients. The demand for service depends upon the number of infected individuals in that geographic region.

Identify overall objective

Identify overall Objective	
What causes problem owners to seek assistance from analysts	Problem owners want to optimise the resources required for GUM clinic so that patients can be treated without delays.
What is the goal they are seeking	They want to develop a tool capable of predicting the required number of resources for GUM clinic.
What are the internal and external influences on the goal	The main influence on this goal is prevalence and progression of Chlamydia in population. It generates demand for GUM clinics. Demand is affected by interactions between various demographic and clinical factors. Varying demand and uncertainty associated with in the process parameters also affect demand of GUM clinic.
Overall Objective: The aim of the research project is to develop a toolkit which predicts the optimum number of resources required to meet varying demand for GUM clinics.	

Table 4.11: Identification of overall objective for case 6

Divide into smaller objectives

The overall objective of developing a toolkit for efficient management of GUM clinics can be broken down into the following:

- Analysing demand over time which is influenced by disease dynamics as well as by demographic properties of the population.
- Analysing the optimum scheduling and capacity (required resources) of GUM in response to varying demand so that the patients can receive efficient services without experiencing excessive waits.

Method Selection

As mentioned in previous case studies, criteria established in Table 3.1 have been applied for selection of method.

Criteria	**Objective 1** Analysing the demand over time which is influenced by disease dynamics as well as by demographic properties of the population.	**Objective 2** Analysing the optimum scheduling and capacity (required resources) of GUM in response to varying demand so that the patients can receive efficient services without experiencing excessive waits.
Problem Perspective		
Purpose	Understanding, forecast	Optimisation, scheduling
Problem Scope	strategic	operational
Importance of randomness	low	high
Importance of interaction between individual entities	low	high
Required level of Resolution	Low, aggregate	High, detailed
System's Perspective		
System View	Holistic	Microscopic
Complexity of importance	Dynamic complexity	Detail complexity
Evolution over time	continuous	Discrete event based
Control parameter	flows	queues
SD/DES	SD	DES

Table 4.12: Selection criteria applied to objectives defined in Case 6

In order to analyse varying demand it is important to capture the dynamic complexity between various variables affecting disease dynamics. It is important to analyse the way different variables influence prevalence of disease over the time. From Table 4.12 it is clear that for this SD is more appropriate for achieving objective one. For the second objective as mentioned due to the options selected in Table 4.12 DES is more appropriate.

Are there interaction?

Yes demand from SD affect the process activities and resource requirement of DES model and output of DES (treated patients) affect dynamics of disease prevalence and demand.

Phase 2

Identify Format

This step is just to categorise this hybrid into format (Table 3.2). In this context DES represent the operational logistics of a clinic and SD represent the holistic strategic level environment context, It can be categorised as hierarchical format as well as process–environment. Diffusion of boundaries between different formats complicates identification of format. Due to this it is difficult to establish the context for interaction points.

Identify outputs and inputs of SD

Outputs

Demand for GUM clinic

Inputs

Various clinical and demographic factors affecting Chlamydia prevalence

Treatment rate etc, demographic profile of population (Identification of inputs poses challenge in absence of some kind of model)

Identify outputs and inputs of DES

Outputs

Time spent in system, Throughput, Waiting time, Work in process

Inputs

Patient arrivals, Activity duration for various activities in GUM clinic, Resources, Process Logic

Identify SD variables whose values are more accurately captured or influenced by DES variables.

Treatment rate

Identify DES variables whose values are more accurately captured or influenced by SD variables.

Patient arrival influenced by demand

Define Interaction Points

Patient arrival for DES is affected by demand generated in SD model. Throughput of DES, (treated patients) reduces the number of infected individuals and hence affect the progression of disease

As mentioned before in absence of model it is difficult to comprehend inputs, outputs and interaction points.

Phase 3

Input to this phase is output of phase 2.

How two models are going to interact and exchange data depend on the purpose of problem. In order to achieve its purpose, the SD model needs to evaluate projected demand for services and incorporate it into the DES model to find the optimum number of resources required for meeting that demand. As the elements represented by SD and DES are coupled in time and space and this coupling is important for achieving overall purpose, this can be achieved by parallel interactions.

What they could have gained from framework?

Author stated during presentation that they are intending to use hybrid simulation for achieving the purpose. Hybrid framework can assist them by providing step by step instruction for development of a hybrid model.

4.4 Reflections on Theoretical Evaluation

The purpose of this section is to reflect on the findings from theoretical evaluation. These reflections provide basis for the refinement of the proposed framework. As the ultimate objective of the reflections is modification of the framework, only limitations and challenges faced during the application of framework to different case studies have been highlighted. As discussed in Section 4.2 ability of the framework to meet requirements established in Chapter 3 are used as criteria for evaluation. Following subsections provide discussion on the limitations of the framework with respect to achieving each requirement.

4.4.1 Ability to identify whether the problem requires hybrid solution

The evaluation of the proposed framework is based on its ability to provide guidance for identification of problems which can be analysed more effectively with hybrid simulation. As mentioned previously in order to identify problems, the frameworks should be able to provide guidance for selection between SD, DES, "SD and DES" and Hybrid. The framework is evaluated with six cases to reflect on its ability to provide guidance with respect to identification. However the appropriateness of the selection depends upon the objective of the problem. In most of the cases the objective of the problem is quite clear from the beginning as that is the main reason for seeking analysis. However understanding of various influences on objective varies. Understanding of overall objective in light of various internal and external influences widens the scope and assists in understanding the purpose of problem from a wider systemic context. Due to this it was possible to define the objectives in such a way that the improvements initiatives based on this objective are not only valid for the short term but also aids towards long term sustainability. For example in the Case 1, where the problem owners approached the modelling team to improve the efficiency of PSCs in order to meet performance measures, the broadened context of objective with external and internal influences provide the analyst with widened frame of mind to understand the impact of fluctuation in demand for services. This widened context provides with the understanding of interactions between demand and service efficiency. Without this the focus would have been much narrower limited to improvement of PSC logistics.

Decomposition of objective into smaller objectives provided more transparency and ease for selection of methods. The tabular form of criteria for selection provided with simple and easy to use method for selection between SD and DES. Decomposition aided in identification of interactions between objectives and need for hybrid simulation. Without this division of objectives into smaller units, the identification that the problem requires a hybrid simulation would have lacked clarity.

The framework provides detailed criteria for selection between SD and DES. There is clarity about where to apply both SD and DES in isolation and where to apply them in integrative hybrid way.

4.4.2 Ability to identify interaction points between SD and DES

The framework is evaluated with six case studies for its ability to meet all three requirements set in previous chapters. However, not all the problems require hybrid simulation. Phase 2 and Phase 3 are carried out only if it is identified in Phase 1 that the problem requires hybrid simulation. As there were only a few cases where hybrid simulation would have been more useful, only those cases were used for evaluation of these criteria. The focus of the evaluation was the provision of guidance for identification of interaction points.

Although the framework provides detailed guidance for identifying interaction points there were certain steps which were either not required or were posing challenges. From application of Phase 2 to different case studies, it has been observed that the first step of the Phase 2, “Identify formatting”, the purpose of which is to set context for identification of interaction points contribute towards ambiguity. Overlapping features of different formats and diffused boundaries poses challenges for identifying appropriate format. It has also been observed that the framework is quite capable of identification of interaction points without the need of the context provided by format. Identification of format was not providing any added value.

In this framework the identification of interactions depends upon the variables defined in the form of outputs and inputs of models. Robinson (2008b) in his conceptual framework advised to identify outputs and inputs in the conceptual phase as a precursor to actual model. During evaluation it has been identified that although outputs can be identified prior to development of models, for thorough input identification a more detailed model is required. However data is not required at this stage. This problem was more pronounced in larger models such as the holistic model for eighteen week referral to treatment model and Chlamydia infection model where large numbers of variables are involved. It was realised that a detailed model would have aided in identification of inputs and outputs. Hence for detailed identification of outputs and inputs some kind of model is required. The absence of such a model poses challenges for identification of detailed inputs and outputs in Case 5 and Case 6.

The next step “identify the variables which are influenced or accurately captured by DES model” and “identify the variables which are influenced or accurately captured by SD model” contains multiple instructions. Decomposition of this step in to two would have offered more clarity.

4.4.3 Ability to identify mode of interaction between SD and DES

Theoretical Evaluation

The evaluation looks at how the framework has enabled to identify the appropriate interaction mode for exchange of information. The framework acknowledges the importance of identifying the way SD and DES models are going to interact with each other over the time but it does not provide instructions regarding how to identify that mode. It says “Define interaction and synchronisation mechanism”, it does not assist the modeller in the process of defining. The framework modeller is aware that in order to analyse the problem with hybrid solution he needs to define/ identify the interaction mode but how to attain that goal is missing.

4.5 Modification of Framework

This section discusses the different requirements for the modification of the framework. These requirements are based on the discussion in the previous section. In the previous section, it has been realised that although the framework addressed the requirements and provided guidance for conceptualising a hybrid simulation model, it encountered certain limitations as well. Those limitations provide the basis for refinement of the framework. As the challenges arose in all three phases of the framework, the following section will provide a discussion on how these issues have been addressed in each phase.

4.5.1 Modifications of Phase 1

Phase 1 provided concise and clear guidance for identifying the problem which requires hybrid simulation. There was not any major problem encountered during theoretical evaluation of this phase.

4.5.2 Modifications of Phase 2

As discussed before the purpose of format identification in Phase 2 is to provide guidelines for identification of interaction points. It has been observed during evaluation that the framework is capable for identifying interaction points without this step. As it does not provide any added value, it is deleted from the framework (as shown in Figure 4.1). Another problem encountered during evaluation was identification of inputs and outputs in the absence of some kind of representation for SD and DES models. It was realised that representation of SD and DES models is required for identification of inputs and outputs. In order to overcome this limitation another step “development of SD and DES model” is added to framework (as shown in Figure 4.1) prior to identification of inputs and outputs. Development of SD and DES model does not imply fully functional models; models in conceptual stages are fine for this as long as they represent all the variables and their interactions. The next step in Phase 2 “Identify variables being influenced by or accurately represented by SD” “Identify variables being influenced or accurately represented by DES” This is a confusing multi-instructional step. The overarching requirement for any framework is simplicity. In order to simplify this step needs to be decomposed into two (as shown in Figure 4.1).

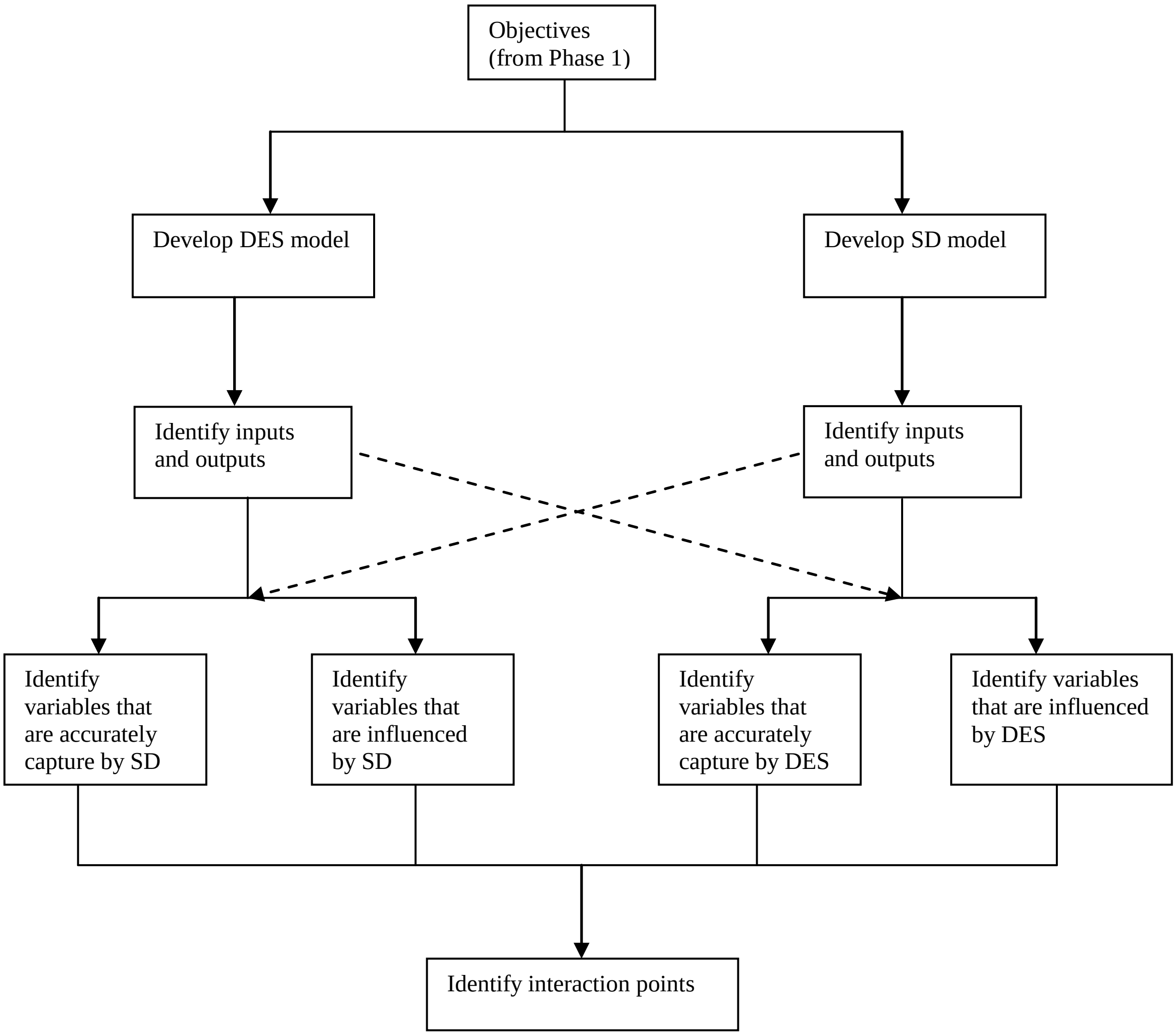


Figure 4.1: Overview of modified Phase 2

4.5.3 Modifications of Phase 3

The proposed framework in its current state make the users aware that there are two possible modes of interaction between SD and DES models in hybrid simulation but it does not provide instructions on selection between modes of interaction. The framework says “define interaction.., it does not provide any guidance on how to do that. The framework should ask analyst some questions which provoke them to think about the problem objective with respect to interactions and synchronisation between SD and DES. The following questions aid in selection between different modes:

- Are the elements represented by SD and DES closely coupled in space and time?
- Are those interactions important for achieving the objective (in other words do they influence the problem)

If the answer to both above questions is yes, then they require parallel interactions, otherwise cyclic interactions are sufficient for achieving objective.

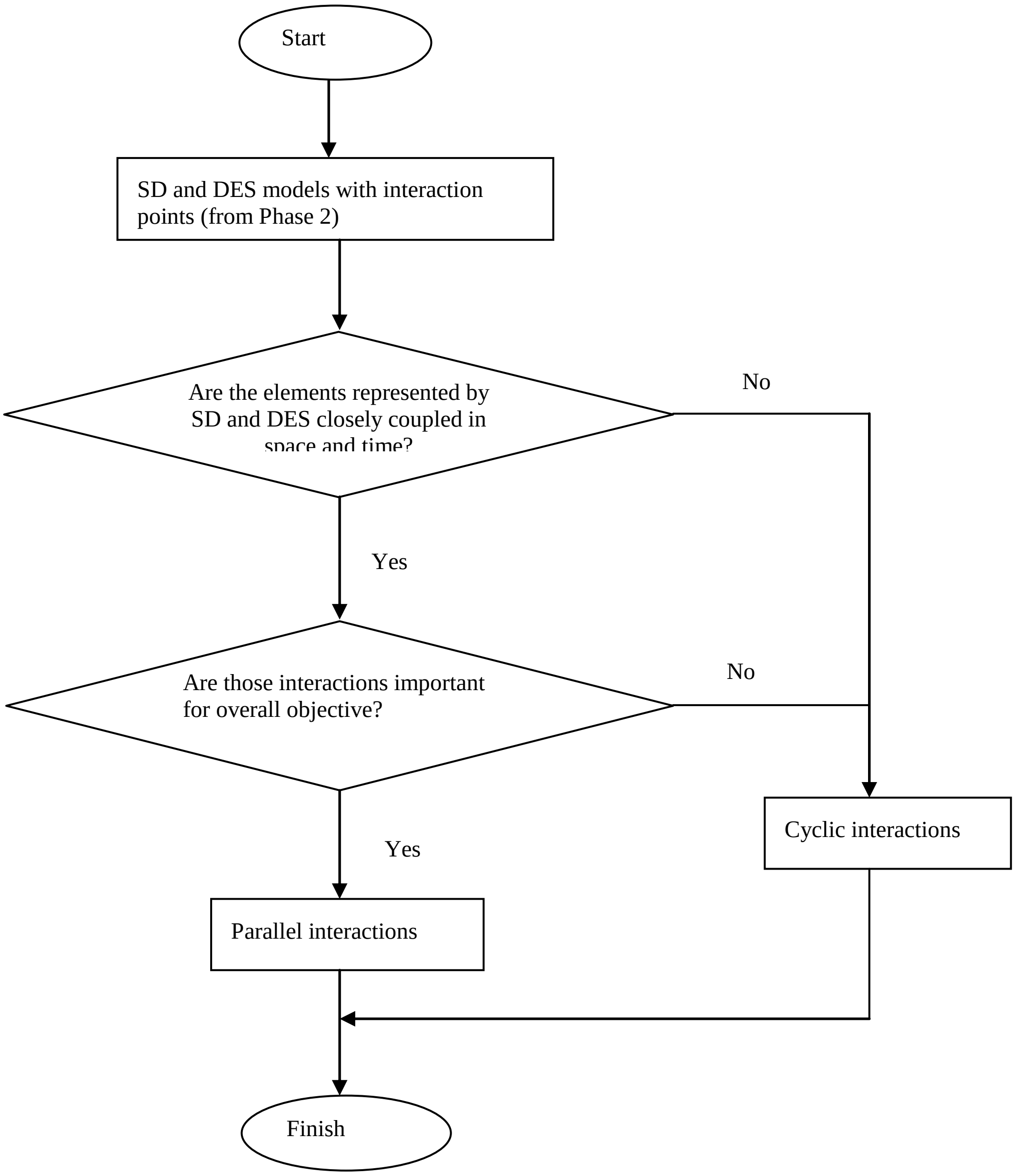


Figure 4.2: Overview of modified Phase 3

4.6 Modified framework

In light of above modifications the framework proposed in Chapter 3 has been modified. As shown in Figure 4.3, the framework consists of three phases to meet the three requirements established in Chapter 3. Each phase correspond towards fulfilling one requirement. Phase 1 aid in identifying problems in need of hybrid simulation. Execution of Phase 2 and Phase 3 depends upon the output of Phase 1. If the output of Phase 1 is that problem requires hybrid solution only then prospective users need to apply Phase 2 and Phase 3 otherwise the instructions provided by the framework terminate there. Phase 2 provides guidelines for identification of interaction points followed by the Phase 3 which aids prospective users of the framework in identifying the mode of interaction between SD and DES models. The following subsections will provide detailed description of each phase.

4.6.1 Phase 1: Identification of Problem seeking Hybrid Solution

It is required that the problem is thoroughly understood. The purpose of Phase 1 is to provide guidance to its prospective users for identifying problems which require hybrid simulation. As shown in Figure 4.3, Phase 1 consists of the following main steps for identifying problems in need of hybrid simulation:

- Identify overall Objective
- Decompose in to smaller objectives
- Method Selection

The following section will provide description of these steps.

Identify overall Objective

As the models are developed for achieving objectives, the first step is to identify the overall objective. Most of the time objectives are defined with myopic emphasis on problem only. Throughout this research the importance of system perspective for method selection has been highlighted. The prospective users of the framework are encouraged to answer these questions while defining the overall objective.

- What causes the problem owners to seek assistance from analysts?
- What is the goal they are seeking?
- What are the internal and external influences on the goal?

It is believed that these simple questions will aid in defining more sustainable objective taking into consideration both problem as well as system perspective. The third question provokes the analysts to analyse the goal they are seeking from a system perspective. It aids in widening the boundaries of the problem by including external influences.

Decompose in to smaller objectives

Once the objective is defined the next step as suggested by third principle of modelling (Pidd, 2001) is to decompose the objective into smaller simpler objectives. This decomposition simplifies both the process of selection of appropriate method as well as process of model building. The broad criteria for decomposition is that if there is a variable which influences the main objective and requires analysis for its estimation, then the overall objective requires to be decomposed, so that instead of an all inclusive model for achieving overall objective, another separate model for estimation of value of that influencing variable is required. Decomposition contributes towards more accuracy and fewer assumptions, as instead of taking average values or making assumption about the value; a separate model for estimation of value is developed. As argued by Pidd (2001), decomposition also enhances the transparency and confidence of clients as it is easier to understand smaller, simple models than highly complex grand models. After the decomposition, the next step is to select the appropriate method for each objective.

Method Selection

Table 3.1 provides guidelines for method selection. Literature reviewed in Chapter 2 supports the criteria provided by Table 3.1. These criteria help in identifying the main characteristics and requirements of the objective. Each objective is subjectively evaluated against these criteria and value for each, depending upon characteristics and requirements of objective is assigned. Method required for analysis of objective is selected on the basis of values assigned. If there is more than one objective then after the method selection prospective users will have one of the following three options:

1. All objectives require DES
2. All objectives require SD
3. Both SD and DES are required

The framework terminates here in the first two scenarios. As shown in Figure 4.3, third scenario is preceded with question **"Are there interactions"** between elements represented by SD and elements represented by DES**.** If the answer is yes, it means that the problem requires hybrid simulation otherwise the overall objective can be achieved by two separate models.

Criteria	**DES**	**SD**
Problem Perspective		
Purpose	Decision: Optimisation, prediction and comparison	Policy making, overall understanding
Problem Scope	Operational	Strategic
Importance of randomness	high	Low
Importance of interaction between individual entities	High	Low
Required level of Resolution	Detailed individual level	Aggregate, high level
System's Perspective		
System View	Detailed Microscopic view	Holistic Telescopic view
Complexity of importance	Detail Complexity	Dynamic Complexity
Evolution over time	Discontinuous event based	Continuous
Control parameter	Holding (queues)	Rates (flows)

Table 4.13: Criteria for selection between SD and DES

4.6.2 Phase 2: Identify interaction points between SD and DES models

The purpose of Phase 2 is to provide guidelines for identification of interaction points between SD and DES models. It helps analysts in identifying the variables whose values are exchanged or influenced during hybrid simulation. As shown in Figure 4.1 Phase 2 consists of the following steps:

- Development of SD and DES models
- Identification of inputs and outputs of both models
- Identification of variables which are accurately captured by other model
- Identification of variables which are influenced by other model
- Identification of interaction points

Development of SD and DES models

As objectives of both SD and DES models are already defined previously in Phase 1, the first step of Phase 2 is development of SD and DES models to meet their respective objectives. There are many books available to provide guidance on building SD (Sterman, 2000) and DES (Law and Kelton, 2000; Robinson 2004) models.

Identification of inputs and outputs of both models

It is important to note that as the purpose of SD and DES models is to aid in identification of inputs and outputs, the potential users are advised to not to indulge in strenuous exercise for data collection. SD and DES models provide platforms for identification of inputs and outputs. All the variables whose values are not calculated/ estimated by model itself but are obtained from outside are considered as inputs. Similarly all the variables whose values can be derived from model itself are considered as outputs. It was observed that comprehension of inputs and outputs in the absence of a model faced challenges. The SD and DES models here act as a platform for identification of inputs and outputs.

Identification of variables which are accurately captured by other model

Once the inputs and outputs are identified the next step is to identify the variables represented in DES which are more accurately captured by SD and vice versa. This is followed by identification of DES variables which are influenced by SD and vice versa.

Identification of variables which are influenced by variables of other model

It was observed in process – environment hybrid format that sometimes relationship between variables of SD and DES is not of replacement of value of variables defined in one model by value of variables defined in other model, but it is more of causal type. From causal type, the author means where variable defined in one models influences the variable defined in other model. For example in example provided by Martin and Raffo (2000), SD variable productivity influences the DES input variable "activity duration". Similarly completion of activity of DES models caused changes in "experience level" variable defined in SD. This purpose of this step is to identify such variables. Identification of this requires thorough understanding of the problem and system context and relationships between variables defined in both SD and DES models.

Identification of interaction points

Identification of variables is preceded by defining of interaction points. Interact points are variables which actively participate during exchange of information between SD and DES during hybrid simulation. Interaction points comprises of both variable being replaced and influenced as well as variables of the other model which are replacing or influencing values. As the variables whose values are more accurately captured by variables defined in other model and variables whose values are influenced by variables defined in other model are already identified, identification of interaction points is straight forward as it only requires the explicit listing of corresponding variables of both models which are involved in information exchange.

4.6.3 Phase 3: Identification of mode of interaction

The purpose of this phase is to identify the mode of interaction between SD and DES. It has been identified that SD and DES model can integrate with each other to exchange information, either via parallel interactions or via cyclic interactions depending upon the interactions between elements of the problem represented by SD and DES and overall objective. Table 4.14 provides a description of cyclic and parallel interactions.

Mode of interaction	Definition
Cyclic interaction	SD and DES are run separately and the information is exchanged between consecutive runs. There is no interaction during the run time..
Parallel Interactions	SD and DES are run for same time synchronously and the information is exchanged during the run time. SD and DES run parallel.

Table 4.14: Different modes of interaction between SD and DES

Identification of mode of interaction depends upon following questions:

- **Are the elements represented by SD and DES closely coupled in space and time?**
- **Are those interactions important for achieving objective?**

Answers to the questions "Are the elements represented by SD and DES closely coupled in space and time" and "Are those interactions important for achieving objective" (as shown in Figure 4.4) assist in selecting the appropriate interactions. If the answer to both question is "yes" then parallel interactions are required otherwise cyclic interacts can provide the required analysis.

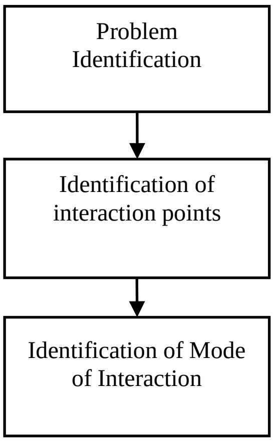


Figure 4.3: Three phases of generic framework for hybrid simulation

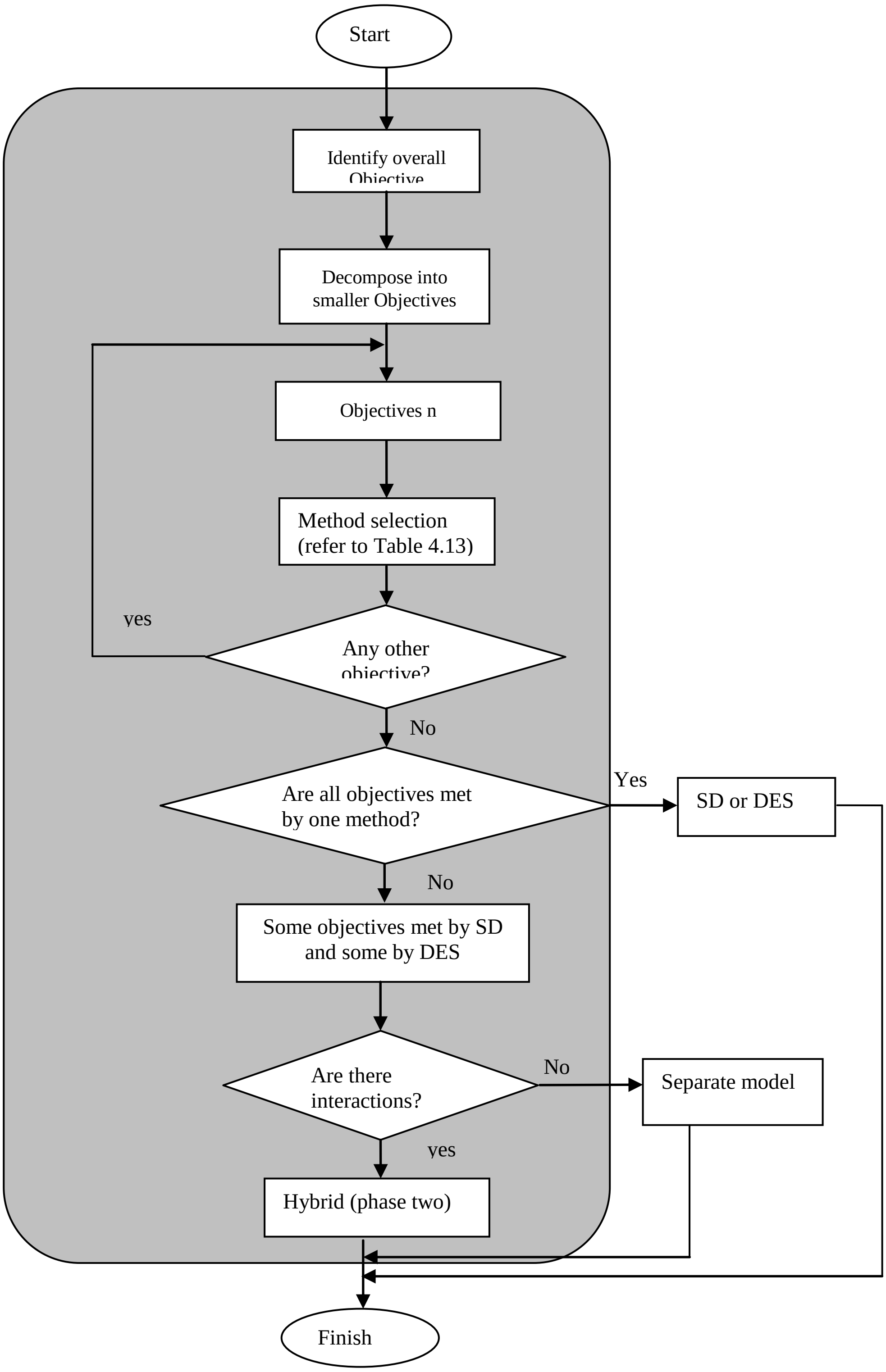


Figure 4.4: Overview of Phase 1 of the modified framework

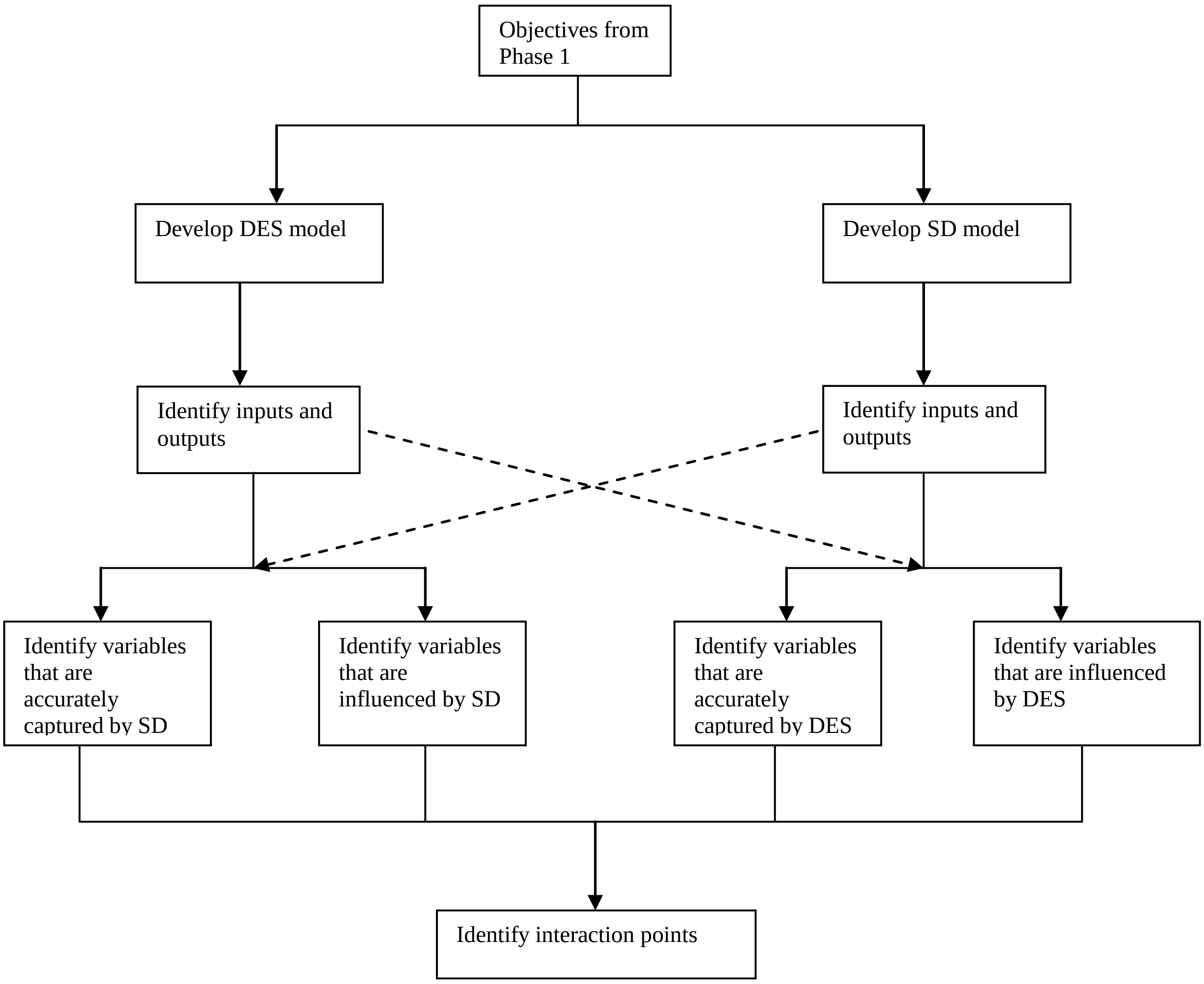


Figure 4.5: Overview of Phase 2 of the modified framework

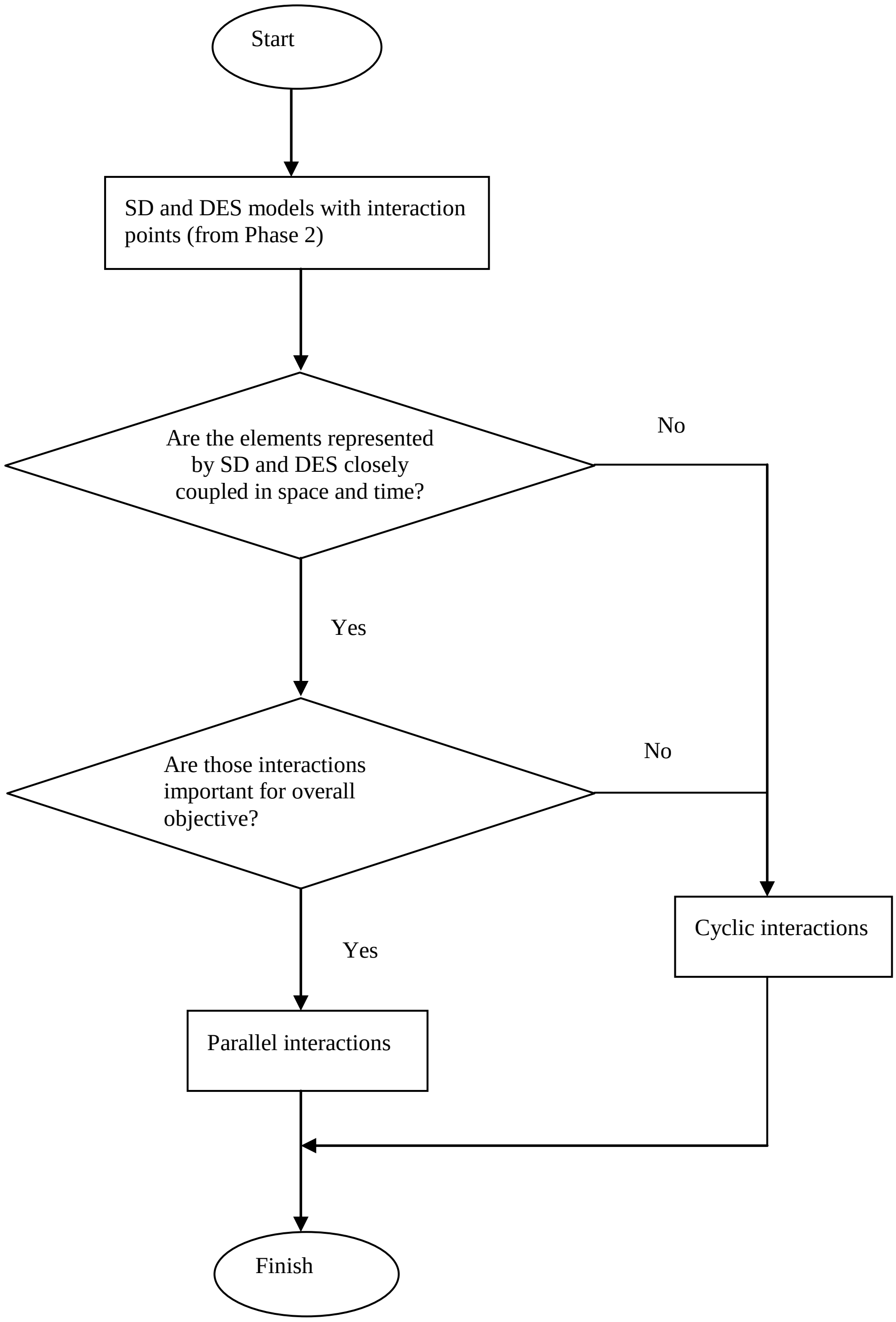


Figure 4.6: Overview of Phase 3 of the modified framework

4.7 Summary

This chapter achieved its objective "theoretical evaluation of the framework proposed in previous chapter" by using multiple case studies. This chapter started by a brief introduction to the rest of chapter. Section 4.2 described the criteria for evaluation. These criteria are based on the requirements established in the previous chapter. The framework is evaluated against its ability to meet these requirements. Section 4.3 applied six cases to different phases of the framework. The problem description is comprehended from multiple cases and three phases of the framework are applied to problem scenario. Out of six, four cases required hybrid simulation and hence been applied to all phases of framework, with the remaining two, evaluation of the framework terminates with Phase 1. The second and third phases of the framework are carried out only if the output of first phase indicates that the problem requires hybrid simulation.

Section 4.4 provides a sketch of reflections from the theoretical evaluation. As the purpose of the evaluation was to refine the framework, discussion on reflection was focussed only on limitations and challenges encountered. Limitations identified during evaluation provides basis for modification. Section 4.5 discusses the limitations encountered and modification of the framework to address these limitations. Mapping of Phase 1 to different problem scenarios did not encounter any challenges, however, it was identified that identification of format was not offering any added value to the Phase 2. The purpose of the second phase is to provide guidelines for identifying interaction points between SD and DES model. It was observed that the framework was capable to achieve that without the help of context provided by hybrid format. Hence the whole concept of format, including Table 3.2 was excluded from the framework. It was also identified that in the absence of SD and DES models, the framework was facing challenges during identification of input and outputs of large collaborated scenarios. In order to address this limitation, Phase two included a step "development of SD and DES models" prior to input and output identification. Some of the steps of framework were giving multiple instructions, causing unnecessary confusions. Those steps were decomposed into single instructions. The purpose of Phase 3 of the framework is to provide guidance for identification of mode of interaction. Although it was making its users aware of the two possible types of interactions between SD and DES, it was not providing any guidance for making selection between those two. The framework was amended by including some questions: answers to these questions aid in selection between two modes. Section 4.6 provides description of the modified framework. Like the proposed framework, the modified framework also consists of three phases. Finally Section 4.7 summarise the chapter. The next chapter will focus on empirical evaluation of the modified framework.

Chapter 5: Empirical Evaluation of the Framework

5.1 Introduction

Chapter 4 evaluated the proposed framework theoretically and modified it to address the limitations encountered during theoretical evaluation. In this chapter the modified framework is applied to a case study for empirical evaluation. The evaluation is extended further to implement the framework manually. The purpose of the implementation is to highlight limitations of the framework which are not conspicuous prior to implementation. Hence the objective of this chapter is to identify the limitations of the framework which could not be visualised during theoretical evaluation and to provide the basis for further refinements.

The structure of the chapter is as follows: The next section provides background of the problem addressed in this case study. The case- study investigates the impact of an electronic whiteboard on performance of physicians working in Accident and Emergency (A and E) department of a London district general hospital. Hospitals are part of service industry. Performance of servers in service industry is affected by the work load (Oliva, 2002). Electronic whiteboards provide A and E staff with live information about work load. The objective of this case study is to capture the impact on performance of physicians in response to live information. Section 5.3 provides a discussion on the application of hybrid framework to the case study. As the overall purpose of this chapter is the empirical evaluation of the framework, all three phases of the framework are applied to the problem context. Section 5.4 describes the details of the implementation focussing on the problems encountered and the way they were addressed. The next section provides a discussion on results obtained. Finally section 5.7 provides brief summary of the chapter.

5.2 Problem Background

There has been continuous increase in waiting times in British hospitals for many years (Audit Commission, 2001). In 'The NHS Plan', the government pledged that by 2004 no one should wait for more than four hours in the Accident and Emergency (A and E) department (The NHS Plan, 2000). Certain exceptions were made since January 2005; from 100% it has been modified to 98% (Department of Health, 2003). Approximately 13 million people attend around 200 major A and E departments in England every year, with no restrictions on attendance. Around 80% of the attendees are discharged home, the rest are admitted to in-patient beds. The 4-hour target is a major national performance indicator for receiving significant increase in funding. It was important to give evidence of attaining such improvement targets; however how to reduce waiting times remained unclear (Cooke et al, 2004).

In many cases, planned improvements are being linked to demanding service targets and hospitals that do not achieve those targets could face financial and other penalties. Many hospitals made strenuous efforts to meet these targets by allocating additional staff or other resources to A and E departments, changing emergency patient management or in other ways (Mayor, 2003). Many effective approaches from operations and management science such as simulation have been applied to improve A and E operations to achieve targets. There is also evidence of deployment of information technology to automate and improve clinical and operational services in A and E (Levin et al, 2006; France et al, 2005;Aronsky et al 2008; Boger 2003).

A & E departments are part of the service sector. The major difference between the service and other sectors is that both servers and customers are humans. Humans, unlike machines, respond to the changing work environment. Another major difference is that services are supplied instantaneously; there is no buffer of finished goods to protect against changing demand. Thus, in order to maintain the quality of services, it is vital to match demand with supply. The high level of uncertainty associated with demand makes the task of aligning demand with supply more difficult. This difference in demand and supply builds up schedule pressure. Unlike machines, servers in service industry, for example doctors and nurses in A and E, respond to this schedule pressure by changing their performance and behaviour. For timely and appropriate response from the human service agents, it is important to have the accurate information about the status of the system where status of the system is ever changing. A and E is an example of such an ever-changing system. Like other service sectors servers in A and E are humans, they respond to environmental schedule pressure by various means. Due to ever-changing scenarios, it is difficult to comprehend the real-time status of A and E without the help of information technology.

Like other service sectors such as banking, hospitals have also sought solutions from information technology (IT). There are many opportunities for IT in healthcare (Mendonca et al, 2004; Berglund et al, 2007). However, successful adoption of new IT applications in healthcare settings has been limited in many instances. A number of barriers against IT adoption have been well documented in literature (Broome and Adams, 2005; Van'tRiet et al, 2001). One of these barriers is the lack of understanding about how IT adoption relates to workflow. Due to its inability to show a tangible impact on workflow, such initiatives struggle to get support from senior management (Wong et al, 2008).This is the problem a London district general hospital (LDGH) was facing. Waiting times in the Majors section of A and E department of the LDGH was putting pressure on A and E department to improve their services. One of the causes attributed towards waiting time is lack of real time information about the status of patients. LDGH wanted to implement an electronic whiteboard to provide real-time information about patient status. A and E management was aware that electronic whiteboards have been successfully deployed in many emergency departments, and was able to considerably improve the processes. Due to the lack of reported studies demonstrating the impact of whiteboard on workflow, the LDGH approached our modelling team to provide the requisite analysis. The major function of whiteboard is to provide information about the dynamic status of the A and E department, the objective of this research project was to capture the impact of information flow on workflow (process of patient flow).

The following section will provide a description of the problem with emphasis on the interactions between information provided by white board, schedule pressure, physician's productivity and workflow followed by a sketch of the application of the framework to deliver hybrid simulation.

5.2.2 Problem Description

As discussed in the previous section, servers in service industry respond to changing schedule pressure by varying their performance (Oliva, 2002). This adaptability reduces the gap between actual performance and desired performance. In order to gain benefit from this adrenalin factor (response to schedule pressure), it is important to have means for providing the real-time information about the system, such as number of patients waiting at a particular time and time in system for each patient in context of the A and E department. As commented by one of the doctors "physician's behaviour in A and E is affected by number of red dots on white board". Red dots on the whiteboard in A and E represent the total number of patients in A and E who have been in the system for more than three hours. This information is documented in LDGH manually. Because A and E is a dynamic environment with ever-changing status, it is difficult to keep pace with this dynamicity without the help of information technology. A and E department of LDGH wanted to implement electronic whiteboard for providing the real-time information of A and E status. The problem A and E department has is to justify this investment in terms of added benefits to work flow of A and E. One of these barriers of adoption of information systems in healthcare is a lack of understanding about how IT adoption relates to workflow. Due to its inability to show a tangible impact on workflow, such initiatives struggle to get support from senior management (Wong et al, 2008). This is the problem management of A and E department of London district general hospital (LDGH) was facing. Majors section of A and E was facing was numerous breaches to the four hour performance measure. Timely information about status of patients was categorised as one the factors contributing towards reducing breaches by increasing productivity of physicians. (Baldwin et al, 2007). It has been reported in literature that electronic white board influences the behaviour of physicians which affects the workflow (references in beginning), but there is lack of empirical work to explain this relationship virtually. LDGH planned implementation of electronic whiteboard so that they sought expertise from modelling team to provide analysis with regards to advantages of electronic whiteboard over manual whiteboard with respect to physicians' productivity and workflow in A and E specifically on the number of breaches.

5.3. Application of Hybrid Framework to Problem

Due to high degree of complexity and dynamic nature of A and E, simulation was chosen as the method. Several papers have emphasized the suitability of simulation for patient flow research (Connelly and Blair, 2004; Bagust et al, 1999; Eldabi et al 2007; Brailsford et al, 2004; Brailsford and Hilton, 2001; Wolstenhome, 1999; Lane et al 2000; Fletcher et al, 2007). Two simulation techniques, DES and SD have become quite popular in the healthcare domain (Brailsford et al, 2003). A fair amount of literature is available on use of both DES and SD for the purpose of A and E improvements. Although an early decision of deploying simulation was made in the initial stages of the project, the main challenge was whether to adopt a DES, SD or hybrid simulation approach. The framework proposed in Chapter 3 has demonstrated theoretically the capability of providing that selection along with the provision of guidance on how to carry out hybrid simulation. Hence the framework was applied to this problem. During the application, step by step instructions provided by the framework were mapped to A and E problem. The following is the detailed description this process:

5.3.1 Phase 1

The first phase of the framework assists prospective users in selection of appropriate method. It provides guidance with regards to selection between SD, DES and hybrid depending upon the requirements of the problem. In order to achieve it, detailed instructions provided by phase 1 of the modified framework are applied. The first step of Phase 1 is about identification of the overall objective. The framework provides a set of three questions (as shown in Table 5.1) for assisting analyst with definition of overall objective. Answers to these questions are provided by the analyst depending upon the problem context. These questions provoke the analyst to consider both the problem as well as the system perspective while defining overall objective. Table 5.1 provides a description of questions, answers and overall objective defined in light of both problems as well as system context.

Identify overall Objective	
Questions	Answers
What causes problem owners to seek assistance from analysts	LDGH wanted to implement electronic whiteboard to improve the time in system (in order to avoid breaches) for patients in majors. In order to justify their investment they sought analysis from our modelling team to visualise the impact of white board on operations in A and E.
What is the goal they are seeking	They wanted empirical explanation of the way information flow from electronic whiteboard affect time in systems (eventually breaches) for individual patients.
What are the internal and external influences on the goal	The internal influence is patient flow and "A and E" logistics. External influence is the variation in productivity of physicians in response to information provided by whiteboard.
Overall Objective: In light of answers to the above questions the overall objective can be defined as understanding the impact of implementation of electronic whiteboard (provision of live information about A and E status) on the time in system (breaches) for patients.	

Table 5.1: Identification of overall LDGH case study objective

Divide overall objective into smaller objectives

This is also known as decomposition of the main purpose (Powell, 1995; Pidd, 2001). As the overall objective deals with the impact of electronic whiteboard on total time patients spend in the system. As explained in the modified framework, decomposition of overall objective is required in scenarios where overall objective is significantly influenced by variables whose values fluctuate in response to multiple factors. In the current scenario, in order to achieve the main objective the model also requires to capture variation in physician's productivity, because it significantly affects the time each individual patient spends inside the system (for calculation of number of breaches). As overall objective is significantly influenced by fluctuation in physician's productivity, the main objective can be achieved by achieving the following sub- objectives:

1. Capture the variation in physician's productivity (which is affected by variables such as schedule pressure, backlog etc)
2. Capture total time each patient spends in A&E department.

Method selection

According the framework as shown in Figure 5.1, the next step is to select appropriate method for all the objectives. Criteria provided by Table 4.13 are used for selecting appropriate method.

Criteria	**Objective 1** Capture the variation in physician's productivity	**Objective 2** Capture total time each patient spends in A&E department.
Problem Perspective		
Purpose	Parameter estimation (estimation of fluctuation in productivity)	Optimisation of operational logistics
Problem Scope	Operational	Operational
Importance of randomness	Low (deterministic)	High (stochastic nature)
Importance of interaction between individual entities	Low	High
Required level of Resolution	Aggregate	Detailed
System Perspective		
System View	Holistic	Detailed
Complexity of importance	Dynamic complexity	Detail complexity
Evolution over time	Continuous	Event based discontinuous
Control parameter	Rates	Queues
SD/DES	SD	DES

Table 5.2: Criteria for selection applied to objectives from LDGH case study

Table 5.2 describe options selected against criteria for both objectives. Objective one although it represents an operational problem but according to other criteria for example aggregate stance, continuous evolution of variation in productivity, high emphasis on dynamic complexity due to non linear feedback dynamics between SP, backlog and productivity, SD is more suitable. It has been observed in literature that the most strategic level problems apply SD for analysis and most operational level problems use DES. This generalisation should not be applied in the reverse manner for selection purposes. A detailed discussion on this will be provided in the next chapter.

For the second objective, due to emphasis on individual level resolution (as in order to analyse number of breaches, time in system for each individual patient is required), and detail complexity and high importance of randomness and interactions among individual patients, DES is selected as the method of choice.

Are there Interactions?

Yes, there are interactions between two models as productivity from the SD model will influence the activities of DES and will have impact on time in system and throughput of patients in A and E which further influences the productivity factor of SD model.

5.3.2 Phase 2

As it is identified in Phase 1 that the problem requires hybrid simulation, the next step is application of step by step interactions provided by Phase 2 of the modified framework.

Development of SD Model

The main objective of the SD model was to capture variation in productivity (performance) in response to information flow from the whiteboard. The whiteboard provides information regarding backlog and number of people waiting over 3 hours (thus indicating the number of people to be discharged in the next hour or the desired discharge rate). The LDGH team maintain that instead of the overall backlog, it is the number of people waiting over three hours (conveyed to them by red dots on a whiteboard) which causes pressure in the system. The interactions between variables such as backlog, number of people over 3 hours and schedule pressure are captured with feedback loops. Feedback refers to information about behaviour returning to affect subsequent behaviour (Gillespie et al, 2004).

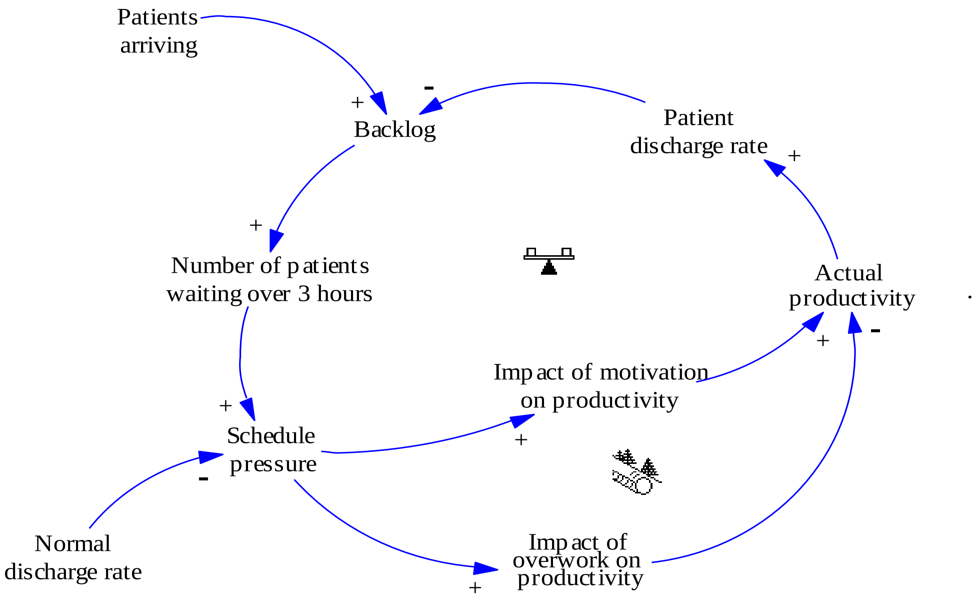


Figure 5.1: Feedback loops between different variables

These feedback loops can be balancing or reinforcing. In Figure 5.1, feedback loops represents the relation between information flow (backlog, number of people over three hours) 'schedule pressure' (SP) and productivity. In this SD model, SP is the core endogenous variable which affects productivity. Schedule pressure is defined as ratio between desired discharge rate and normal discharge rate. According to expert opinion from LDGH, the relationship between SP and productivity is hump shaped. Productivity increases slowly in response to increase in SP and after reaching a plateau, starts decreasing sharply (as shown in Figure 5.2**)**.

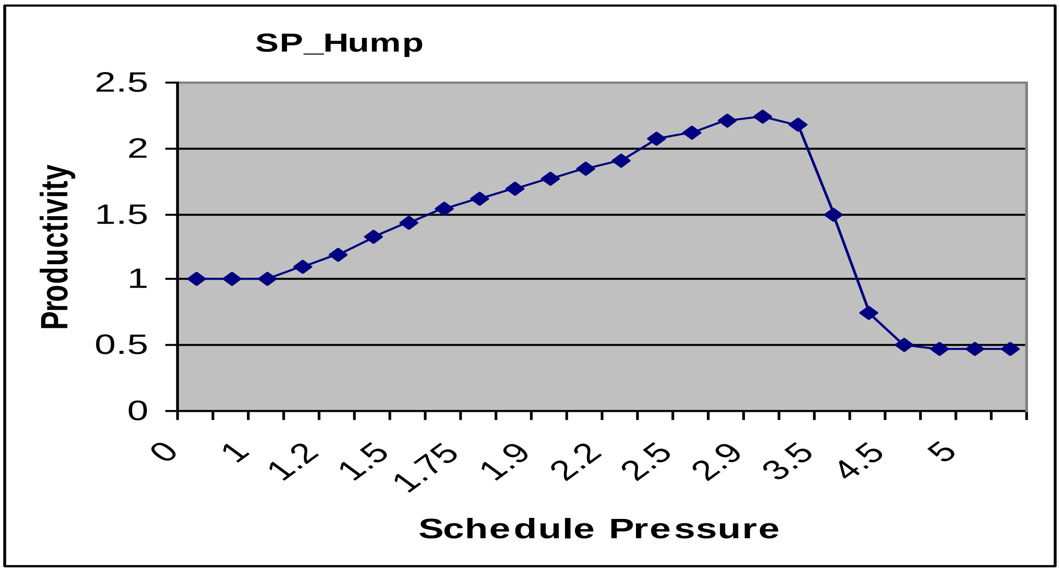
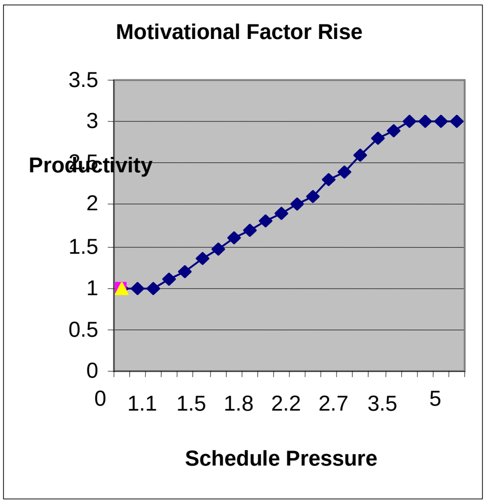


Figure 5.2: Schedule Pressure Vs Productivity

As suggested by Sterman (2000) the hump shaped relationship is avoided by splitting the effect of SP on productivity into two variables: motivational productivity and overwork productivity.



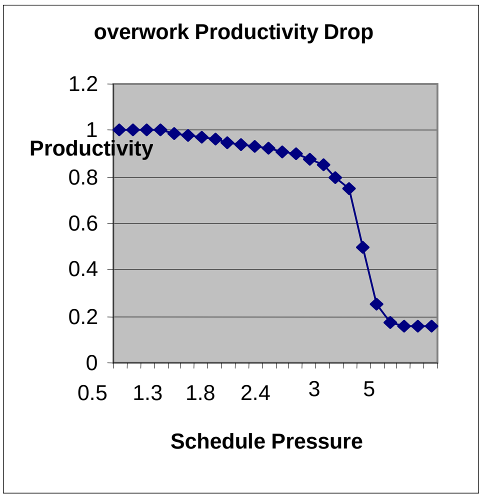


Figure 5.3: Motivational productivity vs SP (left hand side) Overwork productivity vs SP (right hand side)

As shown in Figure 5.3 motivational productivity forms S-shaped curve against increase in SP in the increasing order whereas overworked productivity forms a S-shaped curve with respect to SP in descending order. Look-up tables have been used for these variables (Sterman, 2000). Detailed Table showing relationship between SP, motivational productivity, fatigue productivity and overall productivity is available in Appendix B. *It is important to note that these values are purely based on expert opinion. These values were further modified slightly by using curve fitting property of Vensim.*

Figure 5.1 shows the relation between these variables in the causal loop diagram (CLD). Increase in SP increases the motivational productivity (intensity of work) which increases discharge rate, discharge rate decreases backlog which subsequently decreases the number of people waiting over three hours. This relationship is represented by the balancing feedback loop. On the other hand the relationship between backlog, number of patients waiting over three hours, SP and overwork productivity is represented by the reinforcing loop. The reinforcing loops destabilises the system. An increase in SP can decrease the overwork productivity, which subsequently decreases the discharges rate, leading towards an increase in the backlog and the number of patients waiting over three hours with a subsequent increase in SP. Dominance of these loops is sensitive to SP. As evident from Figure 5.2 up to a certain level of increase in SP, the balancing loop dominates, beyond that level, reinforcing loop becomes dominant. In order to quantitatively analyse these relationships, the causal loop diagram was converted into a mathematical model. Simulation experiments with different scenarios were performed for experimentation. Vensim software was used for experimentation. A screenshot of Vensim SD model and equations can be seen in Appendix A and Appendix C.

Development of DES Model

The main objective of the DES model was to capture detailed activities of Majors section of A and E and provide information such as throughput, time-in-system and number of breaches. DES models of A and E are quite common. The models reported in literature examine patient routing and flows, scheduling of resources, staff planning and reengineering of A and E processes and policy design (Kamoshi and Mousavi, 2005; Cooke et al, 2002; Fletcher et al, 2007; Gunal and Pidd, 2006; Blake and Carter, 1996; Centeno et al, 2003; Miller et al, 2004).In this research Simul8 was used for development of DES model. For the purpose of understanding the flow of patients through Majors department a flow chart of the process was developed. The basic elements of the DES model are:

- Flow chart: represent the flow of patients from arrival to exit
- Entities: items to be processed, patients in this case with their attributes and arrival distribution
- Activities: the various task patients go through from arrival to exit
- Resources: agents or equipment required for performing activities, in this case doctors, nurses and cubicles
- Entity routing: The logic for flow of entities under various conditions

As the main driver for this project was the whiteboard, we emphasised on the inclusion of the whiteboard in the DES model. DES modellers have been criticized that rather than representing the preference of clients, modellers focus more on the technicalities of model. The whiteboard provides information about patients who are still in the system. This feature of whiteboard in the DES model is imitated by a queue which contains information such as time-in-system for all patients still being processed. It provides us with information about total backlog and number of patients who have been in the system for more than three hours. We noticed that the inclusion of the whiteboard enhanced the engagement and interest of clients in the process of model building. The purpose of whiteboard which is represented by a queue in the models is to provide the information about total work in process at a time. Normally work in process is calculated by counting and adding the number of all the entities present in all queues and work station in DES. In previous works on hybrid simulations, as this information is disaggregated in DES it was aggregated and then passed on to SD. Here the question was not only to provide information about number of patients in DES at a particular time but number of patients who were in system for more than three hours. In order to achieve this in DES a command was required which looped through all the entities at all queues and work stations to filter and count the total number of entities who are over three hours. There are two main limitations of this approach:

- It is complicated and causes inefficiencies as it requires looping through all the queues and workstations.
- It does not provide real-time information about the work items which are currently being processed as it only considers the time stamp value when the processing starts and ends.

*In order to overcome these limitations we used "fork and Join" command of DES in a novel way to calculate the work in process***.** The idea is that all the items are cloned when they enter the Major section of A and E. One shadow item follows the normal patient pathway where as other goes straight into the queue named as whiteboard. The red arrow (as shown in Figure 5.4) shows diversion of paths of cloned items. Once the shadow entities has completed all the processes and is about to exit, clones are joined prior to exit. It enhanced the interest of clients in our model as they could see their whiteboard (which was the main driver of the project) being represented in the model.

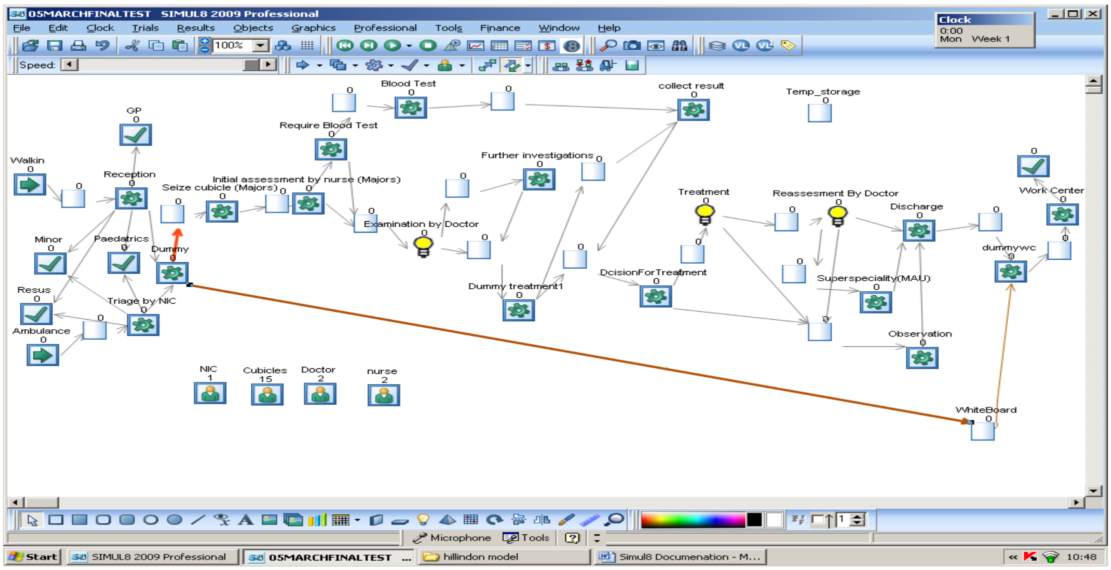


Figure 5.4: A screen shot of Simul8 model of Majors section of A and E

A screen shot of the Simul8 model is shown in Figure 5.4. It shows the overview of flow of patients through Majors section in A and E. Most of the data required was gathered from observations, expert opinion and the LDGH database. As the accuracy was not of prime concern, expert opinion was used to generate most of the data. In the baseline model, real data from LDGH for a 'quiet week' was used. In other scenarios exponential distribution was used for walk-in and ambulance arrivals. Activity durations were modelled using triangular distribution (Appendix D). As the ultimate objective of the LDGH team is to analyse impact of the whiteboard on breaches, the main outputs of interest are time-in-system and number of breaches. After the development of SD and DES models the next step is identification of inputs and outputs of SD and DES models.

Identify SD inputs and outputs

It was observed that development of SD and DES models prior to identification of inputs and outputs simplified this task. The criteria for identification of inputs and outputs are that the variables of the model whose values are obtained exogenously from other sources are classified as inputs and the variables whose values are computed by the model are categorised as outputs.

SD inputs

On the basis of the criteria established above, the following are the inputs of the SD model as these are the values provided to the SD model from external sources.

- Arrival rate
- Normal Discharge rate
- Productivity per doctor
- Number of doctors
- Lookup table for fatigue productivity
- Look up table for motivational productivity

SD Outputs

On the basis of the criteria established above, the following are the outputs of the SD model as these are the values are computed endogenously by SD model.

- Actual discharge rate
- Normal discharge rate
- Number of patients over three hours
- Productivity factor
- Schedule pressure

Identify DES inputs and outputs

Similarly on the basis of the criteria established above, the following variables have been classified as inputs of the DES model as their values are provided to the DES model from external sources.

DES inputs

- Inter- arrival frequency
- Resources
- Process Logic (patient pathway)
- Activity duration for doctor related A and E activities

DES Outputs

On the basis of criteria established, the following variables are categorised under outputs as the values of these variables are computed by the model.

- Throughput
- Time in system (breaches)
- Work in Process (number of patients in A and E)
- Number of patients over three hour

Identify variables accurately represented by DES

- Number of patients over three hours

Identify variables influenced by DES

From variables influenced by DES means those variables whose values are not completely replaced, but are affected by variables represented in DES model. In this case there are no such variables.

Identify variables accurately represented by SD

In case of SD model ,SD variable “number of patients over three hours” is more accurately captured by DES, hence during hybrid simulation value of SD variable “number of patients over three hours” is replaced by DES output variable number

"number of patients over three hours". In the DES model there is not any variable, which is more accurately represented by SD model.

Identify variables influenced by SD

Activity durations of DES activities (performed by physician) are influenced by productivity factor

Define Interaction Points

- Number of patients over three hours (DES variable)
- Number of patients over three hours (SD variable)
- Activity duration (DES)
- Productivity factor (SD)

5.3.3 Phase 3

As SD and DES models are developed and interaction points are defined, the objective of Phase 3 is to identify the way SD and DES are going to interact with each other over time to exchange information. The answer to both questions of the framework: "elements represented by SD and DES are closely coupled in time and space" and "are these interaction important for overall objective" is yes, hence parallel interactions are required.

The framework has been able to provide guidance up to this step however it is not clear that whether information obtained so far with the help of the framework is sufficient for integrating SD and DES models in hybrid simulation. Due to these reasons empirical evaluation was extended further to implementation of exchange of information between two models.

5.4 Implementation of Exchange of information between SD and DES

As interaction points and mode of interaction between SD and DES has been identified, it seems that there should not be any problem for manual exchange of information between SD and DES. However, it was observed that knowledge of interaction points is not sufficient, how these interaction points are related to each other is also required for integration between SD and DES. Phase 2 identifies variables which are exchanged (interaction points) but still does not explain how they are linked. Although implicitly this information is there but there is no explicit logical representation for this. The lack of this poses challenges to the implementation. In order to integrate SD and DES models, relationships between SD and DES variables (interaction points) need to be formulated. Formulation means explicit logical representation of relationships between SD and DES variables. For example during integration between SD and DES, the value of SD variable "number of patients over three hours" is replaced by the value of DES variable "number of patients over three hours" as shown in Equation 5.1

"Number of patient over three hours" (SD variable) = Value of "number of patient over three hours" (DES output variable) Equation 5.1

Similarly although it is clear from Phase 2 that activity durations of DES are influenced by the productivity factor, but how this influence is exercised is not clear. For example it has been argued that the duration of activities on process is inversely proportional to the productivity factor (Martin and Raffo, 2000). For the purpose of integration, mathematical representation of this relationship (as shown in equation 5.2) is required.

Duration of activity (in Hybrid model) = fn. (Triangular distribution (parameters based on expert opinion)) / productivity factor Equation 5.2

As the models were built and *relationships formulated*, it was hoped that integration between SD and DES will not face any further problems. It was realised that integration was still facing challenges as there was ambiguity about mapping between SD and DES variables. Although it is clear that the "productivity factor" from SD and "number of patients over three hours" from DES are the variables whose values need to be passed to DES and SD, but where the values of these variables are going to be transferred is not explicit. The relationship between the productivity factor and activity duration is clear from Equation 5.1 but in order to execute this relationship, a single variable or group of variables in DES is required to be defined for assigning the value obtained from the SD “productivity factor” variable. For smooth integration, the “interaction points” between SD and DES need to be implicitly or explicitly mapped in both models. If the variables are already mapped in both models prior to integration, it will only require new values to be assigned during hybrid simulation. For example in this case study, although the SD model is not able to accurately calculate the number of people waiting over 3 hours, however it is still defined in SD as an endogenous variable. Similarly, the DES model requires defining the variable “productivity factor”. For example, from Equation5.2 it is obvious that in hybrid simulation model, duration of activities is inversely proportional to the productivity factor. In the DES model (in the absence of hybrid simulation) this fluctuation in activity duration due to the productivity factor is not incorporated (as shown in the Equation 5.3).

Activity Duration (DES Model) = Triangular distribution (parameters based on expert opinion) Equation 5.3

Productivity of the servers in DES is normally assumed constant throughout the process as shown in Figure 5.5.

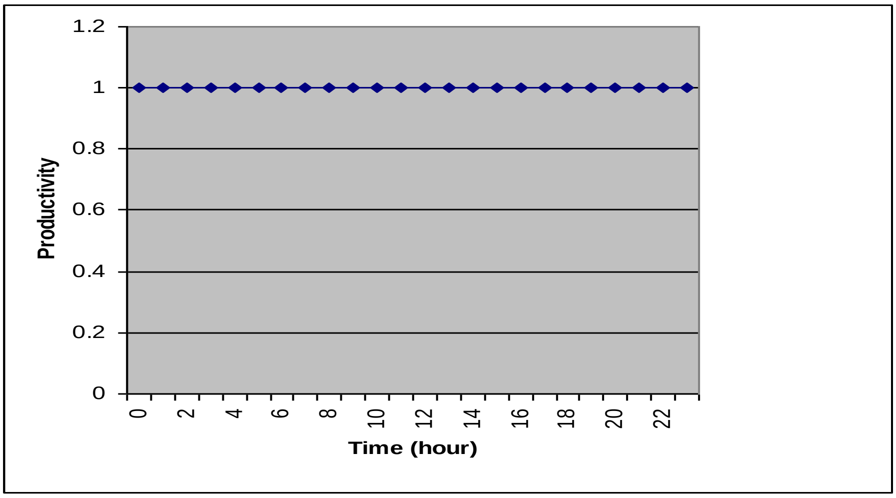


Figure 5.5: Productivity of servers in DES model

However in reality, productivity of servers in the service industry fluctuates in response to schedule pressure and other qualitative factors such as experience, fatigue, motivation etc. Hybrid simulation allows capturing these fluctuations by computing the variation in productivity factor and passing it down to the DES model. Where the value of the SD variable "productivity factor" is going to be transferred in DES is not clear. For the exchange of information between SD and DES during hybrid simulation, it is important that the variable "productivity factor" which is an output of SD is also implicitly or explicitly defined in DES (as shown in Equation 5.4).

Activity Duration (DES Model) = Triangular distribution (parameters based on expert opinion)/ Productivity factor (value of productivity factor is assigned one in absence of hybrid simulation) Equation 5.4

In the absence of integrated deployment of SD and DES (hybrid simulation) the value of the productivity factor is assigned one, hence it does not affect parameter values.
Sometimes these interaction points are implicitly or explicitly defined in both models either in the form of inputs or outputs, for example the number of patients over three hours which is an output of DES also has a corresponding variable defined in SD, but in situations where they are not defined in both, they need to be defined/mapped. Mapping of interaction points in both models makes the transfer of values easy during

the exchange process. It does not mean that both models should have the same variables; the idea is they should have some representations in the model where data from one is transferred to another. For example patient arrival rate has representation in DES in the form of inter-arrival frequency. Hence data from arrival rate (SD) can be disaggregated and assigned to inter-arrival frequency (DES).

After formulation and mapping of interaction points, integration between SD and DES was smooth. As the models are built and relationships are formulated, according to the framework the next step is identification of the way SD and DES interact and exchange information over time. It is clear from Phase 3 that as environment and process in this case are closely coupled in time and space, parallel interactions are required. As the interactions are parallel SD and DES are going to exchange information during run-time. It is ideal to exchange information after small durations, however as the exchange in this case is manual, that is both SD and DES models need to stop during run time, it is difficult to make these exchanges after small steps. Due to these reasons one hour was taken as the time interval for exchanging information between SD and DES. Both SD and DES models are stopped after every hour to exchange data. Both SD and DES models were run for one day and information was exchanged after every hour. Both SD and DES models were stopped after every hour, the value of "number of patients over three hours" at that time is passed to the SD variable "number of patients over three hours". Similarly the value of "productivity factor" which is an output of SD is passed to the implicitly defined "productivity factor" variable in DES. (Table 5.3 shows values which were exchanged between SD and DES models in a quiet week and in a busy week).

Time in Hours	Number of patients over three hours (From DES)	Value of "Productivity Factor" (From SD)	Number of patients over three hours (From DES)	Value of "Productivity Factor" (From SD)
	Quiet Week		Busy Week	
0	0	1	0	1
1	0	1	0	1
2	0	1	0	1
3	0	1	0	1
4	0	1	1	1
5	0	1	1	1
6	0	1	1	1
7	0	1	1	1
8	0	1	1	1
9	0	1	0	1
10	0	1	1	1
11	**0**	**1**	**7**	**2.29**
12	**0**	**1**	**5**	**1.04**
13	0	1	3	1
14	0	1	2	1
15	0	1	2	1
16	1	1	2	1
17	0	1	2	1
18	0	1	1	1
19	0	1	1	1
20	0	1	0	1
21	0	1	0	1
22	0	1	0	1
23	0	1	0	1

Table 5.3: Exchange of values between SD and DES (quiet week and busy week)

This section has highlighted the importance of the formulation and mapping of interaction points for the purpose of integration between SD and DES. How the framework is going to be adapted to incorporate these will be discussed in the next chapter.

5.5 Discussion on Experiments and results

The overall objective of the project was to capture the impact of whiteboard on patient flow. For this purpose two sets of experiments were carried out.

- Hybrid simulation for capturing impact of whiteboard on A and E processes.
- Impact of an increase in frequency of information update on A and E processes.

5.5.1 Hybrid simulation for capturing impact of whiteboard

The first set was to evaluate the effect of information flow (whiteboard) on A and E processes and how hybrid is able to capture it better than DES. SD is not compared here because SD due to its aggregate stance is not capable of providing the desired level of resolution (As the ultimate objective is to find impact of whiteboard on breaches (time in system) which require individual level tracking). The hybrid model was created with 'quiet week' data. In the quiet week, due to an absence of schedule pressure, there was not observed any change in productivity (as shown in Table 5.3). The value of productivity remained constant; hence the output of the hybrid model is same as that of the DES model (Figure 5.6).

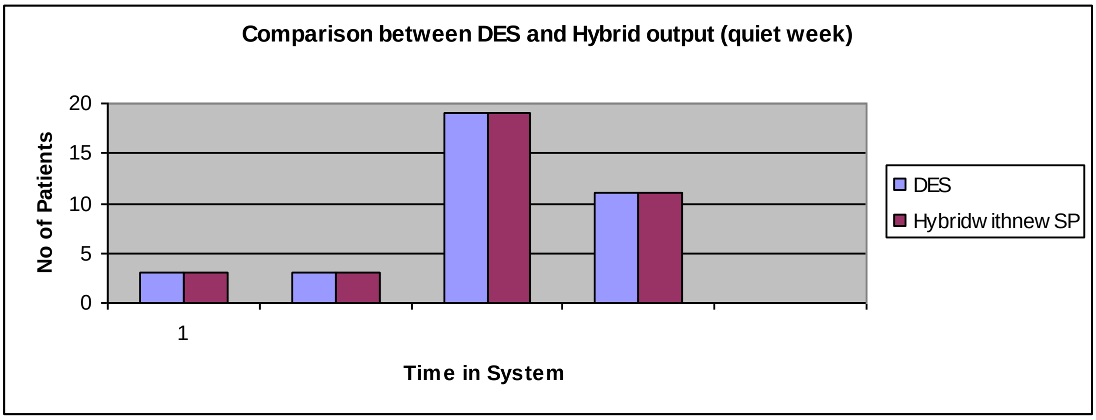


Figure 5.6: Comparison between outputs of DES and Hybrid models (quiet week)

In order to see the impact of schedule pressure on process activities, it was vital for the system to experience it. So another scenario using exponential distribution to represent an increased inflow of patients was investigated. In this scenario, productivity does not remain constant throughout day. As highlighted in Table 5.3, high "number of patients over three hours" in eleventh and twelfth hour build up schedule pressure resulting in enhanced productivity in busy week. Although the fluctuation in productivity has been only for two hours, still there is a significant difference in the outputs of the DES and Hybrid models (Figure 5.7). Although both models provide the same throughput, there is a significant difference in the number of patients treated between 180 - 240 minutes and the number of breaches. In hybrid more patients are treated between 180 -240 minutes and there are fewer breaches. The LDGH staff validated it by saying that this is in accordance with what they observed in hospital i.e. more patients are treated between 180 -240 minutes in busier hours. This clearly indicates that performance of systems is sensitive to schedule pressure. This was further confirmed by hospital staff.

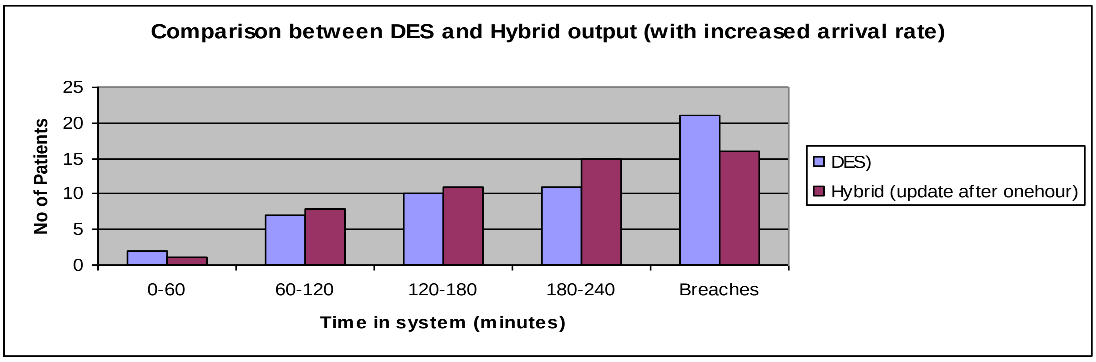


Figure 5.7: Comparison between output of DES and Hybrid (busy week)

In order to experience the schedule pressure, accurate information about the status of the system is vital, whiteboard provides that information. The information conveyed by the whiteboard has an impact on the workflow by influencing the response of physicians to the changing status.

5.5.2 Impact of an increase in frequency of information update

The second set of experiments was conducted to show the impact of increased frequency of whiteboard update. In order to capture the real added value of electronic whiteboard over a manual whiteboard, it was important to see the difference in productivity in response to schedule pressure in both scenarios. For this it is important that information between two models is exchanged in real time. That can be achieved only by automating the exchange process. As automation of exchange is out of scope of this research, data between SD and DES models was exchanged manually. For simplicity, data between the two models was exchanged after every hour. As with respect to schedule pressure, the main advantage of the electronic whiteboard over manual is its frequency of update. In order to show the impact of increased update frequency on A and E processes, two scenarios were considered:

- In first scenario the whiteboard is updated every hour
- In the second scenario the whiteboard is updated every two hours.

In view of understanding the impact of update frequency on process, data between SD and DES of corresponding hybrid models has been also exchanged after one hour and two hours. Figure 5.8 shows comparison between the output of the hybrid models where information between SD and DES was exchanged after one hour and after two hours. It is clear from the Figure 5.8 that increased frequency of information update positively affects the A and E processes. As shown in Figure 5.8 more frequent update of information increases throughput and lowers the number of breaches. Timely response to an increase in schedule pressure improves the performance of the system. In the service industry the way service organisations respond to work pressure is a critical determinant of service quality, satisfaction and overall performance of the service organisation (Oliva, 2002)

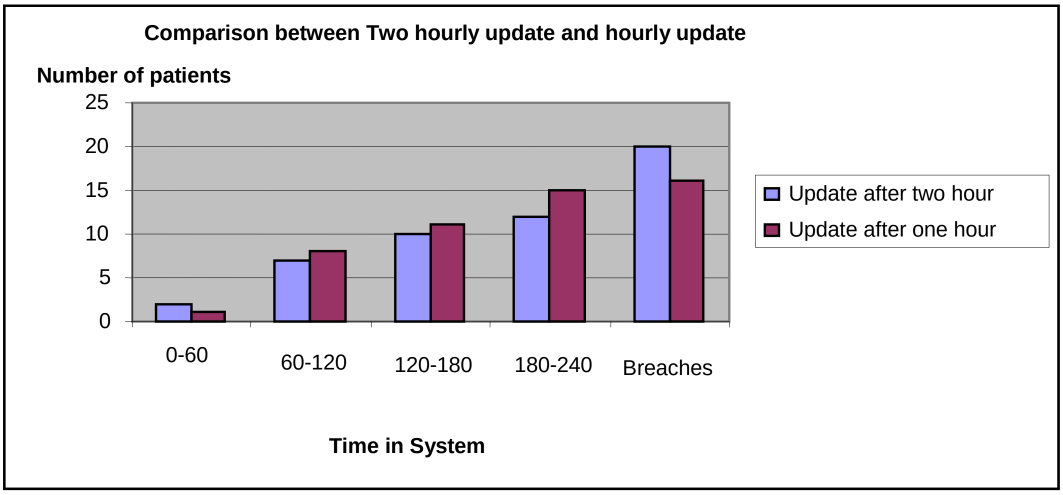


Figure 5.8: Comparison between outputs of Hybrid (hourly and two hourly update)

This study shows the applicability of hybrid simulation in the healthcare domain. By using hybrid simulation an attempt towards quantifying the impact of intangible benefits of information systems to tangible business process improvement has been made. This provides an example of the evaluation of the value proposition of information systems in healthcare setting (Green and Young, 2008). It empirically provides the evidence for benefits of an electronic whiteboard over a manual whiteboard. It is clear that in the service industry, servers respond to pressure by increasing their performance and this increase in performance is subjected to the availability of information. The electronic whiteboard improves the response time of servers by providing real-time information about the status of the system.

5.6 Summary

This chapter starts by providing an introduction and the objective of the chapter. The chapter focuses on empirical evaluation of the framework with single a detailed case study about implementation of electronic whiteboard in the A and E department of LDGH. The purpose of the empirical evaluation is to identify the limitations of the framework which could not be visualised during theoretical evaluation to provide basis for further refinement. Section 5.2 provides the background of the problem followed by a section on application of the framework to LDGH case study. This section provides a brief description of the problem and detailed step by step application of instructions provided by framework to the problem scenario. Phase 1 identified that the problem requires hybrid simulation. It was identified in Phase 1 that criteria for selection between SD and DES require some amendments. In Phase 2, it was identified that “number of patients over three hours”, activity duration of DES activities carried out by physicians and productivity of physicians which is an output of SD are the interaction points. Then Phase 3 was applied to select the appropriate mode of interaction between SD and DES. As the elements represented by SD and DES models are closely coupled in time and space and this coupling is important, it was identified that parallel interactions were required.

Section 5.4 provides a description of the implementation of exchange of information between SD and DES. As the interaction points (what is exchanged) and the mode of interaction (how the information is going to exchange) were already identified up to this point it was hoped that exchange will not pose any problems. However it was identified that this information was not enough. For actual exchange of information regarding the way interaction points are related mathematically and the way information from one model can be mapped to other model is also required. From the perspective of evaluation of framework, discussion up to this point was sufficient. Focus of Section 5.5 is more on the case study rather than the framework.

Section 5.5 described the way SD, DES and hybrid models were validated followed by a discussion on experiments and the results obtained. Section 5.6 is important for the problem scenario used as case study; it does not have much relevance to the rest of the dissertation as the dissertation is about provision of framework for hybrid simulation rather than advantages or disadvantages of hybrid simulation. Finally Section 5.6 provides brief summary of the chapter. The obstacles and issues identified in this chapter such as problem with selection criteria, limitation of framework with respect to formulation and mapping between interaction points will be discussed in detail in next chapter.

Chapter 6: Reflections and Further Modifications

6.1 Introduction

Chapter 3 proposed a generic framework for providing guidance with regards to hybrid simulation. The framework was proposed on the basis of the understanding gained from the literature review. In order to assess the ability of the framework to meet requirements, a retrospective theoretical evaluation was carried out using multiple cases. The framework was modified on the basis of the reflections obtained from theoretical evaluation. In the previous chapter for the purpose of empirical evaluation, the modified framework has been applied to a case study comprising of an accident and emergency department of a district general hospital. As the purpose of implementation is to highlight limitations of the framework which are not conspicuous prior to implementation, the evaluation was extended further to implement the framework manually. It was realized during implementation that the framework in its current state has limitations. This chapter reflects upon the empirical evaluation to discuss the limitations of the framework identified during implementation. These limitations provide basis for further modification of the framework. The ultimate objective of this chapter is to provide a final framework which is the main output of this research.

The structure of this chapter is as follows: The next section provides a detailed account on reflections from empirical evaluation with greater emphasis on limitations encountered. In order to avoid repetitions the reflection focuses only on the challenges encountered during empirical evaluation. It was identified that major limitations were encountered in Phase 2 of the framework. Phase 2 provides guidance for identification of interaction points. It was realized that information up to identification of interaction points was not sufficient for exchange of data between SD and DES during hybrid simulation. Some issues regarding criteria for selection between SD and DES defined in Phase 1 has also been identified. Guidance provided by Phase 3 did not face any challenges during empirical evaluation. Section 6.3 discusses the way the framework has been modified to address these limitations. Only Phase 1 and Phase 2 will be discussed in these sections as limitations have been identified only in these two phases. Section 6.4 describes the final framework in detail and finally the last section provides brief summary of the chapter.

6.2 Reflections from empirical evaluation

The purpose of the theoretical evaluation was to analyse the ability of the framework to meet requirements established. However the purpose of empirical implementation (manual exchange of information) is to highlight the limitations which can not be identified with theoretical evaluation. For this reason the evaluation is extended further to highlight those limitations. As the ability of the framework to meet requirements theoretically has already been analysed and the framework has been modified accordingly, the purpose of this section is not to repeat those steps but to highlight those limitations which arose specifically during the manual implementation. It has been identified in the previous chapter that limitations of the framework were identified in Phase 1 and Phase 2 of the framework, as the purpose of reflections is to highlight limitations so that the framework can be amended accordingly, discussion on only Phase 1 and Phase 2 will be provided in the Section 6.2 and Section 6.3.

6.2.1 Limitations encountered during Phase 1 of the framework

The framework was evaluated with a case study comprising of accident and emergency department of a London District general Hospital. Hospital management approached the modelling team for understanding the implications of implementation of an electronic whiteboard in A and E, on time patients spend in A and E. From the previous chapter it is evident that the framework assisted the modelling team with selection of the appropriate method required for analysis. The understanding of the overall objective in light of external and internal influences guided the analyst to consider the environmental context of A and E operations. Decomposition of the overall objective into smaller objectives simplified both the modelling exercise as well as the selection of appropriate method. However it was observed during the selection process that the "scope of the problem" i.e. whether the problem is of operational level or of strategic level which is defined as one of the criteria for selection between SD and DES poses challenges to the selection process. In the context of the A and E problem, as defined in Section 5.3.1, the first objective "capture the variation in productivity of physicians in response to implementation of electronic whiteboard" requires understanding of the dynamic interactions between environmental factors such as productivity, backlog and schedule pressure. As the productivity affects operational processes, the problem is more of operational nature rather than strategic. The problem analysis requires comprehension of dynamic complexity between various factors and SD lends itself naturally to comprehend that. However on the basis of the selection criterion (as shown in Table 3.1) "scope of the problem", the appropriate method should have been DES as the scope of the problem falls in operational level. Selection of the method on the basis of this criterion would have been quite misleading as fluctuation in productivity can not be captured without comprehension of dynamic complexity between various factors, and DES due to its linear stance struggles to capture that. It has been argued previously that where as DES lends itself smoothly to comprehend detail complexity, it struggles when the problems exhibit high degree of dynamic complexity.

It can be deduced from the above discussion that the selection of method should be based upon the ability of the methods to capture different aspects of the problem and the system in context and not on the overall scope of the problem. From this it means that method selection criteria should be based on problem and system attributes such as importance of randomness, individual tracking, complexity, cross boundary interactions etc rather than scope of the problem such as if the problem is of strategic nature, SD is recommended and if the problem is of operational nature DES is recommended. As the majority of strategic problems focus on a holistic view and require comprehension of dynamic complexity and operational problems focus on the microscopic view and requires comprehension of detail complexity, use of SD for strategic level problems and DES for operational level is the consequence of the ability of SD to capture dynamic complexity and holistic view and ability of DES to capture detail complexity and microscopic view. As a consequence of these abilities it is more likely that SD is required for analysis of strategic problems and DES for operational problems. This consequential use should not be established as criteria for selection. It can be said that there is more likelihood that for strategic problems SD would be required and for operational problems DES would be required, it is not must.

6.2.2 Limitations encountered during Phase 2 of the framework

Throughout this dissertation so far, the ability of the framework to provide guidance with regard to mapping between SD and DES has been restricted to identification of interaction points between SD and DES. The framework provided guidance for the identification of interaction points between SD and DES models. However during the implementation it was realised that in order to execute hybrid simulation, this guidance up to identification of interaction points was not enough. The following problems were encountered during implementation.

1. Lack of information on formulation of relationship
2. Lack of guidance on mapping

Lack of information on relationship formulation

It has been observed in Section 5.4 of the previous chapter that after the identification of interaction points the execution of hybrid simulation was not possible because the framework does not explicitly provide guidance about formulation of relationships between interaction points. Although implicit understanding about the way corresponding interaction points in both models are related to each other is there, however the framework does not provide guidance for explicit mathematical relationships between corresponding interaction points. It was realised during exchange of information between SD and DES that exchange of values of interaction points between SD and DES is not always a case of simple direct exchange of values, sometimes it requires calculations and conversions. In order to do that an explicit formulation of relationship (how corresponding interaction points are mathematically related to each other) is required. The framework in its current state does not provide that information hence is required to be modified to address those limitations.

Lack of Information on mapping of interaction points in SD and DES

In the previous chapter it was identified that even after the explicit formulation of relationship between corresponding interaction points, it was not possible to exchange information between SD and DES. In order to exchange values of interaction points information about where (which variables in other model are going to hold these values) these values are going to be transferred is also required. The framework in its current state does not provide that information. These limitations of the framework will be further discussed and addressed in Section 6.3.2 which focuses on modifications of Phase 2.

6.3 Modifications

The previous section has reported limitations of the framework identified during empirical evaluation. Phase 3 does not require further modifications as there was not any limitation identified in it, hence it is excluded from the modifications section. The following sections will provide a discussion on the way Phase 1 and Phase 2 of the framework has been modified to address the limitations identified during empirical evaluation.

6.3.1 Modifications of Phase 1

It was identified in reflections that generalisations from consequential use of SD and DES such as suitability of SD for strategic level problems and suitability of DES for operational level problems has been established as criteria for selection between SD and DES. It has been observed that it is inappropriate to use this generalisation as criteria for selection between SD and DES. There is more likelihood that SD will be required for strategic problem analysis and DES for operational but it is not a must. As in this empirical work the problem is of operational level, but SD due to its ability to capture dynamic interactions has been deployed. Similarly, in past there have been attempts to deploy DES for strategic problems (Gunal and Pidd, 2006). In order to address this issue, the selection table (Table 3.1) is modified by excluding the "scope of problem" from the list of criteria. Table 6.1 represents the modified version of selection criteria.

Criteria	**DES**	**SD**
Problem Perspective		
Purpose	Decision: Optimisation, prediction and comparison	Policy making, overall understanding
Importance of randomness	high	Low
Importance of interaction between individual entities	High	Low
Required level of Resolution	Detailed individual level	Aggregate, high level
System's Perspective		
System View	Detailed Microscopic view	Holistic Telescopic view
Complexity of importance	Detail Complexity	Dynamic Complexity
Evolution over time	Discontinuous event based	Continuous
Control parameter	Holding (queues)	Rates (flows)

Table 6.1: Criteria for selection between SD and DES

6.3.2 Modifications of Phase 2

As discussed in the previous section, during implementation, the framework in its current state faced challenges which were not encountered during theoretical evaluation. As implementation was not possible without addressing these issues, solutions to most of the challenges were suggested in the implementation phase. The purpose of this section is to modify the framework to incorporate these suggestions.

Lack of information on formulation of relationships

It has been identified during empirical evaluation that in order to exchange information between SD and DES models, guidance up to identification of interaction points was not sufficient. Formulation of the logical relationship between interaction points was required for exchange of information between two models. Hence it is vital that the framework explicitly advises its potential users to formulate these relations.

From review of literature and theoretical evaluation it has been observed that the relationship between corresponding interaction points in SD and DES models can be of following three types:

- direct replacement of values of variables
- aggregation/disaggregation
- Causal relationships.

Direct replacement of values of variables

Direct replacement of values of variables implies that corresponding variables which have been identified as interaction points are already defined in both models and both represent variables equivalent to each other. During hybrid simulation, for the purpose of accuracy, values of one interaction point are replaced by its equivalent corresponding interaction point defined in other model. In LDGH case study "number of patients over three hours" provides an example of this type of relationship. During hybrid simulation, the value of "number of patients over three hour" (SD variable) is replaced by the value computed by its equivalent DES variable ("number of patients over three hour" DES variable). In both SD and DES models, the corresponding interaction points represent variables whose values are equivalent to each other. As the interaction points represent equivalent variables no further conversions or calculations are required during exchange of information between SD and DES.

Aggregation/ Disaggregation

From aggregation/ disaggregation means that corresponding interaction points hold values which are required to be aggregated or disaggregated for exchange of information during hybrid simulation to make them equivalent. Mostly SD represents the aggregated version of the variables which are disaggregated in DES and can be represented in DES either by single or group of variables which holds value equivalent to the SD variable. For example the "work in process (WIP)" variable of SD defined in the study by Venkateswaran et al (2005) holds values equivalent to the aggregated sum of all the entities present in queues and activities of DES model.

During exchange of information between SD and DES, all the entities present in queues and activities are counted and added before passing the total aggregated value to the "WIP" variable defined in SD model.

Causal Type Relationship

Unlike the previous two types the corresponding interaction points neither represent equivalent values directly nor represent the aggregated/ dissagregated representation of equivalent values. In this type of relationship the corresponding interaction points influence each other. Productivity factor and activity duration in the LDGH A and E case study discussed in the previous chapter provides an example of this type of relationship. The productivity factor affects the activity duration of activities represented by the DES model. Similarly in the combined model for software project management described by Martin and Raffo (2000), productivity of software developers affects the activity duration of the development task. The duration of development activity in their model is inversely proportion to the productivity. In causal relationship explicit mathematical formulation of relationship between corresponding interaction points is a must prior to exchange of values.

The first scenario (direct replacement of values) is simple as in this values of variables of one model are replaced by values of corresponding variable of the other model, in the second scenario values of corresponding interaction points are aggregated or disaggregated during exchange of information, in third scenario, one needs to carefully understand and formulate the relationship between corresponding interaction points. In order to incorporate this in the framework, the framework is extended to include another step "formulate relationship between interaction points" (as shown in Figure 6.1) after the "identification of interaction points". Formulation implies mathematical representation of the relationship between corresponding interaction points.

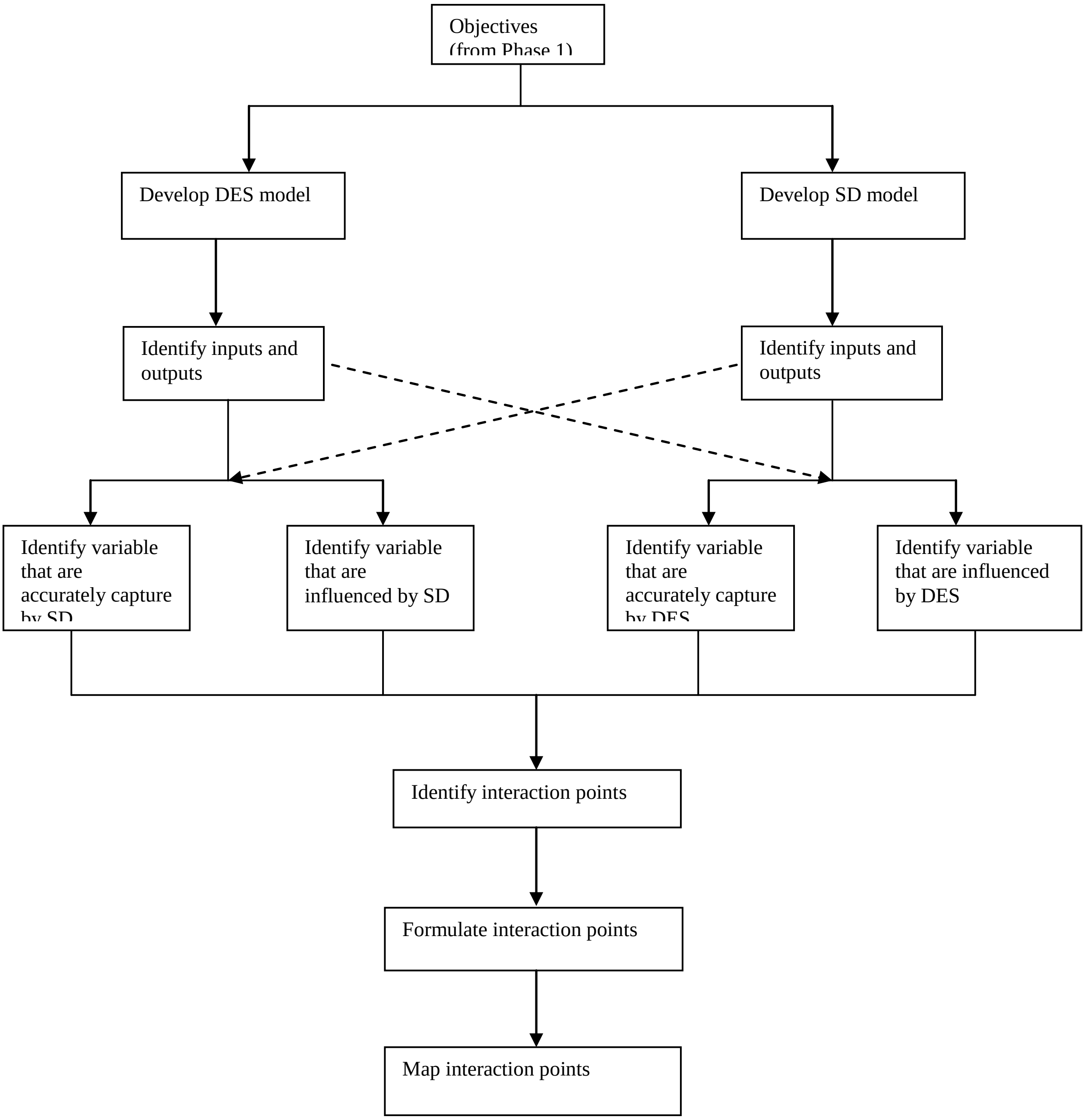


Figure 6.1: Overview of modifications of Phase 2

Lack of guidance on mapping

It was observed that even after the formulation of relationship between interaction points, exchange of values between interaction points was not smooth. Although the relationship was clear there was still ambiguity about the exchange of values between interaction points. It was more of a problem in scenarios where the relationship between interaction points was expressed by the causal type instead of aggregation/disaggregation or direct type of replacement of values of the variables. In both these types variables which are required for exchange of information are already defined. However in causal type relationships, this exchange of values is not easy. For example, the problem encountered in the A and E example was that although it was clear that the productivity factor influenced the duration of DES activities, but the productivity factor did not have a corresponding variable defined in DES where this new value of productivity (calculated by SD) can be stored. During implementation this problem was tackled by defining a corresponding variable in DES. The value of this variable in absence of SD input was assigned one. The framework is modified as shown in Figure 6.2 to incorporate this step "map corresponding interaction points in both models". This step implies that variables for representing equivalent values for corresponding interaction points should be defined implicitly or explicitly in both models. In scenarios where the relationship is simple replacement of values or aggregation/ disaggregation, no further mapping is required however in the case of causal relationship, an influencing variable needs to be defined in the model where it exercises its influence so that data can be exchanged. It is required only in those situations where interaction points do not have corresponding representations in both models for exchanging values.

From the above discussion it is clear that the title of the Phase 2 "identification of interaction point" is not an ideal representation for the purpose it serves, as for actual exchange of information knowledge up to identification of interaction points is not sufficient, guidance about formulation of relationship and mapping between SD and DES models is also required. After careful analysis it has been deduced that mapping between SD and DES models covers all aspects required for the exchange of information between SD and DES as mapping cannot be achieved without identification of interaction points and formulation of relationship between interaction points. Hence it was decided to replace the title of Phase 2 "identification of interaction points" with "mapping between SD and DES models". From now onwards "mapping between SD and DES models" will be the title for the Phase 2.

6.4 The Final Framework

In the light of the above discussion on modifications, the final framework is discussed in this section. A generic framework for hybrid simulation which is capable of addressing the requirements set previously in Chapter 3 is the main outcome of this research. The proposed framework has been modified twice on the bases of reflections from theoretical and empirical evaluations. The framework was evaluated theoretically in order to find and address its limitations. On the basis of reflections from the theoretical evaluation, the framework was modified. The modified framework was evaluated empirically with a case study from the healthcare sector. Although the implementation is not required as part of evaluation, it was carried out in order to find and address any issues or limitations which could not be identified with theoretical evaluation. Quite a few shortcomings were identified and addressed. This section presents the final modified framework which is the main output of this research.

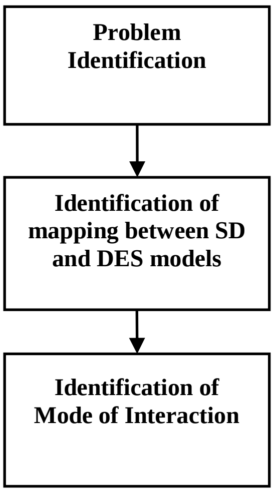


Figure 6.2: Overview of the final hybrid simulation framework

As shown in Figure 6.2 the framework consists of three phases. The first phase of the framework provides guidance for identifying that the problem in hand requires hybrid simulation. It has been argued previously that effort and investment in hybrid simulation is only justified if some aspects of the problem require SD and some require DES for analysis and there are strong interactions among the elements represented by SD and DES (Farhland, 1970). Once it is identified the problem requires hybrid simulation, then Phase 2 and Phase 3 of the framework provide detail instructions on how to carry out hybrid simulation. Phase 2 provides guidance for identification of mapping between SD and DES models. Mapping between SD and DES models comprises of identification of interaction points, followed by formulation of relationship and finally the way corresponding interaction points are mapped in both SD and DES models. Phase 3 of the framework assist its potential users in identifying the way SD and DES models are required to interact with each other over the time (mode of interaction) for exchanging information. The following subsections will provide elaborate discussion on each phase.

6.4.1 Phase 1: Identification of Problem seeking Hybrid Solution

The Phase 1 assists prospective users in identifying whether the problem requires hybrid simulation or not. The framework is based on the assumption that problem is fully understood. Quite a few articles are available on problem understanding. The author encourages potential users to understand the problem thoroughly prior to deployment of this framework. Understanding of the problem is a major task and it requires a framework of its own. Due to the appreciation of importance and effort involved in problem understanding this has not been included in this framework. As shown in Figure 6.3 Phase 1 consists of the following main steps for identifying problems in need of hybrid simulation:

- Identify overall Objective
- Decompose in to smaller objectives
- Method Selection

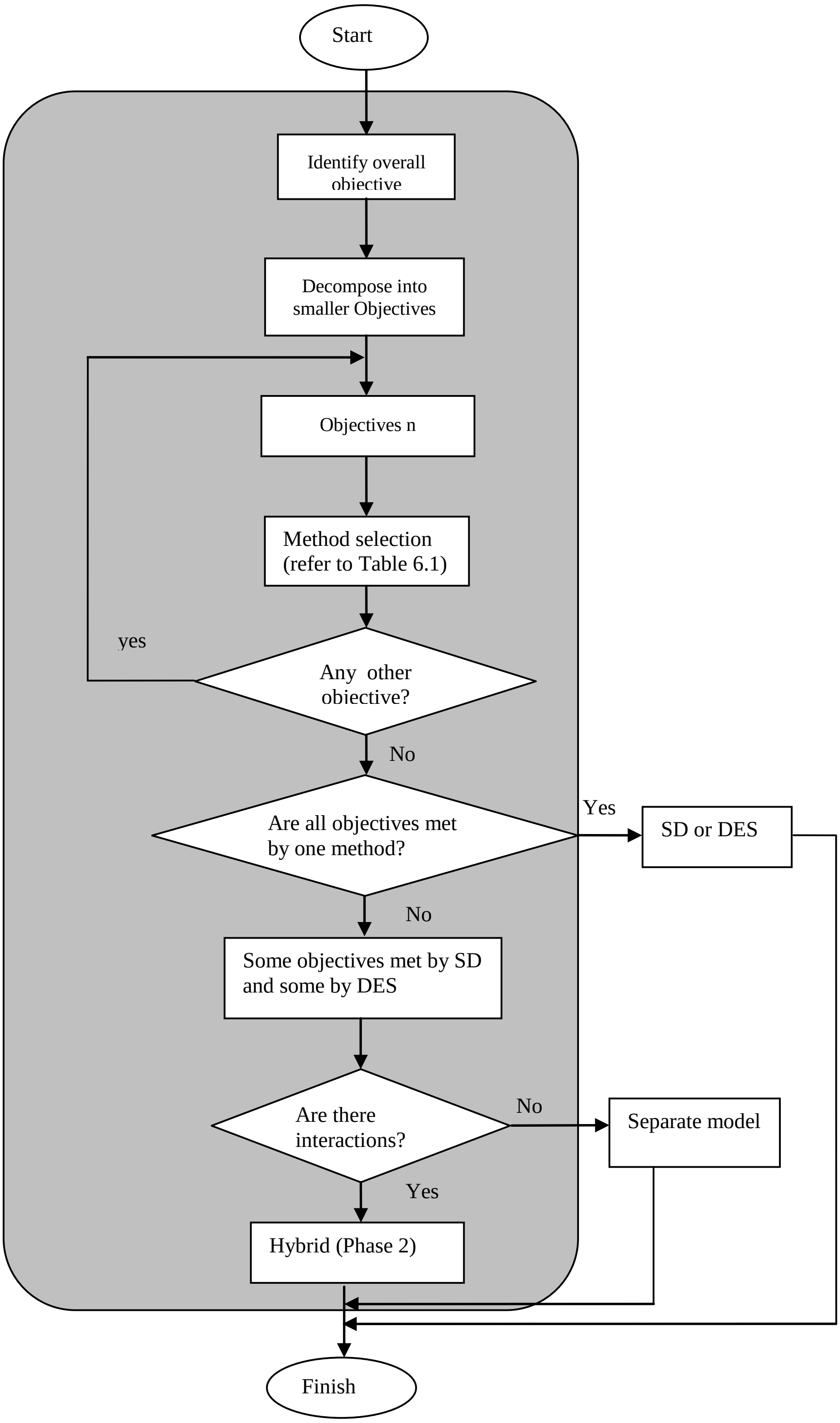


Figure 6.3: Overview of Phase 1 of the final framework

Identify overall Objective

The framework starts with identification of overall objective (as shown in figure 6.3). The following questions help in defining the overall objective:

- What causes the problem owners to seek assistance from analysts?
- What is the goal they are seeking?
- What are the internal and external influences on the goal?

The above questions provoke the potential users of the framework to analyze problem from a wider context. The overall objective is defined in light of both, problem as well as system perspective.

Decompose in to smaller objectives

In accordance with the third principle of modeling (Pidd, 2001), the overall objective is then decomposed into simpler smaller objectives. The broad criteria for decomposition is that if there is a fluctuating variable that is significantly influencing the overall objective and is being influenced by multiple factors then it is crucial to have a model that facilitates in determining the value of that variable in a timely manner, and in order to do so it is needed to decompose the overall objective into smaller components or sub-objectives. For example, in LDGH case study, the productivity of physician(s) acts as the fluctuating variable significantly influencing the time-in system for individual patients, which is the output corresponding to the overall objective. The productivity of physicians is also influenced by multiple factors such as schedule pressure, number of patients over 3 hours, etc. In the scenario of LDGH, the overall objective was achieved by decomposing it into the following sub-objectives:

1) Develop a model for determining the value of productivity of physicians

2) Develop a model which captures process logistics and determines time-in system for individual patients

Decomposition of overall objective into smaller objectives simplifies both modeling as well as the selection process.

Method selection

The selection process implies selection between SD and DES. Depending upon problem attributes and system context, Table 6.2 provides the criteria for selection of appropriate method. Once the methods are selected for each objective the next step is to identify whether all objectives are met by SD or DES or by both. If all objectives are met by a single method then the framework terminates (as shown in Figure 6.3) otherwise the users are asked to identify whether there are interactions between different objectives met by SD and DES. If there are interactions between elements represented by SD and elements represented by DES, then hybrid simulation is required, otherwise the objective can be achieved by independent SD and DES models, in that case the framework terminates there.

6.4.2 Phase 2: Mapping between SD and DES models

Once it has been identified that the problem requires hybrid simulation then the prospective user is led towards the Phase 2. If the problems do not require hybrid simulation then Phase 2 and Phase 3 are not required. Execution of Phase 2 and Phase 3 depends upon the outcome of Phase 1. As shown in Figure 6.4 Phase 2 consists of following steps:

- Development of SD and DES models
- Identification of inputs and outputs of both models
- Identification of variables which are accurately captured by the other model
- Identification of variables which are influenced by the other model
- Identification of interaction points
- Formulation of the relationship between interaction points
- Mapping of interaction points in SD and DES models

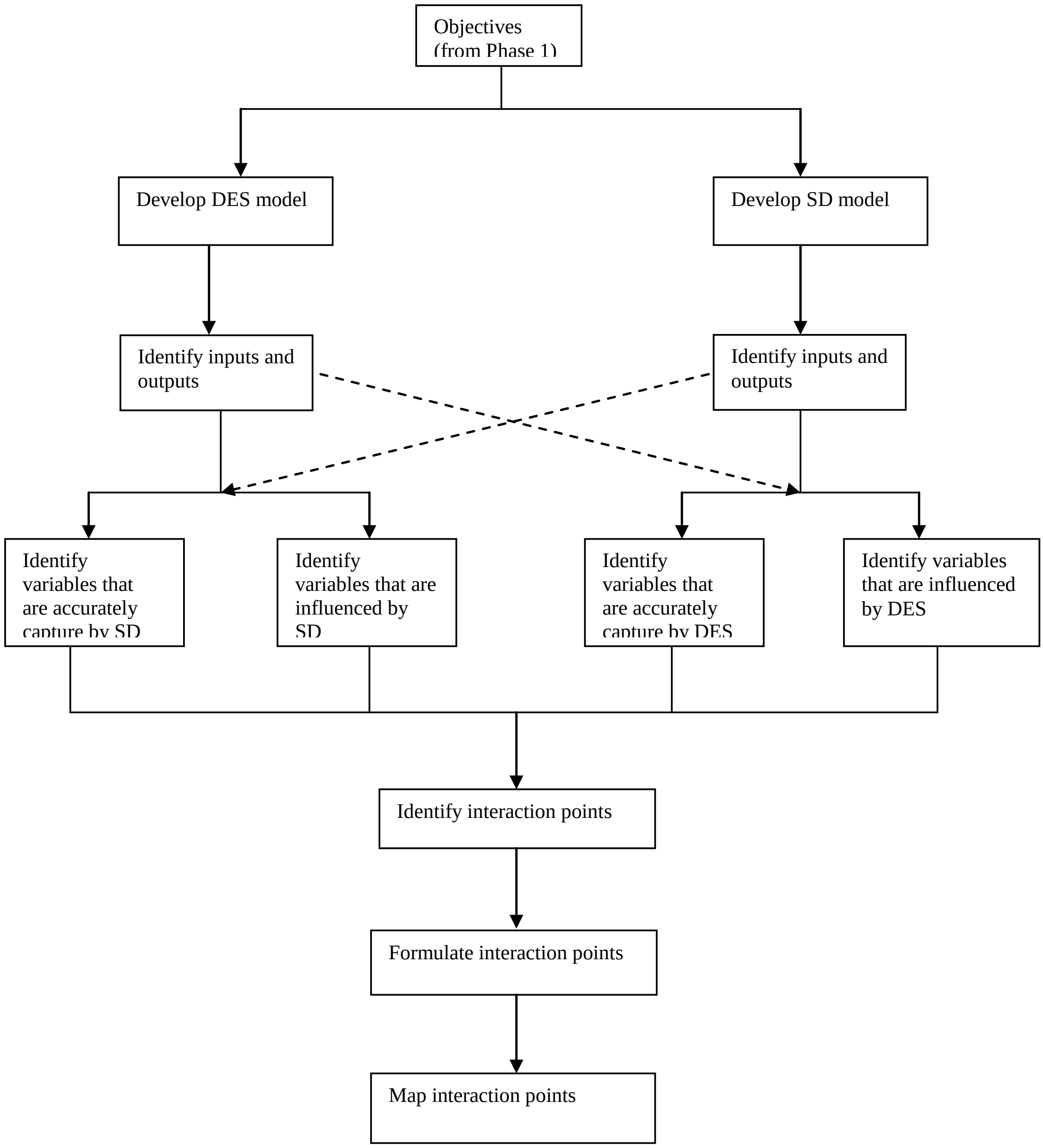


Figure 6.4: Overview of Phase 2 of the final framework

Develop SD and DES Model

Once it is identified that problem requires hybrid simulation, the next step is to develop conceptual models for SD and DES. As objectives of both SD and DES models are already defined previously in Phase 1, the first step of Phase 2 is development of SD and DES models to meet their respective objectives. Literature is available for providing guidance with regards to building SD (Sterman, 2000) and DES (Law and Kelton, 2000; Robinson 2004; Robinson 2008a; Robinson 2008b) models. It is important to note that as the purpose of SD and DES models is to aid in identifications of inputs and outputs, the potential users are advised not to indulge in strenuous exercise for data collection. Data is not required at this stage but the models should be capable of representing all variable and interactions among them. SD and DES models provide platforms for identification of inputs and outputs.

Identify inputs and outputs of SD and DES models

The next step is to identify inputs and outputs of the model. The relationship between identification of inputs/outputs and model development is iterative. All the variables whose values are not calculated/ estimated by the model itself but are obtained from outside are considered as inputs. Similarly all the variables whose values can be derived endogenously from the model itself are considered as outputs.

Identify Variables which are accurately captured by other model

After the identification of inputs and outputs the next step is to identify the variables which are accurately captured by the other model (identify from inputs and outputs of SD which of these are more accurately captured by DES and vice versa).

Identify Variables which influence or are influenced by other variables of the other model

The next step is to identify the variables which are influencing or are being influenced by variables of other models (again this implies variables of SD influenced by DES variables and vice versa).

Define Interaction Points

Once these interactions are captured the next step is to define interaction points. Identification of variables is preceded by defining of interaction points. Interact points are variables which actively participate during exchange of information between SD and DES during hybrid simulation. Interaction points comprise of both variables being replaced and influenced as well as variables of the other model which are replacing or influencing values. As the variables whose values are more accurately captured by variables defined in other model and variables whose values are influenced by variables defined in other model are already identified, identification of interaction points is straight forward as it only requires the explicit listing of corresponding variables of both models which are involved in information exchange.

Formulate Relationship between Interaction Points

Once the interaction points are defined the next step is to explicitly formulate the relationship between interaction points. *The relationship between interaction points can be of three different types: Direct replacement of values, aggregation/disaggregation and causal as defined in Table 6.2.* In Direct replacement of values of variable of one model by values of variable of another model, equivalent variables for representation of corresponding interaction points are defined in both models. e.g., in the previous example, the relationship between the SD variable “number of people over three hours” and DES output variable “number of people over three hours” is of direct replacement type. As shown in the Equation 6.1, during hybrid simulation values of interaction points in a model are simply replaced by the values computed in the corresponding interaction point defined in the other model.

Value of SD variable “number of people of three hours” = value of DES output “number of people over three hours” Equation 6.1

In aggregation/disaggregation, the corresponding interaction points have equivalent representation in both models but the transfer of values between SD and DES for exchange of information is not direct. For example in Venkateswaran et al’s (2005) hybrid model for production planning , production order rate is estimated in SD, it is disaggregated and passed to the DES entry point variable in the form of inter-arrival frequency (as shown in Equation 6.2). Similarly all the entities present in queues and corresponding activities in the DES model are aggregated and are passed to equivalent SD stock WIP (work in Process) variable (as shown in Equation 6.3).

Inter- arrival frequency of orders = Desegregated (SD production order rate) Equation 6.2

SD Work in Process = Aggregated (entities present in all queues and activities in DES) Equation 6.3

In third type the corresponding interaction points do not have equivalent representation in both models but the relationship is of causal type i.e. the variable defined in one model influences the variable defined in other model. These relationships are required to be explicitly understood and represented by a mathematical equation. For example in the previous example productivity factor from SD affects the activity duration variable of DES. The value of activity duration is inversely proportion to productivity. The Equation 6.4 has attempted to represent the relationship between activity duration and productivity factor.

Duration of activity (in Hybrid model) = fn. (Triangular distribution (parameters based on expert opinion)) / productivity factor Equation 6.4

Type of relationship	Definition
Direct replacement of values of variables	Direct replacement of values of variables implies that the corresponding variables which have been identified as interaction points are already defined in both models and both represent variables equivalent to each other. During hybrid simulation only values of one variable are replaced by its equivalent variable defined in other model. Number of patients over three hours provides an example of this type of relationship. During hybrid simulation value of "number of patients over three hour" (SD variable) is replaced by value computed by its equivalent DES variable ("number of patients over three hour" DES variable).

Aggregation/ Disaggregation	From this it means that the same thing has been represented in both models but this representation does not have same face value. Mostly SD represents the aggregated version of the variable which is disaggregated in DES and can be represented in DES either by single or group of variables which holds value equivalent to SD variable.
Causal Type Relationship	Unlike in the previous two types the corresponding interaction points neither represent equivalent values directly nor represent the aggregated/ desegregated representation of equivalent values. In this type of relation ship corresponding interaction points influence each other. Productivity factor and activity duration in A and E case study provides example of this type of relationship. Productivity factor affects the activity duration of activities represented by DES model.

Table 6.2: Different types of relations between corresponding interaction points

Map Interaction points between SD and DES models

Once the relationships are formulated then the next step is to map interaction points between SD and DES models. For smooth interactions between SD and DES models it is required that interaction points defined in SD have equivalent representation in DES model and vice versa. Additional mapping is not required in scenarios where relationship between interaction points is of direct replacement of values or of aggregation/ disaggregation type as variables for representing equivalent values are already defined in both models. However it poses challenges where relationship between interaction points is of causal type. The mathematical relationship is required in cases where the variables of DES model are influenced by variable of the SD model and vice versa. In this it is required that the influencing variable have some implicit or explicit representation in the model whose variable is being influenced. For example in the previous example productivity is the influencing variable and activity duration is the influenced variable, hence productivity needs some representation in DES where the value of productivity can be stored. It was achieved in the previous model by defining an implicit variable “productivity factor” defined in the information store in the DES model. The value of the productivity factor in absence of Schedule pressure is assigned one, hence in absence of Schedule Pressure there is no difference in the actual activity duration and sampled activity duration.

6.4.3 Phase 3: Identification of mode of interaction

Once the interaction points are defined and explicitly mapped the next step is to identify the way SD and DES models are going to interact with each other over the time to exchange data. The main objective of this phase is to provide guidance with respect to selection of appropriate mode of interaction. It has been identified in this research that there are two types of modes of interactions between SD and DES: Cyclic interactions and Parallel interactions.

Cyclic Interactions: In this mode SD and DES models run separately and the information is exchanged between consecutive runs in a cyclic fashion. There is no interaction during the run time. They interact with each other only after the completion of their run.

Parallel interactions: SD and DES run concurrently and the information is exchanged during run time**.** SD and DES run in parallel. Continuous variables represented by SD causes changes in the variables defined by DES and DES variables cause changes in SD variables.

Guidance regarding situations where these different types of interactions are appropriate will aid in selection. As shown in Figure 6.5, selection between cyclic and parallel mode of interaction depends upon the answer of following questions.

- **Are elements represented by SD and DES closely coupled in time and space?**
- **Are these interactions important for overall objectives?**

If the elements represented by SD and elements represented by DES are closely linked in space and those interactions are important for overall objective then parallel interactions are required otherwise the objectives can be achieved with cyclic interactions.

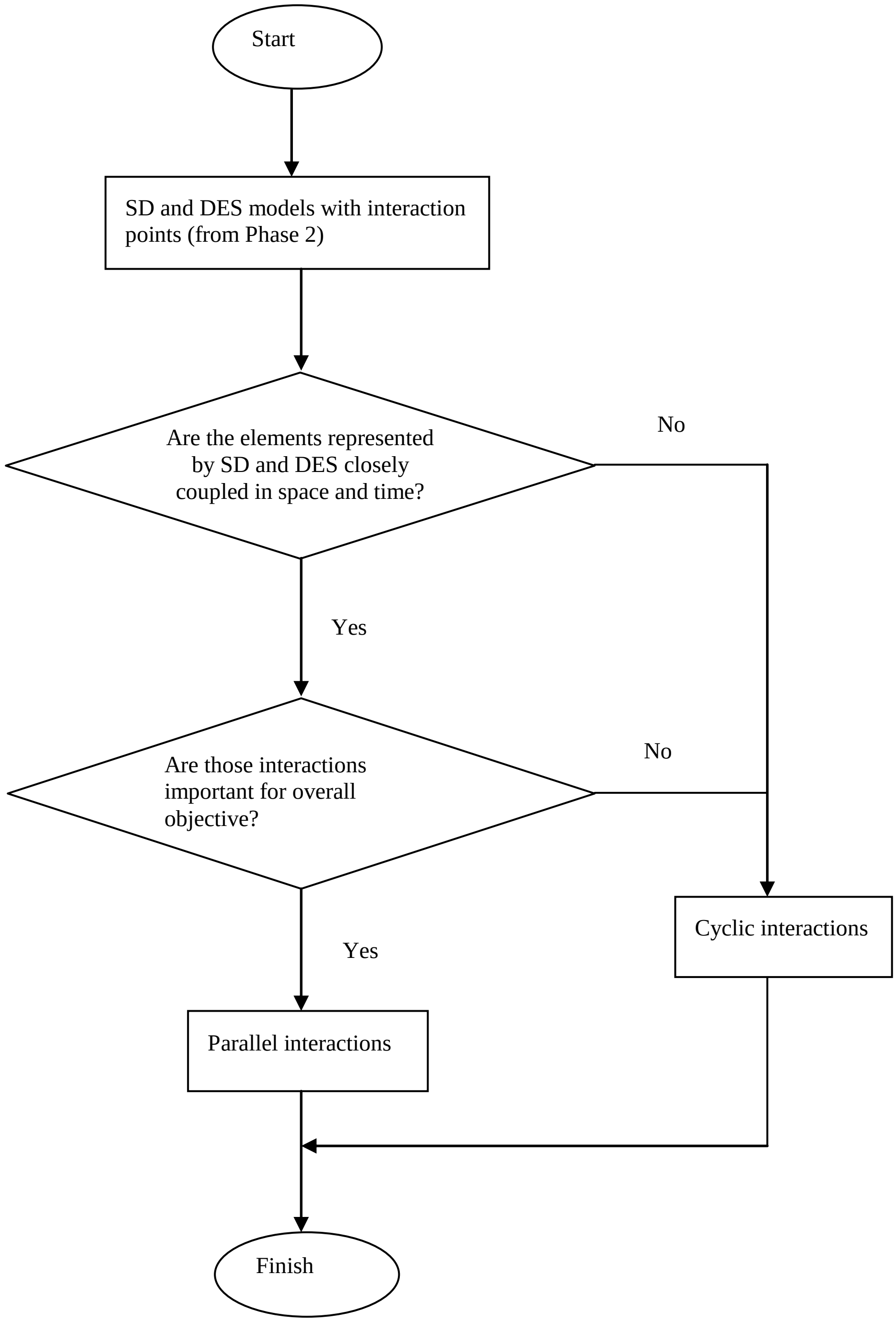


Figure 6.5: Overview of Phase 3 of the final framework

6.5 Summary

The main purpose of this chapter was to present the final framework after further refinement of the framework to address the limitation encountered during empirical evaluation discussed in previous chapter. This chapter provides discussion on reflection from the empirical evaluation. As the purpose of the chapter is further refinement of the framework, the emphasis during discussion on reflections has been mainly on limitations encountered. The framework has been modified to eliminate the shortcomings. The main output of this chapter is the final framework for hybrid simulation which is evaluated and has proved to be capable of providing concrete instructions to prospective users. The following paragraph describes the structure of the chapter.

Chapter 6 starts with Section 6.1 which established a link with the previous chapter and provided introduction to the rest of the chapter. Section 6.2 provides discussion on reflections obtained from empirical evaluation of the framework which was conducted in the previous chapter. As limitations provide the basis for improvement, the main focus in reflections has been on limitation and issues encountered during empirical evaluation. The major obstacles have been encountered in Phase 2. The absence of explicit guidance on formulation of relationship and lack of guidance on mapping between "interaction points" has been identified as the major drawbacks of the framework. It was not possible to implement a hybrid model without addressing these. It was identified that for exchange of information between SD and DES models was not possible without explicit mathematical representation of relationship between corresponding interaction points. It was identified that relationship between corresponding interaction points can be of three types: direct replacement of value of variable of one model by value of corresponding variable of other model, aggregation/disaggregation and causal type. It was further realized that formulation of relation was not enough for exchange especially in case of causal type relationships. As in causal type relationship corresponding interaction points do not represent equivalent variables, it was required that corresponding interaction points are mapped in both models so that their values can be exchanged.

Other issues encountered were, inappropriate use of “problem scope” as criteria for selection between SD and DES. Section 6.3 provides discussion on the way these limitations can be addressed followed by Section 6.4 which provides the description of final framework after incorporating the modifications discussed in previous sections. Finally Section 6.5 provides summary of the chapter. The main contributions, limitations and areas for future work will be discussed in next chapter.

Chapter 7: Contributions, Summary, Limitations and Future work

7.1 Introduction

This research proposed a generic conceptual framework for hybrid simulation (integration of SD and DES). The framework consists of three phases. The first phase of this framework guides the modelers to identify that the problem requires hybrid simulation followed by the second phase which provides detailed instructions for identification, mapping of interaction points between SD and DES models and finally Phase 3 provide guidance for selection of "mode of interaction" (the way SD and DES models interact over time for exchanging information). This chapter summarizes research, its contributions, limitations and future work. The structure of the chapter is as follows. The next section provides discussion on contributions of this research. Section 7.3 provides a brief summary of all the chapters followed by Section 7.4 which provides discussion on limitations and finally Section 7.5 provides directions for future work.

7.2 Contributions

The research has identified a need for a hybrid simulation approach that can respond to the shift of healthcare management from a fragmented to a more holistic integrated perspective. It identifies that the tool should be able to aid in decision making by comprehending both detail and dynamic complexity as well coupling between these two. The major contribution of this research is the provision of a generic framework for hybrid simulation. A three phase framework is developed for provision of guidance for those who want to deploy hybrid simulation. There is strong interest in multi- method approaches, complementary nature of SD and DES and potential benefits of their symbiotic integration that has been highlighted by many. Despite this emphasis, there has not been any reported generic conceptual framework which provides guidance regarding how to develop hybrid models. This research contributed by filling that gap. As the Phase 1 of the framework provides guidelines for identifying that the problem requires hybrid simulation, it is prerequisite for that to establish the criteria for selection between SD, DES, SD and DES or hybrid. For that a thorough understanding of overlapping and contrasting features of SD and DES is required.

In order to fulfil that, this dissertation further contributed by providing a literature review on comparisons and criteria for selection between SD and DES. It has been identified that in most of the previous studies, selection between methods focuses on alignment of problem attributes with the capabilities of methods. However this research argues that the system is an integral aspect and provides context for the problems, hence the selection criteria should be based on alignment between system, problem and methodology. Considering the importance of these, system problem and methodology has been deployed as parameters for both comparisons as well as selection criteria. The criteria for selection between SD and DES provided by this research are adapted from criteria provided by Brailsford and Hilton (2001) by incorporating the system's perspective. It has been argued previously that for strategic problems SD should be used and for analysis of operational problems DES should be used (Brailsford and Hilton, 2001). In this research it has been argued that wider use of SD for strategic problems is consequence of the ability of SD to capture dynamic complexity and a holistic view which are required for analysis of strategic problems. Similarly wider use of DES for operational problems is due to its ability to capture detail complexity and high resolution which are required for analysis of operational level problems. This dissertation argues that this consequential use should not be established as the criteria for selection. It can be said that there is more likelihood that for strategic problems SD would be required and for operational problems DES would be required, but it is not must. This argument is contradictory to prevalent wisdom and further contributes towards establishing criteria for selection between SD and DES.

Another contribution of this research is the provision of comprehensive literature review on existing hybrid studies deployed/proposed with in organisational context across different industries. It provides an overview of the way SD and DES models have been deployed for representing different aspects of the system (hybrid formats) and the way the they interacted with each other over the time for exchanging information (mode of interaction) during hybrid simulation The knowledge gained from this comprehensive review provided foundation for the development of generic framework for hybrid simulation.

Healthcare is complex exhibiting both dynamic as well as detail complexity. It has been argued that DES, with its ability to capture detail is ideal for problems exhibiting detail complexity. On the other hand SD with its focus non linearity and feedback is ideal for comprehending problems exhibiting dynamic complexity. Both paradigms provide valuable insights but none of them is capable to capture both detail and dynamic complexity to the same extent. It has been argued in literature that hybrid simulation in healthcare will aid in enhanced understanding of problems for effective decision making, however no study which has deployed hybrid simulation in healthcare context has been reported. By using the A and E example for evaluation of the framework, this research has attempted to fill that gap. This case study has not only filled the long standing gap of deployment of hybrid simulation in healthcare context but also has shown the need and advantages of hybrid simulation.

By using hybrid simulation an attempt towards quantifying the impact of intangible benefits of information systems into tangible business process improvements has been made. This provides an example of evaluation of the value proposition of information systems in the healthcare domain. Evaluation of the value proposition of Information Systems in healthcare has been a challenging issue (Green and Young, 2008). This case study which implements an electronic whiteboard in A and E provides the evidence for benefits over a normal whiteboard empirically. It is clear that in the service industry, servers respond to pressure by increasing their performance and this increase in performance is subjected to the availability of information. Electronic whiteboard improves the response time and performance of servers (Physicians in A and E example) by providing real-time information about the status of the system. The impact of enhanced performance can be visualised on tangible process outputs. By using hybrid simulation this research has attempted to provide a tool for conversion and evaluation of impact of intangible qualitative factors on tangible process outcome.

7.3 Summary of the Dissertation

Chapter 1 provides an introduction to the problem context of this thesis, which is the highly complex nature of healthcare problems exhibiting both detail and dynamic complexity and limitations of widely used simulation methods with regards to comprehension of these complexities. An overview of the application of DES and SD in the context of healthcare is provided. This chapter highlights the need of hybrid simulation in healthcare and the lack of a suitable generic framework of hybrid simulation for providing guidance with regards to its deployment. It has been argued that healthcare problems comprise of both dynamic and detail complexity. It is argued in this research that in order to make effective decisions, tools are required to comprehend both these types of complexity. There is the realization that both these dynamic and detail complexities are coupled and influence each other and integrated use of SD and DES in the form of hybrid simulation will be useful. Although ad-hoc use of hybrid simulation has been reported in other industries, there is an absence of a conceptual framework which guides the potential users. This thesis has tried to fill this gap by providing such a conceptual framework. The aim "development of generic framework for hybrid simulation" and objectives of the research to realise this aim are discussed in this chapter. It also provides description of the methodology used and an outline of the dissertation.

The aim of this research was to develop a generic framework for hybrid simulation which can be applied to healthcare problems. As mentioned in section 1.4, in order to achieve this aim five objectives have been outlined. The first objective of the dissertation focuses on development of in-depth understanding of comparisons and selection between SD and DES. This objective has been achieved in chapter two. In order to achieve this objective, chapter two focused on the comparison and selection between SD and DES. Alignment between problem perspective, systems perspective and methodology perspective has been argued as a recipe for accurate representation of problem scenarios (Lorenz and Jost, 2006; Pidd 2004; Chahal and Eldabi, 2008a).

These three parameters are used as criteria for comparisons and for making selection between SD and DES.

The second objective of the dissertation emphasises on thorough knowledge of existing hybrid models. This objective has been achieved in chapter 2 which further provides a comprehensive literature review on existing hybrid studies deployed/proposed within an organisational context across different industries. The purpose of this review is to understand the way hybrid simulation has been deployed in the past so that this understanding serves as a foundation for the development of the hybrid simulation framework It provides an overview of the way SD and DES models have been deployed for representing different aspects of the system and the way they interacted with each other over the time for exchanging information during hybrid simulation. Chapter 2 concludes by highlighting the limitations of existing frameworks of hybrid simulation leading towards establishment of a research gap. The knowledge induced from this comprehensive review provided the foundation for the development of the generic framework for hybrid simulation

The third objective of the dissertation is proposition of generic framework for hybrid simulation. In order to achieve this objective, Chapter 3 proposes a generic framework for hybrid simulation on the basis of knowledge induced from literature reviewed in Chapter 2. Chapter 3 describes requirements of the framework. It is argued that the framework for hybrid simulation should be able to provide answers to Why (Why hybrid simulation is required for this problem), what (what information is exchanged between SD and DES in hybrid simulation) and How (how the information is going to exchange) within the context of problem scenarios and hybrid simulation. Each of these requirements is discussed in detail in the following sections. Detailed discussion regarding identification of problems which require hybrid simulation has been provided. It highlighted the need and provided discussion on the criteria for selection between SD and DES. In order to identify interaction points (variables of SD and DES which are involved in exchange of information during hybrid simulation) relationships identified between different formats and interaction points have been discussed followed by a discussion on the description of different modes of interaction between SD and DES. In order to satisfy these requirements a three phase framework for hybrid simulation has been proposed. Each phase of the framework is mapped to a requirement and provides guidelines for meeting those requirements.

The fourth objective focuses on evaluation and refinement of the proposed framework. In order to achieve this objective the framework has been evaluated both theoretically as well as empirically. After evaluations the proposed framework was consequently modified to overcome the limitations. This objective is achieved in chapter 4 and chapter 5. Chapter 4 conducts theoretical evaluation of the proposed framework with multiple cases from the healthcare domain. The chapter starts with a description of the criteria for evaluation. These criteria are based on the requirements established in the previous chapter. The framework is evaluated against its ability to meet these requirements. The framework has been applied to six cases from the healthcare domain. The first phase of the framework identifies whether the problem requires hybrid simulation or not. The second and third phases of the framework are carried out only if the output of first phase indicates that problem requires hybrid simulation. Out of six, four case studies required hybrid simulation and hence subject to all phases of framework being applied, with remaining two, evaluation of the framework terminates with Phase 1. Application of framework is followed by reflections. As the purpose of evaluation was to refine the framework, discussion on reflection was focussed only on limitation and challenges encountered. Limitations identified during evaluation provided basis for modification. Finally the modified framework which is the main output of this chapter is described.

Chapter 5 focuses on empirical evaluation of the framework with a single detailed case study about implementation of electronic whiteboard in the A and E department of LDGH. The purpose of the empirical evaluation is to identify limitations of the framework which could not be visualised during theoretical evaluation and to provide the basis for further refinement. Chapter 5 starts with background and description of the problem followed by application of the framework to the case study. All three phases of the modified framework are applied to the problem scenario. Phase 1 identified that the problem requires hybrid simulation. It was identified in Phase 1 that the criteria for selection between SD and DES require some amendments. In Phase 2, it was identified that “number of patients over three hours”, “activity duration of DES activities” carried out by physicians, and “productivity of physicians”, are the interaction points. Then Phase 3 was applied to select the appropriate mode of interaction between SD and DES. As the elements represented by SD and DES model are closely coupled in time and space and this coupling is important, it was identified that parallel interactions were required.

Application of framework is followed by implementation of exchange of information between SD and DES. As the interaction points (what is exchanged) and the mode of interaction (how the information is going to exchange) were already identified up to this point it was hoped that the exchange would not pose any significant problems. However it was identified that this information was not enough. It was identified that for actual exchange of information, the way interaction points are related mathematically and the way they are mapped to other model in both SD and DES models is also required. With respect to mode of interactions it was detected that there is possibility of another mode of interaction which can be applied in some situations in place of parallel interactions. Although it is not of direct relevance as the purpose of this chapter was empirical evaluation of the framework rather than validation and utility of hybrid modelling, discussion on experiments and results obtained has been provided for the case study used for empirical evaluation. The obstacles and issues identified in this chapter such as problem with selection criteria, limitation of framework with respect to formulation and mapping between interaction points and possibility of another mode of interactions provide the basis for further modification and are discussed in detail in Chapter 6.

The fifth and final objective of the dissertation is development of the final framework. This objective is achieved in chapter 6. Chapter 6 focuses on development of the final framework, which requires further refinement of the framework to address limitations encountered during empirical evaluation discussed in the previous chapter. The main output of this chapter is the final framework for hybrid simulation which is evaluated and proved to be capable of providing concrete instructions to prospective users. In order to achieve this Chapter 6 provides discussion on reflections from the empirical evaluation of the framework. As limitations provide the basis for improvement, the main focus in reflections has been on limitation and issues encountered during empirical evaluation. Major obstacles have been encountered in Phase 2. The absence of explicit guidance on formulation of relationship and lack of guidance with regards to mapping of corresponding interaction points in SD and DES models have been identified as the major drawbacks of the framework. It was not possible to implement a hybrid model without addressing these. Other issues encountered were, inappropriate use of “problem scope” as criteria for distinction between SD and DES and the possibility of another type of interactions “planetary interactions” which were not addressed in the previous version of the framework. Chapter 6 provides discussion on the way these limitations can be addressed, followed by the description of final framework after incorporating the modifications. Finally Chapter 7 provides summary of the dissertation, highlights its main contributions, limitations and areas for future work.

7.4 Limitations

This research has contributed towards hybrid simulation by providing a generic framework. Although it has attempted to cover all the different formats in which hybrids has been deployed, we do not claim to have exhausted this area.

The framework is limited to only to SD and DES, agent based is another simulation method which is emerging as a promising tool for analysing problems such as spread of infectious diseases in the healthcare context, inclusion of this into the framework will enhance the utility of the framework.

As the purpose of the models was to evaluate the framework rather than attempt to accurately model A and E, quite a few compromises have been made such as limitation to the majors section of A and E only and inclusion of a few factors. Due to the time constraint, the analysis of A and E problem has been limited to physicians and majors section only and dynamic interactions between only few qualitative factors such as Schedule pressure, productivity and backlog have been considered. As rather than accuracy of the models, applicability of the framework was the main objective, compromises have been made with regards to accuracy of the model. The equations for productivity and activity duration are very crude. In order to develop sophisticated equations more research, data and time were required.

The framework does not provide any guidance with respect to technical automation of integration between SD and DES. Due to lack of automation, utility of hybrid could not be achieved to its full potential. For example in the case study, although it would have been more advantageous to have smaller time interval between interactions, data was exchanged between SD and DES after each hour because smaller intervals mean more interactions and more consumption of time.

7.5 Future work

Restriction of the framework to SD and DES only, has been highlighted as one of the limitations. Agent based simulation is another emerging approach for modelling dynamic behaviour of complex systems. In agent based simulation, a series of interaction rules are defined for entities which give rise to complex emergent behaviour. Due to its ability to model behaviour of agents it has advantages over other modes when it comes to modelling spread of infectious diseases and emergent behaviour of crowd. Inclusion of agent based simulation into the framework will strengthen the proposed framework.

This research does not provide guidance with regards to automation of exchange of information between SD and DES. It has been identified in this research that the full potential of hybrid simulation can not be achieved without automation of the exchange process. Currently we are working on a proposal which will focus on the inclusion of agent based simulation and automation of exchange of information between SD and DES.

In this dissertation three different formats of hybrid simulation have been identified: Hierarchical, Process – Environment and Process performance – environment format. During empirical evaluation, application of process- environment format to healthcare problems has been evaluated. It would be interesting to apply this framework to healthcare problems which fall in other hybrid formats.

Although it is a generic framework, it has been applied only to the healthcare context. Application of the framework to other areas will enhance the utility and generalisation of the framework. It is hoped that in future this framework will be applied to hybrid problems from other industries.

As the main purpose behind the development of the hybrid model for the LDGH problem in Chapter 5 was evaluation of the framework rather than attempt to accurately model the A and E department, quite a few compromises have been made such as limitation to majors section of A and E only, only physicians have been included in the model and dynamic interactions between limited factors have been captured. The extension of the model in future to include other departments, such as minors, resus, paediatrics and other resources, such as nurses will enhance the accuracy of the model. In the SD model dynamic interactions between limited factors such as productivity, SP, backlog etc have been captured. Inclusion of other environmental factors such as time based fatigue, impact of enhanced communication on productivity of human resources during busy periods, quality (wavering of safety procedures in response to enhanced schedule pressure) and patient satisfaction etc will provide more insight and rigour into the A and E dynamics.

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Appendix A: SD model

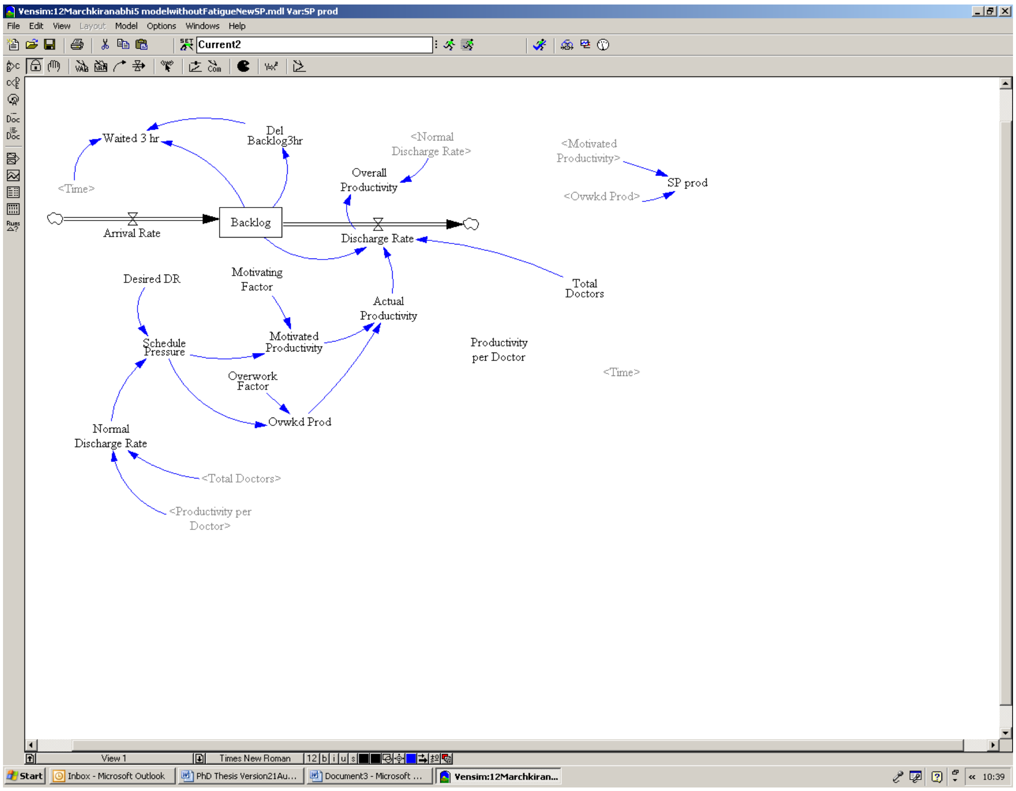

Figure A.1: Screen shot of Vensim SD model

Appendix B: Table showing relationship between Schedule pressure and productivity

Schedule Pressure	motivational productivity	fatigue productivity	Productivity
0	1	1	1
0.5	1	1	1
1	1	1	1
1.1	1.1	1	1.1
1.2	1.2	0.99	1.188
1.3	1.35	0.98	1.323
1.5	1.47	0.97	1.4259
1.6	1.6	0.96	1.536
1.75	1.7	0.95	1.615
1.8	1.8	0.94	1.692
1.9	1.9	0.93	1.767
2	2	0.92	1.84
2.2	2.1	0.91	1.911
2.4	2.3	0.9	2.07
2.5	2.4	0.88	2.112
2.7	2.6	0.85	2.21
2.9	2.8	0.8	2.24
3	2.9	0.75	2.175
3.5	3	0.5	1.5
4	3	0.25	0.75
4.5	3	0.17	0.51
5	3	0.17	0.51

Table B.1: Relationship between SP, motivational productivity, fatigue productivity and overall productivity

Appendix C : Equations of SD model

(01) Actual Productivity=
Motivated Productivity*Ovwkd Prod
Units: **undefined**

(02) Arrival Rate=
50
Units: patients/Minute

(03) Backlog= INTEG (
Arrival Rate-Discharge Rate,
0)
Units: patients

(04) DelBacklog3hr=
DELAY FIXED (Backlog, 180, 0)
Units: **undefined**

(05) Desired DR=
4
Units: **undefined**

(06) Discharge Rate=
MIN (Total Doctors*Actual Productivity, Backlog)
Units: patients/Minute

(07) FINAL TIME = 1
Units: Minute
The final time for the simulation.

(08) INITIAL TIME = 0
Units: Minute
The initial time for the simulation.

(09) Motivated Productivity=
Motivating Factor (Schedule Pressure)
Units: patients/ (Minute*persons)

(10) Motivating Factor (
[(0,0)-(8,4)],(0,1),(0.5,1),(0.7,1),(1,1),(1.1,1.1),(1.2,1.2),(1.3,1.35),
(1.5,1.47),(1.6,1.6),(1.75,1.7),(1.8,1.8),(1.9,1.9),(2,2),(2.2,2.1),(2.4,2.3

),(2.5,2.4),(2.7,2.6),(2.9,2.8),(3,2.9),(3.5,3),(4,3),(4.5,3),(5,3))
Units: **undefined**

(11) Normal Discharge Rate=
Productivity per Doctor*Total Doctors
Units: patients/Minute

(12) Overall Productivity=
Discharge Rate/ (Normal Discharge Rate+1e-007)
Units: **undefined**

(13) Overwork Factor (
[(0,0)-(6,2)],(0,1),(0.5,1),(1,1),(1.1,1),(1.2,0.99),(1.3,0.98),(1.5,0.97
),(1.6,0.96),(1.75,0.95),(1.8,0.94),(1.9,0.93),(2,0.92),(2.2,0.91),(2.4,0.9
),(2.5,0.88),(2.7,0.85),(2.9,0.8),(3,0.75),(3.5,0.5),(4,0.2),(4.5,0.17),(5
, 0.17))
Units: **undefined**

(14) Ovwkd Prod=
Overwork Factor (Schedule Pressure)
Units: **undefined**

(15) Productivity per Doctor=
1.2
Units: patients/Minute/persons

(16) SAVEPER = 0.0625
Units: Minute [0,?]
The frequency with which output is stored.

(17) Schedule Pressure=
Desired DR / (Normal Discharge Rate+1e-008)
Units: Dmnl

(18) SP prod=
Motivated Productivity*Ovwkd Prod
Units: **undefined**

(19) Total Doctors =
5
Units: **undefined**

(21) Waited 3 hr=
IF THEN ELSE (Time>180, MAX (0, Backlog-DelBacklog3hr), 0)
Units: **undefined**

Appendix D: Distributions applied for duration of activities performed by physicians

The value of fluctuating productivity has been incorporated in DES model during hybrid simulation is by using triangular distributions based on expert opinion divided by productivity factor. ***Productivity factor is an implicit variable defined in Information Store*** In the absence of hybrid simulation value of productivity factor is assigned one. During hybrid simulation the value for productivity factor is imported from SD. This is achieved by defining following six named distributions for tasks performed by physicians.

- **DstExamination**
- **DstTreatment**
- **DstRe-assesment**
- **Dist Examination**
- **Dist Treatment**
- **Dist Re-assessment**

First three distributions are defined purely on the basis of parameter values obtained from experts. The parameter values and distribution applied for these is as follows:

DstExamination

Named Distribution

Distribution Detail: Triangular 11 22 44

DstTreatment

Named Distribution

Distribution Detail: Triangular 11 22 44

DstRe-assesment

Named Distribution

Distribution Detail: Triangular 8 12 15

The following distributions are the actual distributions specified for different activities performed by physicians in A and E. The value of these distributions depends upon the named distributions defined above and real time value of "productivity factor" which is an implicit variable defined in information store.

Dist Examination

Dist Examination is distribution based on triangular distribution obtained on the basis of observations and expert opinion and fluctuation in productivity of doctors in response to varying schedule pressure.

Dist Examination = DstExamination/ Productivity factor *Equation A.1*

Dist Treatment

Dist Treatment is distribution based on triangular distribution obtained on the basis of observations and expert opinion and fluctuation in productivity of doctors in response to varying schedule pressure.

Dist Treatment = DstTreatment/ Productivity factor *Equation A.2*

Dist Re-assessment

Dist Re-assessment is distribution based on triangular distribution obtained on the basis of observations and expert opinion and fluctuation in productivity of doctors in response to varying schedule pressure.

Dist Re-assessment = DstReAssesment / Productivity factor *Equation A.3*