Participatory system dynamics modelling approach to safe and efficient staffing level management within hospital pharmacies

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Participatory System Dynamics
Modelling Approach to Safe and Efficient Staffing Level Management within Hospital Pharmacies

Mohammed Ibrahim Shire

Human Factors and Complex Systems
Design School
Loughborough University

A doctoral thesis submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy of Loughborough University

September 2018
You can never be overdressed or overeducated – Oscar Wilde
DECLARATION

This dissertation is the result of my own work and includes nothing, which is the outcome of work done in collaboration except where specifically indicated in the text. It has not been previously submitted, in part or whole, to any university of institution for any degree, diploma, or other qualification.

Signed:______________________________________________________________

Date:_______________________________________________________________

Mohammed Ibrahim Shire BSc, MSc
ABSTRACT

With increasingly complex safety-critical systems like healthcare being developed and managed, there is a need for a tool that allows us to understand their complexity, design better strategies and guide effective change. System dynamics (SD) has been widely used in modelling across a range of applications from socio-economic to engineering systems, but its potential has not yet been fully realised as a tool for understanding trade-off dynamics between safety and efficiency in healthcare. SD has the potential to provide balanced and trustworthy insights into strategic decision making. Participatory SD modelling and learning is particularly important in healthcare since problems in healthcare are difficult to comprehend due to complexity, involvement of multiple stakeholders in decision making and fragmented structure of delivery systems. Participatory SD modelling triangulates stakeholder expertise, data and simulation of implementation plans prior to attempting change. It provides decision-makers with an evaluation and learning tool to analyse impacts of changes and determine which input data is most likely to achieve desired outcomes. This thesis aims to examine the feasibility of applying participatory SD modelling approach to safe and efficient staffing level management within hospital pharmacies and to evaluate the utility and usability of participatory SD modelling approach as a learning method.

A case study was conducted looking at trade-offs between dispensing backlog (efficiency) and dispensing errors (safety) in a hospital pharmacy dispensary in an English teaching hospital. A participatory modelling approach was employed where the stakeholders from the hospital pharmacy dispensary were engaged in developing an integrated qualitative conceptual model. The model was constructed using focus group sessions with 16 practitioners consisting of labelling and checking practitioners, the literature and hospital pharmacy databases.

Based on the conceptual model, a formal quantitative simulation model was then developed using an SD simulation approach, allowing different scenarios and strategies to be identified and tested. Besides the baseline or business as usual scenario, two additional scenarios (hospital winter pressures and various staffing arrangements, interruptions and fatigue) identified by the pharmacist team were simulated and tested using a custom simulation platform (Forio: user-friendly GUI) to enable stakeholders to play out the likely consequences of the intervention scenarios. We carried out focus group-based survey of 21 participants working in the hospital pharmacy dispensaries to
evaluate the applicability, utility and usability of how participatory SD enhanced group learning and building of shared vision for problems within the hospital dispensaries.

Findings from the simulation illustrate the knock-on impact rework has on dispensing errors, which is often missing from the traditional linear model-based approaches. This potentially downward-spiral knock-on effect makes it more challenging to deal with demand variability, for example, due to hospital winter pressures. The results provide pharmacy management in-depth insights into potential downward-spiral knock-on effects of high workload and potential challenges in dealing with demand variability. Results and simulated scenarios reveal that it is better to have a fixed adequate staff number throughout the day to keep backlog and dispensing errors to a minimum than calling additional staff to combat growing backlog. Whilst having a significant amount of trainees might be cost efficient, it has a detrimental effect on dispensing errors (safety) as number of rework done to correct the errors increases and contributes to the growing backlog. Finally, capacity depletion initiated by high workload (over 85% of total workload), even in short bursts, has a significant effect on the amount of rework.

Evaluative feedback revealed that participatory SD modelling can help support consensus agreement, thus gaining a deeper understanding of the complex interactions in the systems they strive to manage. The model introduced an intervention to pharmacy management by changing their mental models on how hospital winter pressures, various staffing arrangements, interruptions and fatigue affect productivity and safety. Although the outcome of the process is the model as an artefact, we concluded that the main benefit is the significant mental model change on how hospital winter pressures, various staffing arrangements, interruptions and fatigue are interconnected, as derived from participants’ involvement and their interactions with the GUI scenarios.

The research contributes to the advancement of participatory SD modelling approach within healthcare by evaluating its utility and usability as a learning method, which until recently, has been dominated by the linear reductionist approaches. Methodologically, this is one of the few studies to apply participatory SD approach as a modelling tool for understanding trade-offs dynamics between safety and efficiency in healthcare. Practically, this research provides stakeholders and managers, from pharmacists to managers the decision support tools in the form of a GUI-based platform showcasing the integrated conceptual and simulation model for staffing level management in hospital pharmacy.
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2. Shire, M. I., Jun, G. T., & Robinson, S. (2018). A system dynamics approach to workload management of hospital pharmacy staff: modelling the trade-off between dispensing backlog and dispensing errors. IISE Transactions on Occupational Ergonomics and Human Factors (Published)


4. Shire, M. I., Jun, G. T., & Robinson, S. A system dynamics approach to workload management of hospital pharmacy staff: modelling the impact of interruptions on efficiency and safety. (under preparation)

Conference Presentations:


1 Pertains to Chapter 2

2 Pertains to Chapter 4 and 5
Workshop (SW16), Stratford, Warks, 11-13th April, pp. 238-247. (Conference Proceeding)


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1 INTRODUCTION

1.1 Context
Healthcare systems are faced with various conflicting challenges in regard to safety, efficiency and sustainability. These include increasing demand for healthcare service, increased employee turnover, shortage of healthcare staff, increasing healthcare costs, higher patient expectations, limited resources, and the general economic crises worldwide (Faezipour and Ferreira, 2013; Mutingi and Mbohwa, 2012). These challenges and factors add to the complexity of the healthcare system. As a result, it is highly challenging to understand and manage the dynamics of healthcare systems.

Within the pharmacy sector, there is a growing concern about the number of patients harmed by medication errors; as it is one of the most common patient safety incidents reported in hospitals (Cousins et al., 2012; NHS England, 2015). It contributes to harmful events that endanger patient safety and has the potential to incur a substantial monetary strain on the health service. In England and Wales, approximately 176,000 medication errors were reported to the National Reporting and Learning System (NRLS) by National Health Service organisations between 1 April 2014 and 30 March 2015 (NHS England, 2015). Dispensing medication is a complicated process that goes beyond taking medicines from a robot or shelf, labelling the pack, and handing it to the patient after dispensing it (Kelly, 2011). The majority (85%) of the dispensing errors are detected by pharmacists prior to the medication being supplied to the patient (Milch et al., 2006). However, some errors often go undetected and as a result may cause serious patient harm and occasionally death (Sleinitz et al., 2012). Errors are intractable when a culture de-emphasises safety
and instead prioritises competing concerns (e.g., cost, efficiency) that can produce errors (Litvak et al., 2005).

Recent years have revealed an alarming concern that pharmacists’ workload and frequent dispensing errors are interlinked. These worries are corroborated in the literature that looks into the frequency and causes of a number of dispensing errors in hospital and community pharmacies. The most frequently repeated factor has shown to be high workload (James et al., 2009), interruptions, inappropriate skill-mix, poor handwriting, inadequate staffing levels and knowledge have also been significantly cited to contribute to dispensing errors (Ashcroft, Quinlan, & Blenkinsopp, 2005; James et al., 2009). More significantly, any work becomes more effortful when these factors are added to the mix.

The level of incidents caused by complex relations between technical, social and environmental factors have unveiled the limitations of conventional staffing level and safety management approaches (Anacleto et al., 2007; Ashcroft et al., 2005; Beso et al., 2005; Bond and Raehl, 2001; Gidman et al., 2007). Studies of nurse-to-patient ratios discovered that adequate staffing is associated with fewer adverse events (Aiken, 2002; Needleman et al., 2006). In contrast, less adequate staffing levels (indicated by workload, overtime, or increased nonregistered nurse hours of care) resulted in unexpected deaths (Kc and Terwiesch, 2009) and medication errors (Seago et al., 2006).

Within healthcare, the complexity of hospital pharmacies is evident as they deal with different types of prescriptions, employ a wide range of staff with different possible combinations of roles and incorporate many advanced technological solutions to improve the accuracy and speed of drug dispensing. For each prescribed item, a label must be created, and then the relevant product selected and self-checked, the correct number of dose units counted and repackaged if necessary, and the product labelled. The completed prescription is then rechecked by a qualified pharmacist, who may also have to confirm that a valid dosage regimen has been prescribed before handing out to the relevant patient, hospital ward or department.

At the organisational level, the primary result is that the well-intentioned decisions, which initially aimed to improve the performance of these systems, generally lead to opposite results, a syndrome often known as “policy resistance” (Homer and Hirsch, 2006). A reason advanced to explain these disappointing results is the tendency to simplify and underestimate the level of the complexity of the problem in question. Most often, problems are the result of the interaction between a complex set of interconnected
elements. However, the limited cognitive capacity of decision-makers results in a simplistic analysis of the situation and the problem in question. As a result, the most important sources of the problem are either missed or overlooked (Sterman, 2000). The result is that the decisions taken to eliminate a problem can have unforeseen consequences and lead to undesirable outcomes, resulting in what is known as “policy resistance” (Sterman, 2001, 2000).

A remedy for the “policy resistance” syndrome is to alter the way of framing, formulating and analysing problems within healthcare systems. There is a growing need to apply more holistic approaches, which incorporates all the sub-systems and their interconnections (Eldabi et al., 2006). This is crucial since an isolated action taken within the content of a part of the system may upset the current equilibrium of the whole system and cause the other sub-systems to resist the action and defeat.

It is vital to capture the existing decision-making framework that both encompasses the managers and the staff. However, this will prove to be challenging considering the pluralist view and the ever-changing processes of the NHS. Some of the factors that affect decision-making, in general, include the depicted state as being in a continual state of crisis of under-funding (Rivett, 1998). In addition to having to make sacrifices, difficulties pop up in funding improvements to services. Often cited as evidence of this funding crisis are the budget deficits that apply to the existence of rationing. Another factor is the limited information possessed by the management team. The decision-makers taking decisions in complex systems are not always aware of what other decisions are being made at the same time (Doyle and Ford, 1998; Kulin, 1970; Senge, 1990). This is known by the concept of 'bounded rationality' (Meadows and Wright, 2008) which influences the mental model that we hold which affects our approach and decision-making.

This level of trade-offs is also repeated with the operational staff within the healthcare (Amalberti, 2013). Given the finite resources available, trade-offs have to be made when setting priorities between the various demands (Hollnagel, 2012). Hollnagel argues that human error is unintentional; otherwise, failures would be something people desired and planned to do, thus would be preventable (Hollnagel, 2012). In a complex system, it is discouraged to classify certain actions as good or bad as the situation dictates (Hollnagel, 2012).
In healthcare, rules tend to be less binding and enforced as they are defined less explicitly than in any other high-risk industries. Despite the fact that many policies and guidelines are in place, they are often viewed as mere recommendations rather than strictly enforced rules. For instance, a busy practitioner may not follow procedures strictly and logically but instead may choose the pathway that appears to be the most useful and productive at the time. If this approach does not contribute to censure or other untoward consequences, then the individual may continue to deviate from the original procedure in pursuit of better performance and productivity (Lawton, 2002).

To extend this into a pharmacy setting, pharmacy workers who violate rules or guidelines by providing less assessment than recommended are not making a human error. In reality, it might be a deliberate choice not to follow the guidelines. Consequently, less assessment is undertaken in a shorter period of time. From a neutral view, this process is a win-win situation for both the pharmacist and the patient. Hollnagel brought forth a theory to elucidate why unwanted outcomes occur through the ETTO (efficiency-thoroughness trade-off) principle by stating that “if demands for productivity or performance are high, thoroughness is reduced if demands for safety are high, efficiency is reduced” (Hollnagel, 2012). For this reason, Berwick’s review into patient safety (Berwick, 2013) emphasised the critical need for introducing systematic methods and regulation on the correct staffing level based on a dynamic understanding of existing staff workload.

System Dynamics (SD) simulation can model complex healthcare systems and the dynamic interactions between safety factors. The SD method can be used to obtain an in-depth understanding of the system and to answer ‘what if’ questions, investigating the effect of system changes over time. Whilst SD modelling has gained popularity as a tool in a variety of industries such as engineering, economics, defence, ecology and business (Homer and Hirsch, 2006), its potential has not yet been fully realised as a tool for making strategic decisions in planning health services as new needs and priorities emerge in the NHS system. Implementation of SD models in healthcare has not been universally widespread (Fone and Hollinghurst, 2003) and the practical impact of SD simulation in healthcare settings has not been as high as expected (Proudlove et al., 2007). Moreover, this is more or less the same although there has been an increase in later years in literature promoting the utility of SD approach in healthcare and redesign of the healthcare system, the published and grey literature suggests its practical application to inform health policy is not widespread (Atkinson et al., 2015). The following reasons for the low impact were
Chapter 1: Introduction

mentioned by several authors, in particular, Harper & Pitt (2004), Brailsford (2005) and Eldabi et al. (2006):

- The complexity and number of different stakeholders at different levels in healthcare settings;
- Lack of involvement of stakeholders in the modelling process;
- Lack of interest, commitment and reluctant to accept the importance of SD simulation on the part of healthcare professionals;

Senior managers in hierarchical organisations usually rely on accountability, control of planning, and reinforcement of rules (Hoff, 2003; Senge, 1990). However, it is not always feasible to manage the staff from the top. Performance in healthcare depends on staff motivational levels, abilities and traits, and role perceptions amongst other factors (Mills et al., 1983; Porter and Lawler, 1968). The operators play an important role in the effectiveness of the delivery of services (Robertson et al., 2005; Sharrard, 1992). There is ample evidence that service output depends on the collaborative efforts of the healthcare staff and the patients (Gwinner et al., 1998). Therefore, without considering the viewpoints of the healthcare staff, any healthcare managerial decision is likely to bring short-term gains at the expense of longer-term results.

Furthermore, to avoid applying short-term symptomatic solutions, managers need to know more about how soft factors (i.e. motivation, morale, stress and management support) affect organisational performance. They need tools that will allow them to develop a “learning organisation” (Senge, 1990) so that structured input from the staff and their stakeholders can be used for their decision-making. The “learning organisation” concept aims to align managers’ understanding of the underlying cause of a problem, achieve consensus on a course of action, and facilitate broader decision adoption and successful implementation (Homer and Hirsch, 2006). For these reasons, safety and sustainability in healthcare can be investigated using the SD approach to give decision-makers a better understanding of the system.

SD has rarely been utilised for safety and efficiency trade-offs within the healthcare and has a low impact primarily due lack of involvement from the operational staff. As a result, this research aims to fill two gaps. One is assessing how the SD approach can help hospital management view and decide the staff workload management issue by supporting them to consider better the factors that impact safety (dispensing errors) and performance (backlog). The second gap is the utility and usability of participatory SD approach. In
modelling a system, it may assist decision-makers in seeing where and how their interventions influence the behaviour of the whole as well as the parts of the system, allowing them to group learn how factors contribute to the overall behaviour of the healthcare system. Thus, usefulness is considered in terms of the ability to contribute to the existing decision-making process. This probes beyond the ability to provide existing decision insights, but to also consider the value of these insights, and the level of ease of use of applying SD.

1.2 Research Objectives
The study aims to examine the feasibility of using SD approach to address safety and evaluate the utility and usability of participatory SD as a learning tool in healthcare. To achieve that, the following objectives of the research are:

- To investigate how the SD framework can help hospital management view and decide the staff workload management issue by supporting them to better consider the impact of staff levels, interruptions and workload on safety (dispensing errors) and performance (backlog).
- Evaluate the applicability, utility and usability of how participatory SD can enhance group learning:
  - What kind of benefits (or drawbacks) in knowledge will pharmacy decision-makers gain by applying the SD approach?
  - How easy is it to use (in terms of modelling, analysis and result interpretation) the SD approach to improve group learning?
  - How applicable is the participatory SD approach in the healthcare environment

1.3 The Scope of the Research
Keeping patients safe is a complex and large-scale undertaking. This research seeks to address the conceptual challenge of how to improve the understanding of operational influences on patient safety using SD modelling. It brings a system thinking approach to the task.

The assumption is often made that things go wrong due to ‘human error’. It is far easier to blame the individual practitioner as being a ‘bad apple’ (Dekker, 2004). However, there
is an increasing awareness of broader system issues that contribute to failures, which requires a different approach to learning and improvement (Cook et al., 1998; Dekker, 2004). The initial scope of this research is limited to the hospital pharmacy services provided by the NHS in England but has the potential to extend to other institutions. Predictive models and simulation results is a secondary focus of this research, and greater focus is assigned to the feasibility and realistic aspect as a decision and learning support tool.

1.4 Thesis Organisation
This thesis consists of seven chapters, and the outline of the subsequent chapters is as follows:

Chapter 1: introduces the context of the research, research aims and objectives and its scope. The report structure is also summarised.

Chapter 2: showcases an in-depth review of the literature related to existing SD applications in a variety of sectors, the concept of system safety and the existing safety frameworks currently utilised and employed in the industry. It introduces participatory SD (Group Model Building) and its applications in healthcare.

Chapter 3: presents the overall research paradigm employed in this research. It reveals an overview of the approach utilised in this study. The case study research is discussed and the iterative participatory SD simulation framework that will be implemented.

Chapter 4: presents the group model formulation phases of the hospital pharmacy system. Relevant factors and interrelations from the qualitative model conducted in a group setting are mapped into the model structures. Variables in the model structures are explained in each section. In the end, the structure of the quantitative model is developed, by combining all phases. Scenarios are developed, and the web-interface is designed. It also explains the expert elicitation study that is conducted to collect data on the estimates from practitioners, then provides a summary of assumptions, equations and data used in the simulation studies.

Chapter 5: presents a detailed description of the simulation model and demonstrates the data collection for simulation. Simulation experiments are presented, and system behaviours are observed under different scenarios.

Chapter 6: develops a discussion by critically reflecting on how the results relate to the aim and objectives. This is achieved by discussing the findings at each stage of the
participatory modelling process, and the development of the model. Following this, the chapter presents and then discusses the results of the evaluation of the approach with the stakeholders. It analyses the feasibility of applying participatory SD modelling approach to safe and efficient staffing level management within hospital pharmacy and evaluates the utility and usability of participatory SD modelling approach as a learning method.

Chapter 7: revisits the research questions, summarises the key contributions to knowledge, collates the findings, considers the implications of these findings for future participatory SD modelling research, and ends with recommendations for decision-makers and research limitations as well as future research.
2 LITERATURE REVIEW

In this chapter, the first section analyses and presents SD approaches applied within safety-critical domains. The second section looks at the concept of participatory SD framework (Group Model Building) and how it has been applied in healthcare sector. SD has the potential to study the aspects of complex systems including its likely effect of modifications to structural and dynamic system properties that cannot be achieved with traditional approaches. This chapter aims to present a review of literature addressing safety issues using SD across safety-critical domains and how participatory SD has been applied in healthcare. In Section 2.1, sixty-three studies were included and classified based on a customised human factors safety taxonomy framework. The thematic analysis of the literature resulted in five themes: external factors, organisational influences, unsafe supervisions, preconditions for unsafe acts and unsafe acts. Section 2.2, six studies of participatory SD interventions in healthcare were identified and analysed and discussed.

2.1 SD Application to Safety

Understanding the mechanism of complex systems is a daunting task. Several existing methods used for examining the causal nature of events are unable to account for the non-linear interactions and feedback in complex systems because they are based on a linear paradigm. Equipment or humans are wrongly held responsible for any mishap when accidents are described sequentially in a system. Thus, learning how to prevent the reoccurrence of accidents becomes very difficult as opportunities for understanding the system mechanism are not utilised (Underwood et al., 2016). Unfortunately, majority of the tools used within safety-critical industries are based on these linear, sequential models
of causality (e.g. Root Cause Analysis, Human Performance Enhancement System, and the Swiss Cheese Model). Nevertheless, there is an increasing awareness that the current tools are becoming ineffective due to the complex nature of the systems within which they are used (Marais et al., 2009; Svedung & Rasmussen, 2002; Leveson, 2004; Le Coze, 2005; Reiman and Oedewald, 2007; Rasmussen, 1997). Several accident models based on a System Safety paradigm have been developed to address these challenges since linear and sequential tools are only suitable for industries with loose coupling and linear interactions (Hollnagel, 2008). Some of the models that adopt this System Safety paradigm include AcciMap (Svedung and Rasmussen, 2002), Functional Resonance Accident Model (Hollnagel and Goteman, 2004) and the Systems Theoretic Accident Model and Process (STAMP) (Leveson, 2004). Although they have a limitation in predicting system responses to policy changes, these models have been shown to be effective in analysing accident occurrence in complex socio-technical systems (Nancy Leveson et al., 2003). Whilst some policy decisions appear not to have any effect on safety; they might drastically reduce safety in reality as well as increase risk.

Various aspects of complex systems such as the possible effect of changes in the dynamic and structural system properties cannot be understood using traditional approaches but can be studied with SD. Organisations can be better prepared for accidental occurrences if they are able to analyse the causal structure and dynamics behind such events as well as learn from them, which makes it more easy to comprehend the warning signs (events and behaviours) for accidents and errors. These warning signs may appear as frequent patterns of behaviour or structure that precedes an event. Several authors such as Wolstenholme (2003) and Senge (1990) have identified these common patterns and behaviours or system archetypes in different contexts.

SD is a computer-based simulation method primarily used for qualitative and quantitative analysis of complex problems that develop or persist over time. It has been widely used in modelling across a range of applications that range from socio-economic to engineering systems, but its potential has not yet been fully realised as a tool for understanding system safety and supporting important strategic decision-making. The objective of this review is to examine the connection between safety improvement and SD by reviewing literature that attempts to improve system safety in complex systems by utilising SD modelling. In doing so, the following four questions are explored: what safety issues have been addressed by SD, how has SD been applied to improve system safety, how might SD be further applied to system safety and how has participatory SD been applied in healthcare?
The rest of the review is organised as follows: section 2.3 will briefly look at the concept of system safety with a clear emphasis on the evolution of existing system safety tools and its present limitations. Section 2.4 will briefly explain what SD is. Section 2.5 will describe the safety framework used to compartmentalise and analyse the findings from the literature analysis and the approach to the literature review. Findings are presented in section 2.6. Section 2.7 describes the concept of participatory SD framework: Group Model Building and finally, we return to discuss our findings with respect to the four research questions.

2.1.1 System Safety in Complex Socio-Technical Systems

Earlier types of accident models (sequential and epidemiological) have viewed safety in a reactive way as opposed to a proactive manner by primarily focusing on retrospectively ‘learning from events’ instead on proactively assessing the safety (Hollnagel et al., 2007). This ‘learning from events’ strategy has obviously pointed out several faults in a large number of past accidents, which has further emphasised the need to address safety proactively as well as to focus on organisational processes that are involved in ‘safety management’. As a result, systemic models have been introduced in a bid to carry out a more detailed investigation on managerial and organisational failures in connection with the occurrence of accidents (Reason, 1990). There are two basic concepts used in existing literature on system safety, and these include the notion that safety is a ‘control problem and that a ‘system theoretic’ approach is required to address safety (Saleh et al., 2010). Safety is regarded as a control problem since accidents occur whenever the management control system cannot sufficiently handle component failures, external troubles and deteriorating interactions.

Today, accident occurrence is still largely being attributed to human error. Incentives exist for organisations to blame operators to evade or avoid possible lawsuits and public outcry. According to Johnson (1980), an accident is more likely to be attributed to human error when less is known about the specific circumstances. Perrow (1999, 1984) said that “human error” is usually the only reasonable explanation given by organisations for accidents whose real cause is either complex or uncertain or plainly embarrassing. The truth is that accidents are not usually caused by humans because they are always governed by a set of rules and behaviour which determines how they interact within a social and physical context. Thus, it is easy for an organisation to detect any form of deviation with such rules and behaviour in place.
Rasmussen and Svedung (2002, 2000) attributed the Zeebrugge ferry accident to those in charge for making decisions about scheduling and operation, vessel and harbour design as well as cargo and passenger management because they failed to understand the impact of their decisions on the system-level processes and other decision makers. Rasmussen (1997) stated that most decisions are affected by budget pressures, time and short-term contextual incentives which affect behaviour, and they are only locally rational. Although these decisions may seem safe and reasonable within the individual work environment and local pressures, they may interact in unexpected ways to create accidents when considered in relation to the entire system operation (Dulac and Leveson, 2004).

The actual cause of accidents in complex socio-technical systems is poor decision making, which is often due to poor safety culture or excessive performance pressure. As a result, unknown failure modes are usually not the cause of accidents in such systems. Thus, in order to carry out an effective risk analysis, a more inclusive approach is required which encompasses the managerial, technical, organisational, political and social aspects of the system and its environment. Complex systems often become unstable or unsafe when accidents occur in such systems, which may lead to catastrophes whenever there are small deviations (Leveson, 1995; Leveson, 2004; Rasmussen, 1997). Thus, it is important to keep risk at a sustainable level throughout the lifecycle of the system in order to avoid the occurrence of accidents.

2.1.2 Systemic Accident Models

The occurrence of accidents in complex socio-technical systems has been analysed using several systems techniques. Whilst individual-centred approaches were used in the late 1970s to find the causes of accidents; the systems approach to safety became popular in the 1980s as it was observed that disasters were primarily caused by managerial failures (Salmon et al., 2010). Up to now, several risk analysis methods have emerged that dominate system safety literature such as the Risk Management Framework (Rasmussen, 1997), Human Factors Analysis and Classification System (Shappel et al., 2000), Functional Resonance Analysis Method (Hollnagel and Goteman, 2004) and STAMP (Leveson, 2004). These non-linear methods have been very effective in investigating the complex interactions amongst systemic factors that may lead to accidents.

- Risk Management Framework was introduced by Rasmussen wherein he developed multi-levels to explain the complexity of a socio-technical system involved in the control of safety. Rasmussen observed that the dynamic character
of today's society dramatically changed the types of methods needed to understand structure and behaviour of socio-technical systems. Factors such as high degree of coupling of technologies, the volatility of economic and political climates and a fast-moving technological change each contribute to an environment in which pressures and constraints that define work practices are continuously shifting (Vicente and Christoffersen, 2006). Consequently, to fully appreciate why such systems fail or work, modelling tools are required that provide an integrated view of various factors that directly and indirectly input on complex socio-technical systems. Here, the complex socio-technical systems involved in risk management generally consist of five levels including government, regulators and associations, company, management, and staff and work.

- **HFACS** was developed by Shappell and Wiegmann (2000) based on sound human error theory. It recognises all the holes in Reason’s (1990) famous Swiss cheese model. It includes the following four levels; unsafe acts, preconditions for unsafe acts, unsafe supervision and organisational influences. Each tier is broken down into yet lower sub-tiers. At the lowest level are the definitions utilised to categorise and classify the identified causal and contributing factors (Leplat and Rasmussen, 1984). It was primarily developed to investigate accidents/mishaps in the aviation sector; however, it has been adapted to a range of industrial domains, e.g. maritime and railway.

- **FRAM** was introduced by Hollnagel to capture emergent phenomena in complex nonlinear systems (Hollnagel & Goteman, 2004). The concept behind this risk analysis method is that accidents occur in a system due to unforeseen resonances between the system and typical noise in its environment. Because this model focuses on system designs which are resistant to noise and interruptions, it is suitable for accident prevention. In addition, an analysis is performed on the system to detect resonance modes which may be created through actions. Whilst this method does not take the linear-event chain into consideration; it recognises the fact that safety is an emergent system property. Moreover, it places importance on the very real problem of the unexpected effects of disturbances on system operation.

- **STAMP** was introduced by Leveson as a new causality model based on systems control theory. STAMP is not based on the premise of a chain of events, but rather is a constraint-based model that focuses on the important interactions between
system components (Leveson, 2004, 2003). Whilst safety is considered to be a control problem; hazards are referred to as system states which lead to accidental events when merged with certain conditions in the system environment. Hierarchical control structures, which cover the whole socio-technical system, should be employed throughout the lifetime of the system in order to enforce constraints on the system states. In this hierarchical control structure, every level receives feedback from the level below it since all levels impose control on the levels below them. Military defence, aerospace, chemical, energy and transportation systems, as well as health, are some of the fields in which this structure has been used.

All these approaches have limitations. The Risk Management Framework suffers from analysts’ hindsight leading to potential oversimplified causality, and counterfactual reasoning (Dekker, 2002) and its approach can only be used retrospectively. HFACS suffers from forceful ‘fitting’ of data into categories provided by the analyst which makes validation difficult (Salmon et al., 2005). FRAM does not provide the ability or instruction for how to discover resonance modes within the system or address system migration to high-risk operations (Stringfellow, 2010) and heavily relies on expert judgement in assessing system variability. Several authors have employed STAMP in conjunction with SD to investigate the causes of the control failures identified, however, it requires significant accurate data and becomes less useful when used for the analysis of smaller scale accidents as data required is often not readily available (Salmon, 2011). For SD to be used as a step in the STAMP process, several steps have to be implemented as a requisite. Furthermore, a STAMP analysis does not incorporate a timeline as the control structure diagram represents a ‘snapshot’ of the system’s dynamic control relationships and organisational constraints (Johnson and Almeida, 2008). The aforementioned approaches may increase the system and risk understanding, but lack adequately supporting the decision-making on dynamic risk issues (Bjerga et al., 2016) and SD has the potential to addresses these limitations.

2.1.3 System Dynamics
SD is an analytical modelling approach for studying complex feedback systems (Forrester, 1961). The approach has two key aspects, namely qualitative and quantitative. The qualitative aspect, known as Causal-Loop Diagram (CLD), is a diagramming approach that maps the causal relationships between pairs of elements within a system.
and recognises feedback loops revealing types of system behaviour. These loops can either be balancing (goal-seeking) or reinforcing (vicious) cycle and can demonstrate unintended consequences of their interactions as illustrated in Figure 2.1 (dispensing errors in a pharmacy setting). An increase in schedule pressure leads to higher dispensing errors, more rework (re-dispense medications), increased amount of work to be done and back to even higher schedule pressure (reinforcing loop); an increase in schedule pressure, on the other hand, leads to increased productivity (faster work) decreased amount of work to be done and decreased schedule pressure (balancing loop).

![Figure 2.1: Causal-loop Diagram of dispensing errors](image)

The quantitative aspect is based on a stock-and-flow diagram which models the relationships using differential equations. Inflows and outflows alter stocks (the state of the system) and generate information upon which decisions and actions are based on. Figure 2.2 illustrates an example of a stock-and-flow diagram based on Figure 2.1.

![Figure 2.2: Stock and Flow Diagram of dispensed prescriptions](image)

Figure 2.2: Stock and Flow Diagram of dispensed prescriptions: an inflow is incoming prescriptions; an outflow is dispensing rate; a stock is the accumulation of prescriptions that are ready to be dispensed.
Decision makers are usually faced with the challenge of how to avoid using generalised notions about systems so as to utilise tools and processes that will enable them to have a better understanding of the complexity. This challenge can be addressed by using SD as it helps to enhance learning in complex systems (Leopold, 2016). However, learning about complex dynamic systems requires more than just creating mathematical models using technical tools. SD has a lot of advantages one of which includes providing a strong and transparent model structure which promotes collaboration between stakeholders and SD modellers in the case of participatory or group modelling (Anderson & Johnson, 1997).

Regarding safety, SD has the potential to provide stakeholders with the complex safety dynamics understanding of various contributing factors to errors and accidents and identify and test effective safety measures as described below. SD can address the limitations that other approaches have. The Risk Management Framework’s limitation of retrospective usage is addressed by SD as it can be applied both retrospectively to accident analysis and predictively to risk assessment. SD can address HFACS' limitation of forceful fitting of data into fixed categories by giving the modeller the unlimited restriction to accurately define categories. SD can address FRAM's reliance on expert judgement by presenting complex models in easy to understand visual context. STAMP’s limitation of requiring data at the multiple levels can be addressed by SD’s qualitative aspect which provides insight into the problem's structure in a selected boundary without requiring much data at the whole system levels; successful quantified models in SD can be built based on the availability of limited data (Ortiz et al., 2008). Finally, the uncertainty modelling which cannot be addressed by the aforementioned approaches can be addressed by SD’s traditional process such as sensitivity analysis and testing and by means of qualitative mode of behaviour interpretations (Pruyt, 2014; Walker et al., 2014).

In order to examine how has SD modelling approach been utilised to improve system safety in complex systems, the relevant literature was systematically searched, reviewed and analysed through the method described in the next section.

2.1.4 Methods
A systematic approach was employed to identify literature based on SD and safety. There were no time limits placed on the search, as there is no previous systematic review in this area and the scope of available literature was unknown. The accessed databases were PubMed, Web of Science, Science Direct and Google Scholar databases. The search words used were: system dynamics, causal-loop diagrams, stock and flow, all in
combination with safety, safety management, accident, errors. The keywords were used in Boolean combination, joined by AND. Papers eligible for inclusion were those that described applications of SD modelling to support safety. The literature was further supplemented by relevant publications in the reference lists of the publications collected. The title and abstract of each study were read, and the full-text article obtained if the researchers found that the study applied to the research question, based on previous literature.

We used the most general definition of safety as being free from something undesired, unwanted or unacceptable (ISO/IEC, 2014) although it carries a plethora of definitions. Empirical research articles, review articles, academic book chapters and conference papers addressing safety improvement using SD approach, were selected for the study. We have also included papers that significantly employed SD as part of hybrid approaches with some other methods.

Both qualitative and quantitative SD approaches were included. The literature was analysed using thematic analysis (Braun and Clake, 2006; Howitt and Cramer, 2008), which allows for the identification and exploration of major themes across the literature in a systematic, theoretically flexible manner. The initial stage of analysis involved becoming familiar with the literature by simply reading the articles. A total of 63 articles were finally identified that applied SD modelling to safety.

In order to examine what safety issues have been addressed by SD in the literature, the HFACS framework was chosen and used to identify and classify the SD applications. The HFACS framework comes equipped with its taxonomy to classify and analyses human error and accident causations. It has been validated through a number of studies across different industries such as military (Jennings, 2008; O’Connor et al., 2010; Shappell and Wiegmann, 2001), aviation (Reinach and Viale, 2006; Shappell and Wiegmann, 2001), rail (Baysari et al., 2008; Reinach and Viale, 2006), maritime shipping (Celik and Cebi, 2009), mining (Patterson and Shappell, 2010), Petroleum/Gas (Aas, 2008), construction (Garrett and Teizer, 2009) and healthcare (ElBardissi et al., 2007). The original HFACS framework describes 19 causal categories within Reason's four levels of human failure (Shappel et al., 2000), but it lacks a crucial tier that is equivalent to the government tier in Rasmussen’s (1997) six-levels of risk management framework. Whilst useful as originally designed for aviation, the four levels lacked an essential level to encompass a number of industries. This study introduced a new tier, therefore, changing the original HFACS framework into a modified HFACS framework which is entitled HFACS-EE.
(External Extension). As presented in Table 2.5, changes include adding a layer of Rasmussen’s hierarchical taxonomy to the existing HFACS with an addition of a new tier called External Factors. The additional tier allows us to categorise the SD safety applications in their respective safety category. The thematic content of each paper is classified according to its primary foci (highlighted in dark grey) and its secondary foci (highlighted in light grey). Primary foci are identified as the strong themes of the paper, whilst secondary foci are identified as visible, but not central themes in the papers.

2.1.5 Results

Figure 2.3 shows the number of relevant articles published in each year from 1984 till 2016. It shows that the application of SD to safety started in the academic field in the early 1980s. Since then, a stagnation of no contribution has characterised its trend until 2002 when the number of published articles using SD for safety research increased to around three articles per year. The reasons for the early gap can be explained by the re-emergence of the sociotechnical approach based on complex non-linear models in the 1980s and beyond (Hettinger et al., 2015). In 2000, SD was recognised and proven to be a potent method to gain valuable insights into events of dynamic complexity and policy resistance (Swanson, 2002). In 2015 and 2016, safety applications using SD increased dramatically, generating significant interest.

Figure 2.3: Publication trend on SD application to system safety improvement (from 1984 till 2016)

The next four tables (Table 1-4) summarise SD applications by sector, model type, study type and HFACS framework. Table 2.1 illustrates that the most applied sector is healthcare (25%), then construction (13%) followed equally (10%) by three sectors (disaster, aviation, and traffic).
Table 2.1 SD applications to safety by sector

<table>
<thead>
<tr>
<th>Sector</th>
<th>Healthcare</th>
<th>Construction</th>
<th>Disaster</th>
<th>Aviation</th>
<th>Traffic</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage</td>
<td>25%</td>
<td>13%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>32%</td>
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</table>

Table 2.2 shows that the majority of the applications (78%) used stock flow diagrams, which investigate system behaviours through quantitative models based on real-world data. On the other hand, there were still 22% of the applications that used only causal-loop diagrams (qualitative model).

Table 2.2 SD applications to safety by model type

<table>
<thead>
<tr>
<th>Model type</th>
<th>Quantitative model</th>
<th>Both models</th>
<th>Qualitative model</th>
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</thead>
<tbody>
<tr>
<td>Percentage</td>
<td>37%</td>
<td>41%</td>
<td>22%</td>
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</table>

Table 2.3 shows that there are three main perspectives (i.e. theory development, problem-solving and case study) that altogether represent 90% of the identified papers. The remaining part is made up of methodological development. To contextually define the types of studies, a case study is an empirical inquiry using SD approach that investigates a contemporary phenomenon within its real-life context. Theory development is the application of SD approach for a given undertaken issue, analyse them technically with respect to current theory in order to gain carefully considered conclusions. Policy analysis and problem-solving is the use of SD approach using inquiry and arguments to produce and transform policy-relevant information that may be utilised in organisational settings to resolve policy problems. Methodological development is the application of SD is the use of SD approach using inquiry and arguments to produce and transform policy-relevant information that may be utilised in organisational settings to resolve policy problems. Methodological development is the application of SD modelling approach in areas not utilised before, leading to a significant contribution the development of SD methodology.

Table 2.3 SD applications to safety by study type

<table>
<thead>
<tr>
<th>Study type</th>
<th>Case Study</th>
<th>Policy analysis/problem solving</th>
<th>Theory development</th>
<th>Methodological development</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage</td>
<td>43%</td>
<td>33%</td>
<td>14%</td>
<td>10%</td>
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</table>

Table 2.4 shows the categorisation results based on the extended HFACS taxonomy framework. Around 46% of SD applications focused on issues at the level of organisational influences, in particular, covering the areas concerning resource management, organisational climate and operational process. The second most identified articles were geared towards issues at the work level (29%) whilst issues at management level were the third highest (11%). External factors were the second lowest (9%) which
is relatively low given that exogenous factors influence safety all the time. Unsafe acts were the lowest (5%) revealing a gap in trend as SD is mostly utilised for organisational interventions in order to improve the efficacy of enacted policies (Snabe, 2007).

Table 2.4 SD applications to safety by HFACS framework

<table>
<thead>
<tr>
<th>Taxonomy</th>
<th>Organisational Influences</th>
<th>Preconditions for Unsafe Acts</th>
<th>Unsafe Supervisions</th>
<th>External Factors</th>
<th>Unsafe Acts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage</td>
<td>46%</td>
<td>29%</td>
<td>11%</td>
<td>9%</td>
<td>5%</td>
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</table>

Table 2.5 presents the overall summary of the detailed HFACS framework-based categorisation of the sixty-three articles identified. It shows what each article has addressed aspects of the safety (based on the extended HFACS framework). More detailed analysis for each category are presented in the following sections (2.6.1 – 2.6.5).
Table 2.5 SD applications to safety by the extended HFACS framework – see Appendix A for detail description of the framework

<table>
<thead>
<tr>
<th>Papers</th>
<th>External Factors</th>
<th>Organisational Influences</th>
<th>Unsafe Supervisions</th>
<th>Precondition for Unsafe Acts</th>
<th>Unsafe Acts</th>
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</thead>
<tbody>
<tr>
<td>Homer, J.B., 1984</td>
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<td>Anderson &amp; Anderson, 1994</td>
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<td>Lane, D.C., et al., 2000</td>
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<td>Berg, N., 2001</td>
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<td>Rudolph, J.W. &amp; Reesew, N.P., 2002</td>
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<td>Coole, D.L., 2003</td>
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<td>Johnsson, A., et al., 2003</td>
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<td>Bie, B.Y.P.E., 2004</td>
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<td>Lehman, V. et al., 2004</td>
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<td>Taylor, K. &amp; Dengerfield, B., 2004</td>
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<td>Teng. et al., 2004</td>
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<td>McConnel, G., 2005</td>
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<td>Samnowich, S.P. &amp; Ahmed, S., 2005</td>
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<td>Maryani, A. et al., 2015</td>
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<td>McClune, R. et al., 2015</td>
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<td>Miller, M. &amp; Van Oorschot, K., 2016</td>
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<td>De, S. 2016</td>
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<td>Farnham, D. et al., 2016</td>
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<td>Wang, F. et al., 2016</td>
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<td>Tan, W. et al., 2016</td>
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</tbody>
</table>
2.1.5.1 External Factors

Six SD applications have been identified and constructed that have the potential to impact safety policy from external factors (see Table 2.6). They include regulatory, social, political, environmental, and economic influences. The first five papers in Table 2.6 look at external factors resulting from economic pressure, environmental concerns and legal pressure whilst the last paper looks at regulatory factors. A large portion of the cited applications (66%) applied conceptual modelling (causal-loop diagrams) to investigate ways to improve public health and safety.

Looking at the regulatory influences, a combination of STAMP and SD models was applied by Leveson et al. (2012) to improve pharmaceutical safety by enhancing the safety of current drugs as well as encouraging the development of new drugs. They combined several SD conceptual models to investigate the potential effectiveness and unintended side effects of FDA's post-approval safety policies. Authors identified additional safety controls that could be incorporated in the FDA legislation to improve public safety. Wang et al. (2013) address the rise in demand for PTSD services in military veterans by evaluating the screening and referral processes of the American Veterans Health Administration. Using a conceptual diagram, they include organisational factors and individual factors from pre-enlistment to post-discharge in their analysis of PTSD prevention and treatment. Ellis (2004) developed an SD conceptual model of the Colombian civil war based on the interactions amongst criminal organisations, the guerrilla organisations, the economic base of the Colombian society and its government. From the model analysis, it was observed that the large number of "reinforcing feedback effects" in the system was capable of instigating violence and social chaos across the region, which could hamper the governments’ ability to react faster to narco-terrorism and other regional phenomena than traditional analysis.

Table 2.6 Literature Review – External Factors

<table>
<thead>
<tr>
<th>Researchers</th>
<th>Year</th>
<th>Type of study</th>
<th>System Dynamics Tool</th>
<th>Industry</th>
<th>Purpose of SD Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ellis</td>
<td>2004</td>
<td>Case study</td>
<td>Causal-loop diagram</td>
<td>Drug and Terrorism (Public safety)</td>
<td>To present a systemic analysis of the geopolitical implication of narcoterrorism dynamics in Colombia and the Andean Ridge region and how this can affect public safety in the wider region.</td>
</tr>
<tr>
<td>Tengs et al.</td>
<td>2004</td>
<td>Theory Development</td>
<td>Stock-and-flow diagram</td>
<td>Healthcare (Public Health Safety)</td>
<td>To analyse gains or losses within public health from any change in the hazards or patterns of cigarette use.</td>
</tr>
</tbody>
</table>
2.1.5.2 Organisational Influences

Twenty-nine SD applications have been identified and developed that have the potential to impact safety policy at the organisation level. They include organisational climate, resource management and operational process.

Organisational Climate

Nineteen papers utilised SD applications that address the organisational climate which looks at the organisational culture, policies and structure (see Table 2.7). A vast majority of the papers utilised both a conceptual model and a simulation model to promote effective group learning. This is shown in Cooke et al. (2006) who modelled the organisational memory of lessons learned from past accidents. In order to combat organisational complacency in safety and promote effective learning, the Perrow’s Normal Accident Theory (Perrow, 1984) and High-Reliability Theory (Rochlin, 2007) were combined by the researchers to model an organisational response system in which safety-related or past events were used as the basis for future planning. In their models, safety-related variables such as safety commitment, unsafe acts and production pressure were used to illustrate a bigger picture for future learning. Similarly, Xian et al. (2009) and Li et al. (2009) analysed fatal gas accidents in coal mines in China. Their simulation results revealed that time delay and feedback should be part of China’s coal mine safety organisational decision-making. Goh et al. (2012b) study revealed that risk perception could deteriorate when management had a strong production focus. Also, by using a
group model building approach, Goh et al. (2012c) attempt to understand the reasons why even if the organisation had invested a mass of resources into safety, the injury rate could not be decreased. McClure et al. (McClure et al., 2015) developed an SD safety model that reveals the unintended consequences as well as opposing of health policies and interventions. By explicitly including both positive (increased active transport) and negative (increased transport injuries and fatalities) potential effects of land-use and transport policies, the authors were able to assess the overall benefits of different policies for population health. Guo et al. (2015) created an SD model and applied system archetypes to construction of safety management. They identified eight archetypes, ranging from “workers’ conflict goals” to “blame on workers” or “reactive and proactive learning”.

Table 2.7 Literature Review – Organisational Climate

<table>
<thead>
<tr>
<th>Researchers</th>
<th>Year</th>
<th>Type of study</th>
<th>System Dynamics Tool</th>
<th>Industry</th>
<th>Purpose of SD Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rudolph and Repenning</td>
<td>2002</td>
<td>Theory development</td>
<td>Stock-and-Flow diagram</td>
<td>Aviation Safety</td>
<td>To highlights how catastrophic outcomes can be the result of an overaccumulation of mundane events.</td>
</tr>
<tr>
<td>Taylor and Dangerfield</td>
<td>2004</td>
<td>Case study</td>
<td>Causal-loop and Stock-and-Flow diagrams</td>
<td>Healthcare (Patient Safety)</td>
<td>To analyse why managerial interventions in cardiac catheterisation services in the UK fail.</td>
</tr>
<tr>
<td>Cooke et al.</td>
<td>2006</td>
<td>Theory development</td>
<td>Causal-loop and Stock-and-Flow diagrams</td>
<td>Disasters (Industrial Safety)</td>
<td>To explore dynamics of the incident learning system, thereby motivating managers to introduce incident learning systems as a solution to move safety performance from normal accidents to high reliability.</td>
</tr>
<tr>
<td>Ulrey and Shakarian</td>
<td>2008</td>
<td>Case study</td>
<td>Stock-and-Flow diagram</td>
<td>Aviation Safety</td>
<td>To assess the impact of novel technology on safety and capacity of operations showing that reductions in either reporting interval length and/or control loop delay time resulted in increased safety and throughput levels.</td>
</tr>
<tr>
<td>Topošek and Lipičnik,</td>
<td>2009</td>
<td>Policy analysis or problem-solving</td>
<td>Causal-loop and Stock-and-Flow diagrams</td>
<td>Traffic Safety</td>
<td>To reduce the number of motorway accidents due to wrong-way driving.</td>
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<tr>
<td>Researchers</td>
<td>Year</td>
<td>Type of study</td>
<td>System Dynamics Tool</td>
<td>Industry</td>
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<tr>
<td>Mohamed and Chinda</td>
<td>2011</td>
<td>Theory development</td>
<td>Causal-loop and Stock-and-Flow diagrams</td>
<td>Construction Safety</td>
<td>To examine the relations amongst enables of construction safety culture and look at the potential effect of each enable on the organisational safety goals over a period of time.</td>
</tr>
<tr>
<td>Goh et al.</td>
<td>2012a</td>
<td>Methodological development</td>
<td>Causal-loop diagram</td>
<td>Coal Mine Safety</td>
<td>To look at the dynamic relations between management of protection and production which has the potential effect to turn into an organisational accident.</td>
</tr>
<tr>
<td>Goh et al.</td>
<td>2012b</td>
<td>Case study</td>
<td>Causal-loop diagram</td>
<td>Coal Mine Safety</td>
<td>To analyse accident prevention to assist in better understanding the causal influences of OHS performance.</td>
</tr>
<tr>
<td>Boukiz et al.</td>
<td>2013</td>
<td>Theory development</td>
<td>Causal-loop and Stock-and-Flow diagrams</td>
<td>Multi-Industry (Industrial Safety)</td>
<td>To assess the safety of a storage unit in Morocco by modelling various scenarios to improve the safety of the industrial system and implement managerial tools involving organisational, technical and human factors.</td>
</tr>
<tr>
<td>Goh et al.</td>
<td>2012c</td>
<td>Policy analysis or problem-solving</td>
<td>Stock-and-Flow diagram</td>
<td>Traffic Safety</td>
<td>To provides a range of experimental scenarios that will help policy and decision-makers develop appropriate and suitable traffic safety policies.</td>
</tr>
<tr>
<td>Orjuela et al.</td>
<td>2015</td>
<td>Case study</td>
<td>Causal-loop and Stock-and-Flow diagrams</td>
<td>Multi-Industry (Industrial Safety)</td>
<td>To study the dynamic behaviour between transport infrastructure and the food supply chain in the city of Bogota.</td>
</tr>
<tr>
<td>McClure et al.</td>
<td>2015</td>
<td>Policy analysis or problem-solving</td>
<td>Stock-and-Flow diagram</td>
<td>Healthcare (Public Health Safety)</td>
<td>To illustrate different relationships amongst land use, transport, population health, and economic development in order to contrast the effect of different baseline scenarios and use – transport policies, on the motor vehicle crash deaths and disability-adjusted life years lost.</td>
</tr>
<tr>
<td>Guo et al.</td>
<td>2015</td>
<td>Theory development</td>
<td>Causal-loop and Stock-and-Flow diagrams</td>
<td>Construction Safety</td>
<td>To develop eight construction safety archetypes and apply it to construction of safety management.</td>
</tr>
<tr>
<td>Wang et al.</td>
<td>2016</td>
<td>Case study</td>
<td>Causal-loop and Stock-and-Flow diagrams</td>
<td>Construction Safety</td>
<td>To explore the mechanism of risk migration that resulted from the relations between a contractor’s technical and organisational systems.</td>
</tr>
<tr>
<td>Lu et al.</td>
<td>2016</td>
<td>Policy analysis/ problem solving</td>
<td>Causal-loop and Stock-and-Flow diagrams</td>
<td>Aviation Safety</td>
<td>To reveal the organisational mechanism involving complex dynamic interactions of accident causal factors (technical, organisational and human) within the area of aviation engineering.</td>
</tr>
<tr>
<td>Garbolino et al.</td>
<td>2016</td>
<td>Case Study</td>
<td>Causal-loop and Stock-and-Flow diagrams</td>
<td>Multi-Industry (Industrial Safety)</td>
<td>To propose a dynamic risk analysis and scenarios analysis method using both SD and risk analysis.</td>
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Resource Management

Five papers implemented SD applications that look at resource management which encompasses the realm of organisational-level decision-making vis-à-vis the sharing and maintenance of organisational assets (see Table 2.8). Practically all the studies employed the quantitative aspect of the SD approach. Anderson et al. (1994)’s application of the SD quantitative aspect proved to be useful in evaluating various treatment programs designed to prevent mother-to-infant transmission of the HIV. It provided stakeholders with the ability to examine the effects of screening, treatment, transmission and seroprevalence rates amongst pregnant women on the costs and safety benefits of various prevention programs. It demonstrated that regimens that prevent or reduce perinatal transmission of HIV cannot be implemented because of cost issues.

Table 2.8 Literature Review – Resource Management

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<tr>
<th>Researchers</th>
<th>Year</th>
<th>Type of study</th>
<th>System Dynamics Tool</th>
<th>Industry</th>
<th>Purpose of SD Application</th>
</tr>
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<tbody>
<tr>
<td>Xiao-yan and Jian-hua</td>
<td>2010</td>
<td>Case study</td>
<td>Stock-and-Flow diagram</td>
<td>Healthcare (Patient Safety)</td>
<td>To model a hospital emergency service supply chain by highlighting the risk of illness’ aggravation patients face with no timely treatment.</td>
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<tr>
<td>Maryani et al.</td>
<td>2015</td>
<td>Policy analysis or problem-solving</td>
<td>Causal-loop and Stock-and-Flow diagrams</td>
<td>Construction Safety</td>
<td>To analyse occupational accidents in construction projects and suggest improvements in the supply chain to enhance the quality of workers.</td>
</tr>
<tr>
<td>Chia et al.</td>
<td>2015</td>
<td>Policy analysis or problem-solving</td>
<td>Stock-and-Flow diagram</td>
<td>Nuclear Safety</td>
<td>To examine the complex factors surrounding nuclear energy development in Singapore by evaluating four critical aspects, namely political, social, economic and environmental aspects in various scenarios.</td>
</tr>
<tr>
<td>Turner et al.</td>
<td>2016</td>
<td>Case study</td>
<td>Causal-loop and Stock-and-Flow diagrams</td>
<td>Disaster (Flood Safety)</td>
<td>To explore the potential trade-offs between the use of existing and new infrastructure; water and flood risk security and the accompanying cost implications.</td>
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</table>

Organisational Process

Five papers looked at the organisational process which affects the organisational decisions and rules that govern the everyday activities within the organisation (see Table 2.9). One paper applied the qualitative SD approach only, and the other four papers applied the quantitative SD approach or both. In the first two papers, the SD proved to be useful for healthcare professionals to make decisions on health care priorities based on system analysis. Lane et al. (1998) developed an SD quantitative model that shows the
relation between long waiting times in A&E and bed closures. The key finding of this model is that the major impact of bed shortages is not on emergency admissions, but was felt first on elective admissions so that using A&E waiting times to measure the effect of bed shortages is misleading. Gonzalez et al. (2016) discussed how a set of vicious feedback loops caused by following standard organisational procedures that do not fit the disaster situation, initially increases errors in response. Eventually, learning and sense-making in an improvisation/experimentation process lead to new emergent dynamics whereby the loops act virtuously. Lane at al. (2000) and Gonzalez et al. (2016) findings stress that more emphasis needs to be placed on system analysis and understanding the behavioural structure of key elements within the system that might not seem related at first glance.

**Table 2.9 Literature Review – Organisational Process**

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<tr>
<th>Researchers</th>
<th>Year</th>
<th>Type of study</th>
<th>System Dynamics Tool</th>
<th>Industry</th>
<th>Purpose of SD Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lane et al.</td>
<td>2000</td>
<td>Policy analysis or problem-solver</td>
<td>Causal-loop and Stock-and-Flow diagrams</td>
<td>Healthcare (Patient Safety)</td>
<td>To showcase the interaction of demand pattern, A&amp;E resource deployment, and other hospital processes and bed numbers, allowing decision makers to base their decisions on systemic analysis to improve healthcare quality and safety.</td>
</tr>
<tr>
<td>Lattimer et al.</td>
<td>2004</td>
<td>Case study</td>
<td>Causal-loop and Stock-and-Flow diagrams</td>
<td>Healthcare (Patient Safety)</td>
<td>To investigate the scenarios for changing in terms of patient flows and bottlenecks and ways to intervene to ameliorate the worst-case scenarios.</td>
</tr>
<tr>
<td>Mohagheghi et al.</td>
<td>2009</td>
<td>Methodologic al development</td>
<td>Stock-and-Flow diagram</td>
<td>Aviation Safety</td>
<td>To investigate safety within the aviation by looking at the error probability of technicians over a period of 15 years as well as predicting management’s commitment to safety.</td>
</tr>
<tr>
<td>Du and Zhang</td>
<td>2015</td>
<td>Policy analysis or problem-solver</td>
<td>Causal-loop and Stock-and-Flow diagrams</td>
<td>Aviation Safety</td>
<td>To demonstrate the interactions between flight safety and safety investment so that the optimal safety investment program can be determined in order improve level of flight safety.</td>
</tr>
<tr>
<td>Gonzalez et al.</td>
<td>2016</td>
<td>Policy analysis or problem-solver</td>
<td>Causal-loop diagram</td>
<td>Disaster (Landslide Safety)</td>
<td>To present large-scale disaster response of dissimilar types and what type of controls, such as training and policies, are available to reduce the vicious loops and speed the transition from errors to successful innovation.</td>
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### 2.1.5.3 Unsafe Supervisions

Seven articles identified have applied SD approach to the safety policy at the management level.
Inadequate supervisions

Five papers employed SD methodology that looks at *inadequate supervisions* in safety (see Table 2.10). One paper applied the qualitative SD approach only, and the other four papers applied the quantitative approach or both. A significant portion of the papers used case studies involving major accidents and examined how the SD approach can provide additional insight into the causes of these accidents. Salge et al. (2006) developed two separate SD models to illustrate that the Chernobyl accident was caused by a combination of human failure in the design of the reactor and poor decision-making. They argued that people could be blamed for those who design risk generating structures and those who react to failures in ways that increase the problem. They concluded that individuals who are aware of high-risk situations and wish to repair them would quite often behave in ways that will worsen the situation. Cooke (2003) examines the condition that led to the fatal explosion at the Westray mine in Canada using the SD approach. By providing valuable insights into the behaviour of the Westray mine disaster, Cooke argues that commitment to safety cannot be affected by production pressure. Consequently, he concludes that reduction in management commitment to safety can trigger a vicious cycle of frequent incidents, increase in production losses and pressure, and a further decrease in management commitment to safety.

Minami & Madnick (2009) used an SD approach to look beyond the human error in combat vehicle accidents and studied the organisational problems that were regarded as the real causes. They argued that with the short period efforts aiming to impose safety behaviours of combat soldiers will, in the long run, boost tiredness, fatigue and complacency. This, in turn, would destroy the primary safety policy and consequently recommended that understanding the dynamic effect various delays would yield has the greatest potential for improving safety.

Table 2.10 Literature Review – Inadequate Supervision

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<tr>
<th>Researchers</th>
<th>Year</th>
<th>Type of study</th>
<th>System Dynamics Tool</th>
<th>Industry</th>
<th>Purpose of SD Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooke</td>
<td>2003</td>
<td>Case study</td>
<td>Causal-loop and Stock-and-Flow diagrams</td>
<td>Coal Mine Safety</td>
<td>To examine the contributing factors of the Westray mine disaster, including interactions that could have led to the conditions that triggered the fatal explosion at the mine.</td>
</tr>
<tr>
<td>Simonovic and Ahmad</td>
<td>2005</td>
<td>Case study</td>
<td>Causal-loop and Stock-and-Flow diagrams</td>
<td>Disaster (Flood Safety)</td>
<td>To assess the effectiveness of different flood evacuation policies thereby contributing to a higher quality of decisions and a higher level of emergency preparedness.</td>
</tr>
</tbody>
</table>
Planned inappropriate operations

Two papers looked at planned inappropriate operations of which supervision fails to adequately assess the hazards (see Table 2.11). Both papers developed qualitative models and converted it to quantitative simulation models in order to understand the factors affecting delay within the system. Min et al. (2011) assessed the behaviour of disaster-relief supply chain under adverse conditions. Akkermans and Van Oorschot (2016) modelled a major new aircraft development based on inputs from the industry. The results suggested that major improvements occur when more concurrency is allowed because, in projects of such complexity, concurrent team learning is crucial.

Table 2.11 Literature Review – Planned Inappropriate Operations

<table>
<thead>
<tr>
<th>Researchers</th>
<th>Year</th>
<th>Type of study</th>
<th>System Dynamics Tool</th>
<th>Industry</th>
<th>Purpose of SD Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salge and Milling</td>
<td>2006</td>
<td>Case study</td>
<td>Causal-loop and Stock-and-Flow diagrams</td>
<td>Nuclear Safety</td>
<td>To analyse the accident at the Chernobyl power plant by looking at the human failures in two stages: planning and design of the socio-technical-environment and online operations.</td>
</tr>
<tr>
<td>Minami &amp; Madnick</td>
<td>2009</td>
<td>Case study</td>
<td>Causal-loop diagram</td>
<td>Military Safety</td>
<td>To study the upper-level organisational processes and complications that constitute the root causes of accidents instead of focusing on symptoms and events of accidents which normally specify human error.</td>
</tr>
<tr>
<td>Wu and Xie</td>
<td>2012</td>
<td>Theory development</td>
<td>Stock-and-Flow diagram</td>
<td>Railway Safety</td>
<td>To enhance emergency safety decision-making efficiency in railway management.</td>
</tr>
</tbody>
</table>
quality and safety outcomes in an emergency department to assess the efficiency of healthcare systems. Similarly, Rong et al. (2016) modelled the interrelationships amongst the factors in missile operations which may contribute to accidents. The long-term behaviour of a socio-technical system with several human operations under the given conditions is clearly reflected in this temporal uncertainty analysis, which enables people to examine the possible trade-offs between short-term profits and sustainable long-term improvement. Woo (2015) was able to characterise power uprates in nuclear power plants and found that the cost of nuclear power plants can be minimised through risk assessment which can also help to avert unexpected disasters and increase their safety level.

Table 2.12 Literature Review – Physical and Technical Environment Factors

<table>
<thead>
<tr>
<th>Researchers</th>
<th>Year</th>
<th>Type of study</th>
<th>System Dynamics Tool</th>
<th>Industry</th>
<th>Purpose of SD Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mehmood et al.</td>
<td>2003</td>
<td>Policy analysis or problem-solving</td>
<td>Stock-and-Flow diagram</td>
<td>Traffic Safety</td>
<td>To address the shortcomings of previous car-following models and how that contributes to traffic safety.</td>
</tr>
<tr>
<td>Zhang et al.</td>
<td>2008</td>
<td>Case study</td>
<td>Stock-and-Flow diagram</td>
<td>Traffic Safety</td>
<td>To elevate safety level of traffic accident scene and which factors predominately influence it.</td>
</tr>
<tr>
<td>Woo</td>
<td>2015</td>
<td>Policy analysis or problem-solving</td>
<td>Causal-loop and Stock-and-Flow diagrams</td>
<td>Nuclear Safety</td>
<td>To analyse the economic and safety properties of power increases in nuclear power plants.</td>
</tr>
<tr>
<td>Chong et al.</td>
<td>2015</td>
<td>Case study</td>
<td>Causal-loop and Stock-and-Flow diagrams</td>
<td>Healthcare (Patient Safety)</td>
<td>To study the trade-offs of various quality and safety results in an emergency department in order to assess the efficiency of healthcare systems.</td>
</tr>
<tr>
<td>Rong et al.</td>
<td>2016</td>
<td>Case study</td>
<td>Causal-loop and Stock-and-Flow diagrams</td>
<td>Nuclear Safety</td>
<td>To analyse the Minuteman III missile accident in 2008 that looks at the interrelationships amongst technical and organisational aspects.</td>
</tr>
<tr>
<td>Yan et al.</td>
<td>2016</td>
<td>Case study</td>
<td>Causal-loop and Stock-and-Flow diagrams</td>
<td>Railway Safety</td>
<td>To analyse the typical cases of subway fires over past 20 years, highlighting the causes of the fire accidents and extracting influencing factors such as equipment, human, environment and emergency management.</td>
</tr>
</tbody>
</table>

**Condition of operators**

Nine papers employed SD methodology to address the conditions of individuals that can have the adverse influence on their job performance (see Table 2.13). Majority of the papers addressed safety issues within the healthcare. Homer (1984) applied the qualitative SD to explore the dynamics of "worker burnout" and demonstrate the potential
effectiveness of stabilising techniques that can diminish work-related stress or enhance relaxation which in turn increases overall productivity. The author showed that the individual can effectively manage the self-inflicted nature of burnout. Similarly, Oliva (2001) modelled responses to work-related pressure in service industries and simulated the impacts of increased level of working, cutting corners, lowering standards and expectations which delay the resourcing of additionally required capacity. He illustrated how this is particularly challenging in healthcare, where high professionalism and lengthy training times make the situation considerably worse in comparison to other industries. McDonnell (2005) modelled interactions amongst the key determinants of medication errors, in particular, the complex interactions of patients and staff, information, medications, work practices and the infrastructure and policies within a hospital environment. Rashwan and Arisha (2015) examined a clinical unit in a large hospital in Ireland in order to simulate the impact of nurses’ behaviours at their burnout level on unit performance measures. Working with the nurses and the management team of the unit, the authors developed an SD model to encompass the factors that may contribute to the burnout phenomenon and also the relationship between these factors and the performance measures.

Table 2.13 Literature Review – Condition of Operators

<table>
<thead>
<tr>
<th>Researchers</th>
<th>Year</th>
<th>Type of study</th>
<th>System Dynamics Tool</th>
<th>Industry</th>
<th>Purpose of SD Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homer</td>
<td>1984</td>
<td>Policy analysis or problem-solving</td>
<td>Causal-loop diagram</td>
<td>Healthcare (Patient Safety)</td>
<td>To explore the dynamics of worker burnout.</td>
</tr>
<tr>
<td>Oliva</td>
<td>2001</td>
<td>Policy analysis or problem-solving</td>
<td>Stock-and-Flow diagram</td>
<td>Multi-Industry (Industrial Safety)</td>
<td>To highlight the trade-offs in responses to work pressure in the service industry and how that affects stress and burnout.</td>
</tr>
<tr>
<td>McDonnell</td>
<td>2005</td>
<td>Policy analysis or problem-solving</td>
<td>Stock-and-Flow diagram</td>
<td>Healthcare (Patient Safety)</td>
<td>To represents the interactions amongst the key determinants such as everyday clinical work amongst patients and staff that deliver medications safely.</td>
</tr>
<tr>
<td>Morris et al.</td>
<td>2010</td>
<td>Theory development</td>
<td>Causal-loop diagram</td>
<td>Healthcare (Patient Safety)</td>
<td>To measure vague human factors variables such as stress in a way that is understandable, computable, robust and capable of being validated.</td>
</tr>
<tr>
<td>Researchers</td>
<td>Year</td>
<td>Type of study</td>
<td>System Dynamics Tool</td>
<td>Industry</td>
<td>Purpose of SD Application</td>
</tr>
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<td>----------------------</td>
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<td>-----------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Guo et al.</td>
<td>2013</td>
<td>Methodological development</td>
<td>Causal-loop diagram</td>
<td>Healthcare (Patient Safety)</td>
<td>To identify the relationship between schedule and quality performances and the components related to a safety program and how that impacts safety management in practice.</td>
</tr>
<tr>
<td>Han et al.</td>
<td>2014</td>
<td>Case study</td>
<td>Causal-loop diagram</td>
<td>Construction Safety</td>
<td>To look at the causation of unsafe behaviours in Construction.</td>
</tr>
<tr>
<td>Shin et al.</td>
<td>2014</td>
<td>Theory development</td>
<td>Stock-and-Flow diagram</td>
<td>Construction Safety</td>
<td>To quantify fuzzy human factors variables such as stress in a way that is robust, computable, understandable, and capable of being validated.</td>
</tr>
<tr>
<td>Rashwan and Arisha</td>
<td>2015</td>
<td>Policy analysis or problem-solving</td>
<td>Stock-and-Flow diagram</td>
<td>Healthcare (Patient Safety)</td>
<td>To identify factors affecting nurses’ behaviour when they experience burnout level and its impact on patients’ experience time.</td>
</tr>
<tr>
<td>Da</td>
<td>2016</td>
<td>Policy analysis/ problem solving</td>
<td>Causal-loop and Stock-and-Flow diagrams</td>
<td>Railway Safety</td>
<td>To examine the influence of railway workers’ mental processes and on safety attitudes and safe behaviour.</td>
</tr>
</tbody>
</table>

**Personal factors**

Two papers developed SD models that addressed the *personal factors within the work environment* (see *Error! Reference source not found.*). Wei et al. (2012) modelled the problems of human errors in the aircraft cockpit and discovered that a systems modelling approach can make mid or long-term prediction of the prevention level of human errors in civil aviation incidents. Carhart (2010; 2009) adopted SD group model building using Causal-loop Diagrams (CLDs) as a tool for event investigation in the nuclear industry and demonstrated that CLDs can provide additional insights into the development of an event. Both papers showed the potential of the SD approach for proactively predicting system behaviour/failure.
Chapter 2: Literature Review

Table 2.14 Literature Review – Personal Factors

<table>
<thead>
<tr>
<th>Researchers</th>
<th>Year</th>
<th>Type of study</th>
<th>System Dynamics Tool</th>
<th>Industry</th>
<th>Purpose of SD Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wei et al.</td>
<td>2012</td>
<td>Methodological development</td>
<td>Stock-and-Flow diagram</td>
<td>Aviation Safety</td>
<td>To simulate human error analysis of human cockpit errors and how it can be reduced.</td>
</tr>
</tbody>
</table>

2.1.5.5 Unsafe Acts

Three SD applications have been identified that look at the unsafe acts (operator level) including decision, skill-based and perceptual human errors and violations (see Table 2.15). Jiang et al. (2015) and Nakumura et al. (2015) constructed quantitative simulation models that look at unsafe behaviours of marine engineers and construction workers respectively. Jiang et al. (2015) built upon Shin’s (2014) previous work by introducing an SD model for the causation of unsafe behaviours based on a holistic cognitive analysis of why unsafe behaviours happen. Through the simulation results, they reveal how construction workers can be better understood and how unsafe behaviours can be fundamentally prevented. Similarly, Nakumura et al. (2015) constructed a quantitative simulation model to comprehend how the behaviour pattern of engineers can contribute to marine accidents.

Table 2.15 Literature Review – Unsafe Acts

<table>
<thead>
<tr>
<th>Researchers</th>
<th>Year</th>
<th>Type of study</th>
<th>System Dynamics Tool</th>
<th>Industry</th>
<th>Purpose of SD Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kontogiannis</td>
<td>2011</td>
<td>Policy analysis or problem-solving</td>
<td>Causal-loop diagram</td>
<td>Healthcare (Patient Safety)</td>
<td>To analyse and compare error recovery strategies regarding patterns of system affordances, interaction, and types of recovery plans, allowing safety experts to produce resilient system designs and training solutions for managing human errors in unforeseen situations.</td>
</tr>
<tr>
<td>Jiang et al.</td>
<td>2015</td>
<td>Policy analysis or problem-solving</td>
<td>Stock-and-Flow diagram</td>
<td>Construction Safety</td>
<td>To develop construction workers’ mental process that can help analyse the feedback mechanisms and the resultant dynamics vis-à-vis the workers’ safety attitudes and safe behaviours.</td>
</tr>
<tr>
<td>Nakamura et al.</td>
<td>2015</td>
<td>Policy analysis or problem-solving</td>
<td>Stock-and-Flow diagram</td>
<td>Maritime Safety</td>
<td>To investigate characteristics of human errors in marine accidents by analysing latent factors and onshore management personnel.</td>
</tr>
</tbody>
</table>
2.1.6 Discussion

This review aims to examine the connection between safety improvement and SD by reviewing literature that attempts to improve system safety in complex systems by utilising SD modelling. Based on the adopted safety framework, the extended HFACS, findings from the literature review were analysed and presented across five categories. We return here to discuss our findings with respect to the three research questions posed in Section 2.1: what safety issues have been addressed by SD, how has SD been applied to improve system safety and how might SD be further applied to system safety?

What safety issues have been addressed by SD?

SD was applied to address most of the issues in the extended HFACS framework. The most interesting finding is that organisational influences, more specifically speaking, organisational climate, was the most dominant issue to which SD was applied. It proves that SD is instrumental in analysing complex socio-technical issues in the working environment within the organisation which includes culture, policies and structure. Not surprisingly, organisational climate is linked with safety climate, so SD can be further utilised as a tool for studying dynamic interaction between safety climate/culture and various aspects in the subsequent tiers (supervision quality, working conditions and acts).

The second most frequent use of SD was to address unsafe supervision, concentrating on the issue of inadequate supervision. It is defined as a factor in a mishap when supervision has failed to identify a hazard, recognise and control risk, provide guidance, training and/or oversight, and results in a human error or an unsafe situation (Force, 2005). Much of the literature argues that lack of a solid communication between the workers and management causes management to forgo safety in order to promote production pressure, making way for potential unsafe acts to occur which are ultimately blamed on the sharp end. Much of the identified studies looked at the conditions of the operators as well as decision-based, skill-based and perception-based errors that they generate. The themes that keep repeating are solutions on how to reduce human errors by modelling high workload and fatigue and its interactions with the rest of the tiers. Only one SD application (2005) has encompassed over four tiers (Organisational influences, Unsafe supervisions, Preconditions for unsafe acts and Unsafe acts), revealing a glaring gap and future potential to develop further SD applications that cross across multiple tiers. SD has been utilised for both retrospective analysis (accident analysis) and prospective analysis (policy analysis). Approximately half of the studies were accident case studies where SD was utilised for accident investigation. Cooke (2003) for instance utilised SD to describe
lessons learned from the Westray mining accident of 1992 in which a number of miners lost their lives. His SD model provided a useful means for identifying underlying causes with dynamic considerations. Nearly a quarter of the studies were SD applications that provide problem-solving or policy analysis. Topolšek et al. (2009) investigated why there was an increased number of traffic accidents based on wrong-way driving and highlighted intervention strategies and countermeasures to reduce it. The third most frequent type of study was theory development. One standard usage is reflected in Shin et al. (2014)’s study where they used SD to capture construction workers’ mental process to analyse the feedback mechanism and the resultant dynamics regarding the workers’ safety attitudes and safety behaviours. The least common type of study was methodological development. Practically all the literature for methodological development were published nine years, perhaps an indication that there is a new drive to utilise SD to improve and address issues in system safety. An example of methodological development is Goh et al. (2012b) who focused on modelling and providing analysis between the management of production and production whilst addressing an existing gap. Consequently, SD modelling seems to be more applicable when developed for accident case studies and problem-solving/policy analysis as the literature shows.

**How has SD been applied to improve system safety?**

The second question explores how SD has been applied to improve system safety. Based on the existing literature, SD has been successfully applied to address several safety issues in many different ways: i) proactively preventing incidents; ii) group learning; iii) testing out potential policy impacts on safety. Mental models of the factors that promote accidents were created by Cooke et al. (2006) who also tested the viability of potential methods for their prevention. Similarly, employing the SD approach, Shin et al. (2014) modelled the mental process factors behind the unsafe activities of construction workers. Several interventions for promoting safe behaviours and improving safety-related communications were evaluated by the authors who also demonstrated the suitability of this model as an expressive tool (i.e. a shared mental model). In a different light, the issue of misuse of personal protective equipment (PPE) amongst pesticide applicators was investigated by Feola et al. (2012) who examined how different inventions could be applied to minimise this problem of PPE mismanagement. SD has been utilised as an effective strategy for enhanced learning where one application introduced an organisational response system in which precursor events, or safety-related incidents, are used as the basis for training and planning to combat organisational complacency and
promote effective learning. For policy impacts on safety, Leveson (2012) devised a model that shows the efficacy of the safety policies when new pharmaceutical drugs are introduced.

Not surprisingly, over a third of the identified SD applications are used in healthcare domain, and this is consistent with the increasing usage of SD in healthcare in contrast to other industries over the past decade (Brailsford, 2008) even though practical impact of SD simulation in healthcare is relatively low. Homer et al. (2006) argue that SD modelling is the perfect candidate to address the dynamic complexity that characterises many public health issues.

**How might SD be further applied to system safety?**

The third question explores how SD might be further applied to system safety. The implementation of SD implies capturing the complexity of social reality by developing models based on the mentality of the different individuals involved in a system, so as to interpret or define a phenomenon or problem (Lane and Oliva, 1998). It allows critical issues to be explored from different perspectives, which enables the modeller to have access to insights and changes relating to alternative techniques as well as to compare the outcomes of various scenarios generated from simulation (Lane and Oliva, 1998).

The results of both theoretical and practical implementations suggest that SD has the potential to improve safety in a variety of sectors but is underused. It could produce deep learning with a dynamic and contextual appreciation not provided by the current models and tools. Moreover, there seems to be a lack of applied system dynamic models in safety-critical industries where trade-offs are used all the time. SD has the potential to provide a balancing and strategic learning output in determining the best trade-off. With increasingly complex systems being built, useful tools are needed that allow us to understand their complexity, design better safety policies and guide effective change. SD has the potential to provide and implement enhanced learning for safety, and it continues to be a contender as a sophisticated management decision support tool for complex systems. Decision makers can benefit from virtual scenario testing within a safe simulation environment so that impacts on policy adjustments can be immediately visualised.

A number of studies (Goh et al., 2012a; Han et al., 2014; Lattimer et al., 2004; Taylor and Dangerfield, 2004) argue that the SD approach has the potential to be applicable in related areas with slight modifications. Some others mentioned that fine-tuning is necessary
based on continuous feedback from stakeholders (Simonovic and Ahmad, 2005). Others have argued that given limited time and resources, the qualitative aspect of SD can be a potential tool to elicit insights and enable learning (Carhart, 2009). Goh et al. (2012b) argue that SD modelling should not be considered as a complete replacement or substitute for existing approaches but should be utilised as part of a complementary tool. This is similarly echoed by Wang et al. (2013) and Jiang et al. (2015) who argue that since SD studies high-level effects at an aggregate level, individual differences and data outliers are lost. As a result, having supplementary modelling approaches is beneficial to understand system complexity.

In comparison with the existing accident risk analysis models such as Rasmussen’s Risk Management Framework, STAMP, FRAM, and HFACS, SD has the potential to cover the limitations accompanying those frameworks as it can enhance our understanding of the dynamic behaviour of systems in both qualitative and quantitative aspects. The existing frameworks tend to be qualitative and static in nature, but safety is never a static quality that can be achieved because systems are always moving to states of high risk (Dulac, 2007).

SD enables the behaviour of the system (and its subsystems) to be both represented and simulated. Its simulation capability allows changes such as technical or organisational safety means to be tested to evaluate their potential effectiveness prior to implementation. Changes can be introduced in either the design or the operation phase. As a result, it can form part of a continuous improvement strategy for the prevention and management of safety issues.

The SD framework incorporates delay which can be used to understand the dynamic effect of various time delays in the system. Understanding and using delays can be significant for implementing effective long-term safety measures in lieu of short-term actions. Delays also help understand the impact of unintended side-effects arising from short-term safety measures and also a result, efforts can be made to mitigate its impacts (Minami et al., 2010; Xian-gong et al., 2009).

The SD tool can also be used to generate insights through behavioural archetypes which can visualise complex phenomena. Causal-loop diagrams can be used to identify emerging problems proactively rather than having to resort to event-level interventions (Goh et al., 2010). When the systemic structure is better understood, intervention points to improve and sustain safety culture can be identified (Goh et al., 2010). As has been
previously demonstrated (Senge, 1990) causal-loop diagrams can be sufficient for communicating behavioural archetypes to improve safety.

Unlike existing safety frameworks, SD provides a unique process of participation and model building that gives an insight into the causes of accidents. The participants can be better understood through active investigation and retrospective learning. A safety culture is usually developed through constant learning and examination of these events in various industries. Safety also deals with the ability of a system, especially complex socio-technical systems prone to high impact and low probability events, to react to new and unique developments as well as to keep track of existing processes. A lot of investigations have been carried out on the importance and nature of learning in safety-critical domains. Learning within the organisations was identified by several authors to be disjointed and mainly focused on the local process whilst neglecting the deep learning stage of the underlying processes (Carroll et al., 2002; Huber et al., 2009). It is believed that this deep learning can be obtained from systems models. It is not enough to rehearse emergency plans and ensure they have been learnt (Lagadec, 1997). Effective deep learning is needed in order to prepare for these unique developments, and this deep learning is provided by the participatory model building of causal-loop diagrams and SD models for prospective and external events as well as internal investigations.

It is important to point out that not all potential consequences of a decision can be conveyed by the SD framework. In addition, it is not capable to accurately and wholly predict the nature and effect of all factors endogenous to the system. However, it provides the option to conduct numerous, iterative test-runs of the safety performance of a system in operationally relevant scenarios. This gives stakeholders the access to relevant information pertaining the probabilities of various adverse consequences as well as possible means of eliminating unanticipated and unintended consequences.

In short, the application of SD as a system safety enhancement technique will enable researchers and decision makers to understand how changes in the structural and dynamic properties of a system can influence its current and future behaviours. This allows them to identify safety improvements as well as adverse consequences.
2.2 Facilitated Modelling

Facilitated modelling is defined as “...the process by which formal models are jointly developed with a client group, in real time, and with or without the assistance of computer support” (Franco and Montibeller, 2010). During the process of facilitated modelling, group participants offer ideas in forms of statements; these statements are then linked, structured and modelled. The facilitator’s role is to ensure that the process is followed in an appropriate manner. In the cases of computer-supported facilitated modelling, a modeller is sometimes employed for dealing with the mechanics of the technology (e.g. moving concepts around, merging concepts, changing names and colours of concepts, assigning labels etc.). Often in computer-supported facilitated modelling, a facilitator familiar with the technology also assumes the role of the modeller.

Franco & Montibeller (2010) argue that building a model can be done in two modes, expert and facilitator. In expert mode, the problem situation faced by a client is given to the OR (Operation Research) analyst who builds a model to develop a (quasi-)optimal solution.

In facilitator mode, the researcher jointly develops a model through participant interaction possibly in a group workshop. Checkland & Scholes (1990) add the facilitated approach which can be split into two modes. The traditional facilitated approach is called Mode 1, where there is a formal group level application. In Mode 2, an approach is applied by an individual to structure their own thinking. Mode 1 enables participants to change their views by learning from others about the problem situation.

2.2.1 Facilitated Modelling Types

Specifically, three types of FM are identified in the literature all bearing differences and similarities, these are:

- Facilitated Problem Structuring: The philosophical underlining is that of subjectivism. Their modelling language is that of natural language with little to no emphasis on quantification. Facilitated problem structuring views the group as the key resource for effective Strategic Decision Making (SDM) (Franco and Montibeller, 2010).

- Facilitated System Dynamics: Originating from the development of system dynamics by Forrester (1994). Their focus is on identifying the unintended consequences an implemented decision may produce, thus placing a strong
emphasis on causal feedback loops. The process moves from building qualitative models to quantitative model building (Andersen and Richardson, 1997; Franco and Montibeller, 2010; Richardson and Andersen, 1995; Williams et al., 2003). This type of facilitated approach is also known as Participatory System Dynamics approach (Group Model Building) which will form the approach of this study.

- Facilitated Decision Analysis: Builds on normal Decision Analysis using facilitation for handling the group processes (Belton, 2002; Franco and Montibeller, 2010).

2.2.2 Group Model Building

Group model building (GMB) originated in the 1980s and was first used by a group led by Jacques Vennix in the Netherlands which was further collaboratively developed in the United States at the University at Albany by George Richardson and David Andersen. The methodology can be seen as subscribing to more general modelling with stakeholders’ practices and can be seen as the first in the field that systematically studied the effect of stakeholder involvement and its effects on model buy-in, consensus in decision-making, and heightening motivation to turn insight into concrete action (Vennix, 1999). GMB was initially designed for business and organisational applications.

According to Jones et al. (2009), the success of the participatory effort is seldom evaluated. Consequently, Hewitt et al. (2014) stressed that evaluation of a participatory modelling effort is an essential step of the work, not only because it would assist in evaluating the degree to which the participatory modelling process has contributed or is likely to contribute to the broader aims (e.g., safe and efficient staffing levels management within hospital pharmacies), but also because it is crucial for gauging the effectiveness of the approach deployed. Importantly, the generalisation of the outcome and results of a shared learning and co-constructed model beyond its applied context is difficult, if not impossible (Voinov and Bousquet, 2010). In this situation, evaluating the learning process and the role the model-building process played in the learning become vitally essential (Voinov and Bousquet, 2010).

In this respect, some valid and important questions that follow a participatory modelling effort could be (Videira et al., 2010): “Did the process foster learning and insight? Did the process improve communication and exchange of viewpoints? Did it promote a shared view of the problem or actions?” Currently, there are no widely accepted protocols for evaluating the success of a participatory modelling exercise. However, surveys,
questionnaire and protocols have been suggested as the most appropriate evaluation tools (Voinov and Bousquet, 2010). Also, qualitative measures may be employed (Beall et al., 2011).

2.2.2.1 Methods
A literature review was performed in order to identify studies that utilise GMB approach within healthcare. There were no time limits placed on the search, as there is no previous systematic review in this area and the scope of available literature was unknown. The accessed databases were PubMed, Web of Science, Science Direct and Google Scholar databases. The search words used were: group model building OR participatory system dynamics, in combination with healthcare. The keywords were used in Boolean combination, joined by AND. Papers eligible for inclusion were those that described applications of GMB interventions within healthcare. The literature was further supplemented by relevant publications in the reference lists of the publications collected. The title and abstract of each study were read, and the full-text article obtained if the researchers found that the study applied to the research question, based on previous literature.

2.2.2.2 Results
Table 2.16 lists literature that discusses the use of group model-building interventions applied to healthcare. A common theme across this literature is that the benefits of using participatory SD include structured deliberation, group learning and conveying the effects of feedbacks and time lags. Practitioners comment that the process of model building helps groups establish a shared vision of the problem.

Table 2.16 Group model-building literature with healthcare applications

<table>
<thead>
<tr>
<th>Authors (s)</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lane et al., 2003</td>
<td>Client involvement in simulation model building: hints and insights from a case study in a London hospital</td>
</tr>
<tr>
<td>McKelvie et al., 2010</td>
<td>Using system dynamics to plan investment in alcohol services</td>
</tr>
<tr>
<td>Elf et al., 2016</td>
<td>Using group-modelling in redesign phase of new healthcare environments</td>
</tr>
<tr>
<td>Homa et al., 2015</td>
<td>A participatory model of the paradox of primary care</td>
</tr>
<tr>
<td>Trani, Jean-Francois, et al., 2016</td>
<td>Community-based system dynamic as an approach for understanding and acting on messy problems: a case study for global mental health intervention in Afghanistan</td>
</tr>
<tr>
<td>Weeks, Margaret R., et al., 2017</td>
<td>Using participatory system dynamics modelling to examine the local HIV test and treatment care continuum in order to reduce community viral load</td>
</tr>
</tbody>
</table>
Participatory SD modelling is a unique approach that can engage a broad group of stakeholders in the process of systems examination, critique and to build their capacity as healthcare groups to address problems in the system that interfere with or undermine achieving healthcare outcomes. SD modelling uses a deliberative group process (Pesce et al., 2011) to build visual and computational models that allow decision-makers to illustrate factors that generate and affect the structural and dynamic properties of the system. They can then use these models to theorise and simulate the likely effects of specific interventions anticipated to improve system behaviour and achieve healthcare goals (Foster-Fishman and Behrens, 2007; Stave, 2002; Zimmerman et al., 2016).

Rouwette et al. (2002) looked across case studies and group modelling techniques. They found a wide variety of elements and scripts that were used to elicit information, explore and evaluate policy options. In addition, there was variation in the duration of the intervention, the number of participants and the involvement of the client in the model building phases. Insights from their assessment include two important concepts. First, “[l]earning about the problem seems to be a robust outcome of group model building.” Moreover, secondly, “commitment and consensus are found to increase after participation in modelling” (Rouwette et al., 2002).

Engaging healthcare stakeholders who are deeply involved in the system and invested in its outcomes in a participatory model building process increases the validity of the model, decision-makers’ trust of each other, and their sense of ownership of the model they build together. Because SD modelling is a group problem-solving task, it promotes trust building and buy-in from participants to engage in the effort whilst proposing explanations of the problem, system structure, and leverage points to produce solutions. It can also increase their commitment to using the model for collaborative policy and program decision making for systems change (Hovmand, 2014). Lane et al. (2003) employed the participatory SD modelling approach to build a model in order to understand patient waiting times in an accident and emergency department. The authors argue that participatory modelling in health care is more effective if clients are persuaded of its purpose and benefits. The fact that aggregation is central to SD models is a difficult feature, particularly in healthcare systems, but it can be conveyed and used successfully. The careful modelling can provide an excellent vehicle for eliciting people’s ideas about how a system works (Olabisi et al., 2010). One of the drawbacks of participatory SD modelling in healthcare and many other fields is when models do not represent the views
of those who designed them. Moreover, models may also be limited in their ability to reflect unexpected exogenous causes (Olabisi et al., 2010).

2.3 Summary
This review aims to examine the connection between safety and SD by reviewing literature that attempted to improve system safety in complex systems by utilising SD modelling as we as looking at how participatory SD approach has been applied in healthcare. In Section 2.1, a literature search and thematic analysis of empirical literature addressing SD application in safety-critical domains were conducted. The findings were categorised based on a modified safety framework that we entitled HFACS-EE. In Section 2.2, a literature search addressing GMB interventions in healthcare was conducted.

Simulation has mainly been used in system safety as an instrument for predicting system behaviour, testing model structures, testing different techniques as well as analysing various scenarios as revealed by the literature reviewed in this research. In view of the results obtained, the authors were able to improve safety through greater decision-making by including past behavioural events in modelling structures to create effective safety policies, performing system analysis as well as applying a holistic approach to analyse the causes of accidents beyond human error. In circumstances where the actions, omissions, communications or policies of top management directly or indirectly affect supervisory practices, actions or conditions of the operator(s) and lead to human error, stem failure or an unsafe situation, SD has often been used as a tool to pinpoint the factors responsible for accidents. Within the healthcare context, participatory SD approach can promote engagement by including stakeholders who are deeply involved in the system and invested in its outcomes thereby increasing the validity of the model, group trust, and the sense of ownership for the constructed model.

The future adoption of the SD approach in the field of system safety primarily depends on various factors such as creating more awareness about the feasibility of the SD methodology and applying it in practical safety scenarios.
3 Research Methodology

This chapter explores the research design framework as a broad orientation to the conduct of the research. Accordingly, the chapter provides justification based on literature for the methodological approaches, research methods, the tools and methods of data collection and analysis that were employed that addressed the research aim and objectives, as outlined in Chapter 1. Chapter 4 provides more practical detail of the employed tools and adopted methods of data collection.

3.1 Research Context

A hospital pharmacy dispensary was modelled to help hospital pharmacy management view and decide the staff workload management issue better by considering the impact of staff levels, interruptions and workload on safety (dispensing errors) and performance (backlog). A case study methodology was employed with the SD framework as the modelling approach. The SD approach served in this research as the methodology to build the conceptual model and the simulation model. It also provided the means of eliciting knowledge from key practitioners that participated in the group model building sessions. The SD framework combines two approaches that usually work separately in research design: the qualitative approach and the quantitative approach. The qualitative approach according to Leedy and Ormrod (2010) is typically used to answer questions about the complex nature of phenomena, which occur within its natural context. Leedy and Ormrod explain that “the qualitative research process is more holistic and ‘emergent’, with the specific focus, design, measurement instruments (e.g., interviews), and interpretations developing and possibly changing in the complexity of the situation and interact with
their participants” (Leedy and Ormrod, 2010). As these authors point out, qualitative researchers use mostly inductive reasoning when they draw inferences about the phenomena from the observations they make. Yin (2003) argues that two main conditions are the essence of qualitative research: the use of close-up, detailed observation of complex systems by the investigator, and the attempt to avoid prior commitment to any theoretical model. This is the framework for an SD modelling approach and is true for its qualitative elements and quantitative elements as well. The SD approach combines and makes use of both approaches, in order to achieve the advantages of both, resulting in quantitative outcomes that can be measured and compared.

According to Yin (2003) case studies may be considered the most appropriate research method to deal with and understand complex systems. A case study in this research allowed an investigation to retain the holistic and meaningful characteristics of real-life issues such as staff workload management. Case studies are the most relevant research strategies for situations in which “a ‘how’ or ‘why’ question is being asked about a contemporary set of events, over which the investigator has little or no control” (Yin, 1992). Yin provides a technical definition for case studies that a case study is an empirical inquiry that:

- Investigates a contemporary phenomenon within its real-life context;
- The boundaries between phenomenon and context are not clearly evident;
- Finally, multiple sources of evidence are used.

3.1.1 Case Study Design
Case study research is created out of the desire to understand complex human and social phenomena in order to explain relationships, which exist in reality (Petty et al., 2012; Yin, 2003). Yin (2003) identifies case study research design as an approach of exploring an empirical topic by following a set of specified procedures that are used in various situations to increase our knowledge of individual, group, and organisational, social, political, and related phenomena. Thus, Petty et al. (2012) describe case study research as the singular science that attempts to understand “what is unique of a case defined as ‘specific, a complex functioning thing’ whether it is a person, a clinic, a classroom, an institution, a program, a policy, a process, or a system”. Gerring (2008) went on to say that case study research is the thorough study of a single case where the aim of the study is to clarify or illustrate a larger class of cases.
Considering how case study research should be conducted, Yin (2003) notes that it involves the application of methods from social sciences to practical problems with the intention to contribute to knowledge and theory in a given case. Thus, he concluded that each method has its distinctive strengths and weaknesses that is subject to three conditions: a) the type of research question, b) the control a researcher has over actual behavioural events and c) the emphasis on modern as opposed to historical phenomena. According to Petty et al. (2012) case study research design has no specific data analytical approach and the choice of method(s) to be used depends on the research question and the focus of the case under study.

The benefit of using case study research design in a research study such as staff workload management within pharmacy is that multiple criteria and variables can be examined as well as the holistic description of the complicated nature of hospital pharmacy system. In order to understand a case, a variety of data can be collected in most situations which includes observation, and interview (Gerring, 2008; Petty et al., 2012).

The process undertaken by an SD modelling approach is based on the case study design, which aims to build a simulation model that will represent the situation or the problem in question. The simulation model is created by a collaborated effort of the decision makers with the facilitator, in which their mental models are revealed and challenged. SD will be effective to the extent that one will be able to involve the decision makers in the process of building the model, a participatory SD process which is also known as Group Model Building (GMB). The process is an iterative process, moving from capturing to learning to capturing again continuously until an acceptable model is produced. This process is the opportunity organisations have to share divergent views on a problem. Divergent views are the result of selective perception and selective memory. Through this process, the participants have an opportunity to examine their views critically in an effort to create a shared and better understanding of the problem (Vennix, 1996).

3.1.1.1 Case Study Stages Framework
The research followed the eight stages below. See Figure 3.1 for an illustration of the stages in the form of a flow diagram.

STAGE 1 focused on drafting a research plan. Once drafted, a broad review of literature review was conducted. Subsequently, a literature/interviews-based preliminary model building (a high-level systems model) was developed based on the existing literature on staff workload in hospital pharmacies, backlog, interruptions, fatigue and dispensing
errors in hospital pharmacies and key information from participants. The final output was a literature-based systems model revealing key system concepts, variables and behaviour. Preliminary interviews were conducted involving labellers, checkers and administrators in drafting the preliminary model. After STAGE 1, two studies were carried out in sequence. Two cases consisted of two same hospital pharmacy setting: the labelling and checking flow. Each study followed the prescribed STAGE 2-7 cycles.

**STAGE 2** consisted of system mapping through group model-building. This indicates how causal-loop diagrams (conceptual modelling) is generated that show how the key variables are related and how feedback structures are formed in each local context. The conceptual model was derived from key semi-structured interviews from labellers, checkers and administrators and was validated based on GMB sessions with relevant stakeholders. Then, a stock-and-flow diagram was formulated to model underlying physical structures. Pharmacy practitioners were continuously engaged during the mapping process through interviews and group sessions. The final output was validated through system concepts, variables and behaviour using causal-loop diagrams and stock flow diagrams.

**STAGE 3** looked at baseline data collection. Numerical data for model formulation were collected from the pharmacy management system, interviews with pharmacy practitioners, previous literature and direct data collection at the hospital pharmacies. The information on workload related human reliability was elicited not only from previous medication safety research but also from general human reliability research. Observation of labellers dispensing medication was conducted in the hospital pharmacies as well as interviews with a key number of labellers to quantify soft variables. The final output was used as data sets for STAGE 4.

**STAGE 4** was comprised of simulation model formulation. The conceptual models generated at STAGE 2 were formalised with equations and initial conditions. The final output was a simulation model with all the relationships defined. This was done behind-the-scenes and did not involve any participants.

**STAGE 5** looked at the validation aspects. Several analyses were carried out to validate the model. This involved conducting a number of group sessions with participants to validate the model and the scenarios. They were:

1. comparing the simulated behaviour of the model to the actual behaviour;
2. sensitivity analysis
iii. test under extreme condition;
iv. face validation by stakeholders.

The final output was a validated simulation model

**STAGE 6** looked at scenario testing (what if analysis). This means using the validated simulation models; I will identify and test new staffing scenarios and compare their implications in numerical terms. A range of scenarios were tested which included dynamic staffing scheduling strategy, winter pressure workload, the impact of rework and endogenous factors influencing capacity. The insight from this testing was used to devise strategies and recommendations for the hospital pharmacy dispensary. The testing was conducted with labellers, checkers and managers in a series of group sessions.

**STAGE 7** looked at the evaluation aspects. These consist of the feasibility of SD approach as a planning and evaluation for system safety of healthcare delivery in the hospital pharmacy context and utility, and usability of SD for group learning was evaluated through in the form of group sessions with hospital pharmacy practitioners and managers. The final output was an evaluation detaining the feasibility and utility of the approach.

**STAGE 8** focused on the conclusion part by addressing the predefined research objectives and revealed how the adopted methodology addressed it, highlighted contributions and limitations and finally presented future work.
Generally, the development of an SD model involves a sequence of iterative and interrelated steps (Richardson et al., 1981; Taylor et al., 2010; Wolstenholme, 1994). There is, however, no standard or best modelling process employed by all SD modellers. Although the specifics differ between processes, there is general agreement on some key steps. In this thesis, the SD modelling steps proposed by Sterman (2000) were followed (see Figure 3.2) in conjunction with the GMB approach: It should be noted, though, that the process is flexible; hence, one does not need to follow the depicted sequence in Figure 3.2 strictly. Indeed, the process is iterative and, in many cases, imposed by several considerations such as the project context, time, available resources, the needs of the stakeholders, and the preference of the modeller (Beall King and Thornton, 2016).
The participatory SD modelling process (see Figure 3.3) uses several agreed key steps although the specifics differ between processes. It is used in combination with the traditional SD cycle. It is not imperative for the cycle to be sequential and can involve a great deal of skipping steps. There are three key stages during the whole cycle: (1) preparatory activities which involve stakeholder analysis and preliminary interviews, (2) modelling workshops which is the group modelling sessions, behind-the-scenes activities and group validation/verification and (3) follow up activities which is the evaluation. Table 3.1 illustrates the number of participants involved during the participatory model building process, their roles, the hospital and the total time for each session.

Table 3.1 Participants information during the model building stage

<table>
<thead>
<tr>
<th>Preliminary Interviews</th>
<th>Roles</th>
<th>Participants</th>
<th>Hospital</th>
<th>Time conducted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Administrators</td>
<td>2</td>
<td>Glenfield</td>
<td>1 hour each</td>
<td></td>
</tr>
<tr>
<td>Labellers</td>
<td>4</td>
<td>Glenfield/Royal Infirmary</td>
<td>1 ¼ hour</td>
<td></td>
</tr>
<tr>
<td>Checkers</td>
<td>3</td>
<td>Glenfield/Royal Infirmary</td>
<td>1 hour</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model Building Session</th>
<th>Roles</th>
<th>Participants</th>
<th>Hospital</th>
<th>Time conducted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labellers</td>
<td>4</td>
<td>Glenfield/Royal Infirmary</td>
<td>1 ½ hour (single group session)</td>
<td></td>
</tr>
<tr>
<td>Trainees</td>
<td>7</td>
<td>Glenfield/Royal Infirmary</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Checkers</td>
<td>2</td>
<td>Glenfield</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The systems’ understanding and problem articulation are the initial and most crucial steps to define the problem. It is used to find the relevant system boundaries of the problem. Stakeholders are identified, and preliminary interviews are conducted. The third step involves creating a conceptual diagram with participants in a group environment. The result is a causal-loop (qualitative) diagram. Once completed, it is converted to a stock-and-flow (quantitative) diagram, complete with parameters and initial conditions that can be simulated via computerised software (Kundapur, 2012). The simulated model is then validated and verified by the groups’ participants and refined accordingly. Finally, evaluation is conducted and fed back to the stakeholders (see Figure 3.4).
3.1.2 Case Study Research Site
Glenfield Hospital Pharmacy and Royal Infirmary are the two largest pharmacy dispensaries within the University Hospitals of Leicester (UHL) NHS Trust. The dispensaries employ a staff rota, and skill-mix is decided on a weekly basis by the dispensary team leader. The workload is assigned based on the First-In-First-Out principle. The management decides the total number of staff assigned to each dispensary, and it happens only when someone leaves. The team leader placed huge concern on a number of errors emanating from lack of competent resources. A considerable number of year one and two trainees, as well as pre-registration students, are employed. The reason being is that it is paid for by their respective college/universities and are such easily employed as opposed to qualified pharmacists. This leaves them exposed to committing errors, as they are rarely shadowed, making them more likely to commit unpreventable and prevented dispensing incidents/errors. Only two staff members are allowed on annual leave at the same time; this is the same for when taking a break. Figure 3.5 highlights the flow from receipt of prescription to final dispensing whilst Figure 3.6 reveals a coloured linked map of the actual hospital pharmacy dispensary. In Figure 3.6, the yellow line represents the administrator/receptionist, the receiver of the initial prescription request, the red line represents the clinical checking group who validate certain prescriptions, the green line represents the labelling group who dispense and label the prescriptions and finally the purple line represents the senior staff who check and approve the final medications.

Figure 3.5: Dispensing process
3.1.3 Group Model Building

We adopted the GMB approach for our case study. Chapter 4 explains in detail the actual adoption of the approach whilst I briefly explain here the recommendations and justification for this approach as mentioned in the literature. A model is a substitute for an object or system (Forrester, 1999). We use models as a method for communication and clarification. Our thinking process mainly depends on models, through which we are able to conceptualise and re-organise the world around us. Much of this conceptualisation is done automatically in our mind and is the core of our mental models. Our mental models are representations of the real system, modified and filtered through our experience (Forrester, 1999). Thus, mental models are our general ideas that shape our thoughts and actions and lead us to expect certain results (O’Connor and McDermott, 1997). They are so deep-seated in our mind that we tend to confuse them with facts, and mistakenly believe everybody shares them. Many of our mental models are implicit and, as long as they are such, we cannot change them or argue about them. To attempt to make a change happen, we must have the ability to reveal our mental models, make them formal, explicit, arguable, and discussable.

Figure 3.6: Link Map of the UHL hospital pharmacies
3.1.3.1 Why Group Model Building?

We primarily adopted the GMB approach because large body of literature maintains that the use of SD for group modelling building (GMB) is useful for group learning and consensus building. Wolstenholme (1996) emphasises that modellers maintain involvement with systems agents during problem and model definition to attain a well-balanced model. It is appropriate for complex problems, particularly ones where conflict is anticipated such as the causes of dispensing errors which is ultimately attributed to human error and the staff that work in the sharp-end. The process can meet one or more of the following goals: promote team learning, share information between stakeholders, foster future vision, develop consensus on the actual behaviour of the system, and reach consensus on a decision and finally create a commitment to that decision (Belt, 2004). The process of sharing mental models identifies points of agreement and points of conflict, which is necessary to elicit the potential causes of dispensing errors and causes of workload and backlog. The areas of conflict draw attention to the underlying assumptions, and the modelling activity is a tool to make assumptions explicit so that they can be clarified and challenged. The process ideally results in a model that describes the structural aspects of the system, whilst the model simulations provide information about system behaviour (Vennix, 1996). It is for these reasons that GMB has been employed in the Case Studies Stages Framework in order to get the necessary stakeholders to communicate and promote consensus.

3.1.3.2 Modelling as a learning tool

I tailored the model building session so that its primary focus is learning from the adopted simulation, during and after the process. This will enable the stakeholders to discuss the characteristics of the system model and see if its insights can be applied elsewhere. By implementing a survey questionnaire and evaluation discussions, discussed in Section 3.2, the level of group learning is captured, paving the way for mental models to be updated, the ability to have risk-free experimentation and revealing systemic complexity. The stakeholders' involvement in the development process of the model could change the stakeholders' ways of viewing every issue emerging in their system so that modelling through the systems approach changes the way people think about a system. In this regard, the model acts as learning (Forrester, 1987; Senge, 1990). The shift from "modelling as a prediction" to "modelling as learning" is discussed elsewhere (Bakken et al., 1992; de Geus, 1992; Senge, 1990).
There are several things that can improve the learning process when using SD. Forrester (1987) outlined two basic learning processes related to systems behaviour. Firstly, SD models can help decision-makers to find out the general characteristics of the system behaviour that apply to a broad class of systems. Secondly, during the modelling process, there is a possibility of discovering surprising behaviour, which usually indicates a model defect, though there is a possibility that this unexpected behaviour is exhibiting a new insight about the real-world system. Other learning advantages obtained from group modelling are related to the model building process. During the process of modelling, Lane (1994) identifies five benefits:

(i) changing mental models,
(ii) creating learning and intuition;
(iii) risk-free experimentation
(iv) helping people to know better what they know already and
(v) revealing systemic complexity

3.1.3.3 Stages of Group Model Building
Considerations were given on several issues when designing a group model-building in this research. Even before starting the project, one needs to find out whether an SD approach suits the specific problem and the specific organisation one is targeting. Assuming that the answer to this question is affirmative, one needs to consider several more issues. The first one is whether to go for a qualitative approach or a quantitative approach when a particular problem and organisation are already in mind. The second is about participant selection: how many people to involve in the GMB sessions and whom should they be. The third issue deals with the question of whether to start the project from scratch or with a preliminary model, and the fourth principal issue deals with how to prepare sessions (Vennix, 1996).

3.1.3.4 Qualitative or Quantitative SD?
We adopted both the qualitative and quantitative aspects of participatory SD. Qualitative SD refers to the stages of problem identification and system conceptualisation. Quantitative SD also includes the formalisation stage and the simulations. Both aim to identify the feedback processes causing the behaviour of the system, which will increase the understanding of the relationship between the structure of the system and its problematic behaviour. It is without doubt that the more one ‘plays’ with the model, the better understanding one gains, and therefore the more stages one is involved with, the
more one learns about the influences of potential decisions or policies over the long-run behaviour of the system, a difficult accomplishment to achieve if simulation is not incorporated (Ford and Sterman, 1997; Vennix, 1996).

More ‘playing’ with the model is indeed not achieved without a price. It takes more time and costs to do that. Therefore, the question is when one should be content with the qualitative part of the modelling effort, and when one should seek to achieve a full formalised quantitative model. The answer to this question needs to take into account three issues: 1) What is the goal of the modelling effort, 2) How much resources are dedicated to this effort (Vennix, 1996), 3) Who is the audience for this modelling process and results (Wolstenholme, 1999).

If the goal of the modelling effort is to achieve a full understanding of the system’s behaviour, then a quantitative model is required. If the modelling aims to change management perceptions, to create a shared language for mutual understanding, to foster consensus and commitment with a decision, or to improve the way decisions are made, then a qualitative model may suffice (Vennix, 1996).

If the time and resources devoted to the model-building process are limited, then a qualitative approach might be considered, especially if the nature of the problem and the goals of the modelling effort are the kind a qualitative approach suit (Vennix, 1996).

Another important consideration is the kind of audience involved in the modelling effort. If participants are more inclined to analytical thinking than a qualitative approach is sufficient that will help them to gain more intuition and more holistic thinking abilities. If the audience lacks the abilities required for analytical thinking, then a formalised model may help them to acquire the skills associated with mathematics and analytical thinking (Wolstenholme, 1999).

3.1.3.5 Whom to involve in the model building sessions?
Based on the preliminary interviews, it was decided to concentrate the problem domain and scope to the dispensing process. As a result, we have identified selected staff groups that played a pivotal part in the dispensing process. They are labellers, trainees and checkers. Two main issues concerning the selection of participants in a model building process are how many people to involve and how diverse should the group be. Participation in a group modelling process ‘can never be all-inclusive’ (Voinov and Bousquet, 2010). Vennix’s (1996) recommendation for these issues includes having those present who have the power to act, meaning those who can implement a decision. Also,
he recommends, “increasing the group size will be beneficial to create a larger organisational platform for change and commitment with a decision, but it simultaneously decreases participation and satisfaction of group members” (p. 113). Vennix (1996) suggests the number of five participants in a group model-building as the best size from his experience, but each case needs to be dealt with specifically. The larger the size of the group, the more structured the sessions need to be. In relation to group diversity, Vennix (1996) acknowledges that “Increasing a group’s diversity will be advantageous with regard to the model’s quality, but it might at the same time create more tension within the group, which in turn reduces group performance” (p.113). As a solution to this problem, one of Vennix’s (1996) suggestions is to start the project by employing a preliminary model.

3.1.3.6 With or without a preliminary model?
A preliminary model was employed for this study. The primary benefit of starting with a preliminary model is that it will speed up the model building process and can cut into participant’s time investment. Further, it is easier to start the group discussion when a preliminary model is available (Vennix, 1996). On the other hand, the use of a preliminary model might decrease the degree of ownership over the model as experienced by the group; and low ownership leads to low commitment (Vennix, 1996). The problem of ownership might be tackled by avoiding being defensive in relation to the proposed model and by preparing; it as little as possible so that flaws and corrections can easily be made and thus ownership regained (Vennix, 1996).

A preliminary model cannot always be employed. There are situations where no information is available ahead of time. Sometimes a preliminary model is not necessary, especially when the model-builder is very experienced and can create a model from scratch in the first session (Vennix, 1996). The more it is the effort of the group, the more it creates ownership feelings and therefore leads to more commitment. Starting from scratch may turn out to be very time effective because no interviews have to be scheduled but may be ineffective in terms of time investment from participants. It also may entail specific dangers, because one might not be aware of the specific circumstances surrounding the project (Vennix, 1996).

In most cases when no previous experience with modelling is available, the best approach is to start with a preliminary model, spread the model building over more than one session, start with a qualitative model, and do most of the quantification through backroom work.
(Vennix, 1996). I have employed a preliminary model in this study and discussed in detail in Chapter 4. Figure 3.7 illustrates the choices one has in designing group model-building projects:

3.1.4 Planning the Sessions

We planned several group sessions in order to formulate the group model. Vennix (1996) provides several guidelines that are useful in planning the agenda and Section 4.2.4 explains in detail how these stages were planned for this study. The guidelines of Vennix are listed here for informative purpose. The first stage of the session is the introduction of all participants, and it is advisable to have everyone place his/her name in front of him/her. The next step is to discuss the agenda. If it is the first meeting one may need to provide a short introduction to SD. It is important to find out if there is a consensus in the group about the problem that needs to be modelled. The problem definition should be recorded and placed where everybody can see it. In case this is not the first session, reports and conclusions from the previous session need to be provided. Clarifying what is expected of the group in this session and what outcome is anticipated is important for participants to reduce anxiety and feel at ease. It is important to ensure that there are facilities that enable recording what the group is designing, and as a general rule, Vennix (1996) advises not to write anything before testing whether the group agrees on it. It is
advisable to have the group cycle back and forth between the problem and the model. This means that there can be silences when people reflect on what has been accomplished and on how the group ought to proceed.

Breaks are essential to planning ahead. Finally, it is important to record preliminary, conclusions and insights and leave the participants with a simple but clear picture of the insights, which were gained through the model-building process. Andersen and Richardson (1997) recommend planning the time so that the needs of those present are met, whilst time availability, and the purpose of the intervention is considered. There should always be room for flexibility. They believe that planning for every 15 minutes blocks of time, keeps the group alert, on task, and helps to make progress.

Andersen and Richardson (1997) believe that it is important to maintain visual consistency, meaning that one sort of iconography or vocabulary for discussing the problem under study should utilise for the entire modelling session(s), in order to ease the learning effort. They also believe that it is important to strive for visual simplicity since visual complexity readily emerges in modelling sessions. Andersen and Richardson (1997) suggest avoiding long talks of one-to-many as much as possible. They avoid explaining anything to the group that cannot be discovered first by some other form of group process. An important exception to this rule is the brief and focused description and summary of what the group has completed and decided.

Another important issue raised by Andersen and Richardson (1997) is facilitator’s responsibility to always respond to the concerns being raised by the group. The facilitator needs the ability to distinguish between important insights and other essential comments that do not contribute to the modelling task and write these important insights so that the modeller can use them to structure dynamics relationships. The rest can be written in another place on the board.

Andersen and Richardson (1997) also advise allocating time for the members of the group to develop a group sense. They provide some examples of “icebreaker” exercises and recommend working closely with the gatekeeper to engineer the composition of small groups so that cliques are avoided. Their final recommendation is to allocate the last hour or half hour to summarise the whole day effort in order to build a climax and to leave the session with an accomplishment feeling.

This will be the overarching approach, and the next chapter will talk about in detail the actual model formulation.
3.1.5 Model Validation and Building Confidence
We validated all constructed models based on a number of tests identified by literature. This is explained more in detail in Section 4.2.8. A justification based on literature is provided in this section. A model represents a real system only concerning the specific purpose for which the study is made (Mohapatra et al., 1994). Therefore, unimportant factors, which are considered as not contributing to the mode of the real system behaviour, are left out. Once a factor is left out, the model is subject to the criticism that it is invalid. Greenberger et al. (1976) argued that such criticism was unhelpful by concluding that “There is no uniform procedure for validation. No model has ever been or ever will be thoroughly validated. Since, by design, models are simplifications of the reference system, they are never entirely valid in the sense of being fully supported by objective truth. Useful, illuminating, convincing or inspiring confidence are more apt descriptors applying to models than valid” (Greenberger et al., 1976). Ford (1999) supported this view in his book by indicating this criticism as pointless and against the nature of modelling. He believed that the important question was not "Is the model valid?" but "Is the model useful?".

This criticism importantly brought forward questioning of the perception of "validity". Wehmeier (1993) defined valid as "that can be used or accepted legally at a certain time" and she also gave examples such as a "valid contract" or a "valid passport". With these definitions, "validate" refers to the act of proving a contract is legally binding or verifying that a passport was issued properly. However, Greenberg et al., (1976) thought of validation differently. They argued that “validation is not a general seal of approval” but more general “indication of a level of confidence in the model's behaviour under limited conditions and for a specific purpose”. They suggested that "data provide a tangible link between a model and its reference system, and a means for gaining confidence in the model and its results.” Likewise, Forrester and Senge (1980) described validation as the process of establishing confidence in the soundness and usefulness of a model.

It is essential that the model is rigorously tested in order to gain confidence in the insights and recommendations that emerge from its use. Sensitivity analysis and partial-model testing play important roles in testing SD models in addition to a series of formal tests. These tests provide an indication of the appropriate time to stop refining the model. The formal process of model testing is often referred to as model validation. Validation, in the sense of confirmation, can never be absolute (Popper, 2005); a model cannot be proved to be right, it can only fail to be proved to be wrong. In simulation modelling, a pragmatic
approach is adopted to establish confidence in whether the model is sufficiently accurate for its intended purpose (Coyle and Exelby, 2000; Forrester, 1961; Neelamkavil, 1987; Pidd, 1998; Richardson et al., 1981).

From this perspective, researchers in this field have described a range of tests to build confidence in their models on the basis of the data utilised (Anand et al., 2006; Georgiadis and Besiou, 2008; Karavezyris et al., 2002; Saysel et al., 2002; Shi and Gill, 2005). These are specifically: historical behaviour, boundary adequacy, structural assessment, dimensional consistency, parameter assessment, integration-error, extreme-condition and face validity tests which I have employed in Section 4.2.8.

3.1.6 Scenarios to be tested
The simulation model has modelled two main scenarios which are illustrated in the next chapter. A third scenario was modelled, but its results were incorporated in scenarios 1 and 2. For illustrative purpose, Scenario 3 is discussed included. They are:

Scenario 1: Trade-off between efficiency (production) and thoroughness (safety). The objective of Scenario 1 was to examine the trade-off between efficiency (production) and thoroughness (safety) by analysing staff levels (resources) and their impact on performance. Analyse how a number of labellers and checkers can have an impact on rework and backlog.

Scenario 2: trade-off between interruptions (trainees) and performance (capacity). The objective of Scenario 2 was to achieve a trade-off by examining the effect of interruptions (questions from trainees) can affect efficiency.

Scenario 3: effect of high workload on fatigue and errors. The objective of Scenario 3 was to examine and analyse how the level of workload has an effect on fatigue and eventual burnout which in turn has an effect on capacity and errors. However, for the purpose of clarity and since all scenarios are interconnected, scenario 3’s output will be incorporated into the results of scenarios 1 and 2.

3.2 Questionnaire Survey Design of Model Use

3.2.1 Structure of Questionnaire Survey
In the survey design literature, the structure of the questionnaire is an important aspect (Sapsford, 2007). A well-constructed questionnaire needs to address the objectives of the survey directly. The overall quality of the research depends directly on the quality of the
questions asked (Buckingham and Saunders, 2004) and answers received (Sapsford, 2007). The famous rule: “keep it simple and short” (Buckingham and Saunders, 2004) was incorporated when designing the questionnaire. Therefore, a short questionnaire survey was produced of no longer than two pages, including concise and carefully worded questions to ensure a good understanding and elicit thoughtful responses from the survey participants.

The four main elements that require attention during the construction of the questionnaire survey are: i) deciding the questions to be asked by the study, ii) selecting question type for each question, iii) design of the question flow, iv) the overall questionnaire survey layout. The questions included in the questionnaire are both related to the first and second research question, which aims to find out how the developed SD model are interpreted from both the practitioners and management’s point of view.

The questionnaire is composed of two main sections. The first sections deal with participants’ personal details. In order to ensure strict confidentiality, the questionnaire does not require the participant’s names or hospital names. Furthermore, participants are asked about their prior experience in using a simulation model and if the answer is “yes” they are required to identify the name of the simulation package used. This would allow us to filter if participants have used SD modelling before.

The second section of the survey questionnaire deals with the participants’ opinions about the hospital pharmacy dispensary model, using both the qualitative (causal-loop-diagrams) and quantitative (stock-and-flow) at the beginning of the session. The second part of the survey is divided into five main sub-sections regarding participant opinions about the following criteria:

- a) Model understanding and complexity
- b) Model validity
- c) Perceived Model usefulness
- d) Simulation results
- e) Overall opinion of model

The main question format used to collect participants’ opinions on the models was a 5-point Likert scale, ranking from 1 to 5, giving an ordinal, non-metric measurement. The 1 to 5 response scale is commonly used in social science research (Buckingham and Saunders, 2004). Other types of questions included are rank order/multiple choice
questions, single select (yes/no) questions and open-ended questions. The latter was included to avoid leading participants’ answers, despite the fact that open questions have a lower response rate. This is considered to be a trade-off for better quality information. A multiple-choice question is used in order to collect information on ranking amongst factors that aided model understanding. The ranking scale is deemed as suitable in this case because the aim is to find out participants’ understanding of the developed hospital pharmacy model. The initial version of the questionnaire survey was revised a few times, after consultations with colleagues and supervisors (See Appendix B).

3.2.2 Participants
As part of the SD’s approach, the simulation model is evaluated from the end-users’ point of view. In any organisation, it is the decision-makers who are the ultimate users of a simulation model, whether it be directly experimenting with the model or as recipients of the results. In the latter case, the management would normally interact with the model to, at least, gain some confidence in the results. However, to sense-check the model and interpret its results, pharmacy practitioners were included to create relevant participants for the purpose of this study. A mix of managers, labellers and checkers of the two UHL hospital pharmacies were chosen as the participants for the purposes of this study. There were four different group sessions. The first four groups were made up of 10 participants, and the final group was made up of 13 participants (see Table 3.2).

Table 3.2 Group sessions for validation, experimenting and evaluation

<table>
<thead>
<tr>
<th>Sessions</th>
<th>Time of session</th>
<th>Participants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Labellers</td>
</tr>
<tr>
<td>Session 1</td>
<td>1 1/2 hours</td>
<td>1</td>
</tr>
<tr>
<td>Session 2</td>
<td>1 1/2 hours</td>
<td>1</td>
</tr>
<tr>
<td>Session 3</td>
<td>1 1/2 hours</td>
<td>1</td>
</tr>
<tr>
<td>Session 5</td>
<td>2 hours</td>
<td>0</td>
</tr>
</tbody>
</table>

3.2.3 Participatory Sessions
The questionnaire was administered with two different groups in four different sessions. The first group involved the actual pharmacy practitioners and the second group, the management.

The session with the practitioners was arranged as several group discussions involving the practitioners. Each group discussion had three pharmacy practitioners of labellers and checkers. Given that the hospital pharmacy dispensary is a busy work environment, it was
impossible to get permission to plan for a large group discussion from the team leaders. As a result, the group discussions had to be split into a number of sessions. In hindsight, it was quite useful as it allowed me to interact and present the model to a small number of participants and get their input and feedback directly without moving through a large group. Before the sessions, the participants were presented the simulation model as a web interface to play around with. The sessions started with a brief presentation introducing the concept of system thinking, the basics of SD and then proceeded to show the qualitative (causal-loop diagrams) aspect of the developed simulation model. Finally, the actual simulation model was shown where several scenarios were demonstrated. Two further sets of handouts were given. During the group sessions, the output results of the simulation models were discussed, and a discussion ensued on the perception of the model and how it can impact their hospital pharmacy practice and healthcare in general. At the end of the session, questionnaires were handed out, which the participants were asked to complete. The facilitator went through the questionnaire section by section, explaining each section and asking the participants to fill each section and have a group discussion. This enabled a more enriching discussion whilst answering the questionnaire.

3.3 SD Software & Web-Based Packages

Since the beginning of the SD field, many SD modelling software packages have been introduced. The International SD Society mentioned Dynamo, iThink/STELLA, PowerSim Studio, and Vensim under the core tools section on their website (System Dynamics Society, 2016). Azar (2012) has compiled a concise historical and informative introductions about many SD packages. We have extracted information about the core tools in Table 3.3.
Table 3.3 SD software packages useful background (Azar, 2012)

<table>
<thead>
<tr>
<th>Package</th>
<th>Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamo</td>
<td>“It is the first SD simulation language originally developed by Jack Pugh at MIT; the language was made commercially available from Pugh-Roberts in the early 1960s. DYNAMO is originally designed for batch processing on mainframe computers. It was made available on minicomputers in the late 1970s and became available as ‘micro-dynamo’ on personal computers in the early 1980s. DYNAMO today runs on PC compatibles under Dos/Windows.”</td>
</tr>
<tr>
<td>iThink/STELLA</td>
<td>“Originally developed in by isee systems [<a href="http://www.iseesystems.com">http://www.iseesystems.com</a>] in 1985 by Barry Richmond. iThink and Stella software provided a graphically oriented front end for the development of SD models. They offer a practical way to dynamically visualise and communicate how complex systems and ideas work. Diagrams, charts and animation help visual learners discover relationships between variables in an equation.”</td>
</tr>
<tr>
<td>PowerSim-Studio</td>
<td>“In the mid-1980s, the Norwegian government-sponsored research aimed at improving the quality of high school education using SD models. Powersim was later developed as a Windows-based environment for the development of SD models that also facilitates packaging as interactive games or learning environments [<a href="http://www.powersim.no%5D%E2%80%9D">http://www.powersim.no]”</a></td>
</tr>
<tr>
<td>Vensim</td>
<td>“Originally developed in the mid-1980s for use in consulting projects. Ven-sim was made commercially available in 1992 by Ventana Systems, Inc. (Harvard, Massachusetts) [<a href="http://www.vensim.com">http://www.vensim.com</a>]. It is an integrated environment for the development and analysis of SD models. Vensim runs on Windows and Macintosh computers to simulate the dynamic behaviour of systems that are impossible to analyse without appropriate simulation software, because they are unpredictable due to many influences, feedback, etc. It helps with causality loops identification and finding leverage points.”</td>
</tr>
</tbody>
</table>

The iThink and STELLA software are almost the same software package, from the same developer. Each of them will run models developed by the other and have the same graphical user interface (GUI). They differ in their targeted audience. iThink is targeting business users, whilst STELLA targets academics and researchers (Isee Systems, 2011). Based on that, we have considered only STELLA in addition to other core packages in our comparison, which we have conducted to select a package to use in developing our SD models. We have collected information from the packages’ respective websites mentioned in Table 3.4. All three packages use the same stock-and-flow diagram notation with superficial differences, in addition to the possibility of drawing causal-loop diagrams. All packages have the functionality of model calibration, sensitivity analysis, adding sub-scripts/arrays to models, and basic validity testing via unit checking. All three packages supply a free model reader version, which can simulate models, however, cannot edit. Table 3.4 shows the differences between the three packages.

As one of this study’s goal is to build a web-based interactive portal based on our SD models, the three packages capability of building a web-based portal was taken into consideration. SD web-based tools enable users to use SD models on their computers, phones, and other devices that can browse the internet. We have used the web-based tools
list introduced by the SD Society under the web-based tools section on their website (System Dynamics Society, 2016). These tools are Forio Online Simulations, iMODELER, Insight Maker, Sysdea, isee Exchange, and BROADVIEW. Forio Online Simulations is providing two different solutions: Forio Simulate and Epicenter, so we have included both. More information about web-based tools is available in Subsection 3.3.1

Table 3.4 SD software packages comparison

<table>
<thead>
<tr>
<th>Feature</th>
<th>STELLA</th>
<th>PowerSim Studio</th>
<th>Vensim</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automatically simulate a model on changes</td>
<td>Stella Live</td>
<td>No</td>
<td>SyntheSim</td>
</tr>
<tr>
<td>Advanced validity testing</td>
<td>No</td>
<td>No</td>
<td>Reality Checks</td>
</tr>
<tr>
<td>Advanced simulation reporting (ex. histograms, Gantt charts) and results statistics</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Free personal/educational version</td>
<td>No</td>
<td>Yes, but limited</td>
<td>Yes, but limited</td>
</tr>
<tr>
<td>Web-Based Tools support model format: Forio Online Simulations-Forio Simulate</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Web-Based Tools support model format: Forio Online Simulations-Epicenter</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Web-Based Tools support model format: isee Exchange</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Web-Based Tools support model format: iMODELER, Insight Maker, Sysdea, and BROADVIEW</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

Even though I initially selected Stella as my choice of software, I changed it to Vensim for two primary reasons. First, compared to the Studio Express of Powersim and Stella, Vensim PLE is far more capable in terms of models to run in addition to the modelling process itself. The second reason was that the Vensim model format is supported by more SD web-based tools, including both Forio Simulate and Epicenter, which we have used later to host our models. Advanced validity checks and reporting tools in addition to the SyntheSim mode could be definitely added to the reasons.

3.3.1 SD Web-Based Services

Using the right technologies can save the cost and effort. As mentioned earlier, we have conducted a comparison between the web-based services presented by the SD Society under the web-based tools section on their website (Society, n.d.). These services are:

- Forio Online Simulations which provides two different solutions:
• Forio Simulate (http://forio.com/simulate/)
• Epicentre (http://forio.com/products/epicenter/)
• iMODELER (http://www.consideo.com/)
• Insight Maker (https://insightmaker.com/)
• Sysdea (https://sysdea.com/)
• isee Exchange (https://exchange.iseesystems.com)
• BROADVIEW (http://getbroadview.com)

We have conducted different experiments with these services to recognise their potential and find out which will suit our requirements. Table 3.5 summarises the results of these experiments. We have checked the possibility of having a free account, whether models can be licensed under creative commons, whether they support Vensim model format or at least be able to import it, whether models interface built with these services can be embedded in other services outside their domain so that we can conduct our ILE experiments with users, and whether they rely on web technologies that we can edit and add more functionalities.

Table 3.5 Summary model hosting services

<table>
<thead>
<tr>
<th>Model Hosting Service</th>
<th>Free account</th>
<th>Models can be licensed under creative commons</th>
<th>Vensim model format support</th>
<th>Embeddable interface outside its tool</th>
<th>Editable interface outside its tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forio Online Simulations - Forio Simulate</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Forio Online Simulations - Epicenter</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>iMODELER</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Insight Maker</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Sysdea</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>isee Exchange</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>BROADVIEW</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

Only Forio solutions were able to support the Vensim model format even though its free version was limited. However, given that we needed Forio to design our scenarios and host our model, we paid for the subscription and selected services to host our model. Furthermore, the Forio solution allows building and sharing simulations and making them
interactive using an interface design tool. SD models can be imported or made in Forio Simulate.

3.4 Ethics Approval
An ethical checklist needs to be first completed for any research involving human participants. This acts as a screening mechanism to identify those studies, which merit additional ethical support. The research has obtained a formal ethical review approval from the Loughborough University Ethical Approvals (Human Participants) Sub-Committee (Ethical Clearance Checklist form found in Appendix H). Furthermore, information sheets and consent forms have been provided to the participants and signed (see Appendix H).

During the interviews, consent was asked to record the conversation, whilst during the analysis, coding was implemented to ensure anonymity of the participants (Schutt, 2012).
4 MODEL FORMULATION

The purpose of this chapter is to present the results from the participatory SD (GMB) process. It will discuss how the group model-building sessions were conducted, the conceptual model was formulated, and relevant factors and interrelations from the qualitative model are mapped and converted to quantitative model and refined with stakeholders. The full quantitative model and its relevant variables in the model structures which encompasses the phases of the dispensing process will be discussed in detail, and finally, a list of evaluation assessments for SD model is conducted to build confidence in the model, and assessment results are provided.

4.1 Introduction

To provide a systemic view and better understanding of the pharmacy dispensing process with their factors, a qualitative model of SD is developed in this chapter. This qualitative SD model, reflecting the findings of the systematic literature review and preliminary interviews, links model variables together, graphically presents variable interrelations, and provides clear traces of different hierarchical causes.

The chapter starts with discussions on how the GMB sessions were conducted. Initially, the purpose was identified and the boundary of the model. The details of how the causal-loop diagrams for staff workload management are developed are described. Finally, the qualitative model in the form of a causal-loop diagram is illustrated based on the systematic reviews and expert feedbacks, and the model is explained and discussed in detail. The qualitative model helps to understand the interrelations of the variables of the pharmacy dispensing system. By observing these factors and loops, it encourages
thinking regarding possible strategies. However, causal-loop diagrams cannot show quantitative changes of the variables of the system. To observe quantitative system behaviours and have a more in-depth look into system response to the changes of variables; a developed quantitative model is required. In order to present quantifiable factors such as workload, errors, prescription flows and interruptions, the quantitative model structure is formulated in this chapter.

### 4.2 Conducting the Group Model Building Sessions

#### 4.2.1 Background

The study began with an acknowledgement that the heavy workload of healthcare professionals is a significant problem in the NHS. Increased demand and reduced staffing to contain costs have caused healthcare professionals to experience higher workloads than ever before. Conventionally, the staff workload management in the NHS is based on matching between staff capacity and demand, but it often fails to take account of the unintended impact of dynamic staff workload on patient safety.

The impact of ever-increasing workload on patient safety, however, is not straightforward to understand. Existing research explains only potential conceptual and qualitative impact of heavy workload on patient safety (Carayon and Gürses, 2005; Cook and Rasmussen, 2005). However, it is very challenging to influence health care management practices and decision making without an understanding of the unintended impact on patient safety in quantitative terms. In addition, the recent Berwick review into patient safety, ‘Recommendations to improve patient safety in the NHS in England’ (D Berwick, 2013) identified the urgent need for developing methods and guidance for staffing ratios based on a dynamic understanding of staff workload and scientific data.

#### 4.2.2 Establishing a Modeller-client Relationship

The research project began with a series of semi-structured interviews with the hospital pharmacy dispensary staff and its management (see Table 4.1). The objective was to exploit the potential of systems thinking tools and integrated modelling in learning and decide the staff workload management issue by supporting them to better consider the impact of staff levels, interruptions and workload on safety (dispensing errors) and performance (backlog).
Table 4.1 Preliminary Interviews

<table>
<thead>
<tr>
<th>Preliminary Interviews Conducted</th>
<th>Roles</th>
<th>Participants</th>
<th>Hospital</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Administrators/Receptionists</td>
<td>2</td>
<td>Glenfield</td>
<td>1 hour each</td>
</tr>
<tr>
<td></td>
<td>Labellers</td>
<td>4</td>
<td>Glenfield/Royal Infirmary</td>
<td>1 ¼ hours</td>
</tr>
<tr>
<td></td>
<td>Checkers</td>
<td>3</td>
<td>Glenfield/Royal Infirmary</td>
<td>1 hour each</td>
</tr>
</tbody>
</table>

4.2.3 Preliminary Model

As a starting point for the study and as described in section 3.1.2.6, a preliminary model was created to describe the broad issues which were deemed necessary to understand the hospital dispensary system. The model was based on findings gained through the literature review and group discussions with administrators (n = 2), labellers (n = 4) and checkers (n = 3). It served as a modelling heuristic or an artefact that helped to:

1. articulate the current understanding of the situation,
2. share this understanding with the stakeholders, and
3. guide data collection in the next stage

At this point, decision centred on developing a highly aggregated conceptual model of the labelling and checking processes, deriving data from the initial interviews conducted and avoid the detailed use of causal mapping techniques. Caution was exercised to avoid drawing speculative or premature causal assertions about the problem, noting that to do so would be likely to adversely affect the design of subsequent data collection (i.e. observer’s expectancy bias).

The objective of the interviews was to elicit the mental models that pharmacy dispensary staff possessed about dispensing errors as users’ perceptions and knowledge constitute rich, valuable and legitimate input to problem representation (Jakeman et al., 2006). Moreover, Morgan et al. (2002) argue that it is important to conduct a deep investigation of stakeholders’ mental models before designing effective interventions. Therefore, mental model mapping was employed to:

1. elicit relevant issues as framed by labellers and checkers;
2. capture the salient rules that govern dispensing process; and
3. identify communication gaps, and hence, establish modelling requirements.
The data from each of the interviews were coded, causal links were formulated, from which models were constructed (Bryson, 2004) to provide clarity of thoughts by the problem owners and the modeller.

Figure 4.1: Preliminary model of labelling process

Figure 4.2: Preliminary model of checking process
There were common themes found between the dispensing group and the checking group. They are workload, number of staff, time required to properly self-check, interruptions from colleagues and performance issues (fatigue and stress).

4.2.4 Group Facilitated Sessions and Validation

4.2.4.1 Interview script

The preliminary models presented in Figures Figure 4.1 and Figure 4.2 provided the basis for structuring the group semi-structured interview script for the model. An initial list of questions was generated to foster open discussion through which participants might be stimulated to reveal their perceptions and views. The simple preliminary model of what perceived to be the problem domain was drafted on a whiteboard and interview script was used to jumpstart a group dialogue:

1. Explain that the purpose is here to help you and understand how the system works.
2. Emphasise that we do not aim to apply a blame-approach.
3. Before modelling, participants should write top three probable causes of dispensing errors.
4. Explain briefly what the SD polarity means when it comes to modelling.
5. Which factors affect workload?
6. Which factors affect interruptions?
7. Which factors affect dispensing errors?
8. Which factors affect backlog?
9. What variables would you remove from this preliminary model?
10. What variables would you add to this model?
11. What do you suggest on how to improve dispensing errors?

4.2.4.2 Group Facilitated Sessions

The modelling process was conducted, and the conceptual and quantitative simulation model completed in 12 weeks, which is considerably shorter than many other participatory modelling processes (Antunes et al., 2006; Otto and Struben, 2004; Stave, 2002; Tidwell et al., 2004).
After the preliminary interviews, a single large group session was conducted. The model building group session was attended by 13 practitioners who were either labellers (n = 5), trainees (n = 6) and checkers (n = 2). None of the participants had ever used simulation in any form before.

Table 4.2 Group model building session participants

<table>
<thead>
<tr>
<th>Model Building Session</th>
<th>Roles</th>
<th>Participants</th>
<th>Hospital</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Labellers</td>
<td>5</td>
<td>Glenfield/Royal Infirmary</td>
<td>1 hour</td>
</tr>
<tr>
<td></td>
<td>Trainees</td>
<td>6</td>
<td>Glenfield/Royal Infirmary</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Checkers</td>
<td>2</td>
<td>Glenfield</td>
<td></td>
</tr>
</tbody>
</table>

After the preliminary model was formulated based on early group discussions, a notice was put in the hospital pharmacy dispensary for participatory model building session. The dispensary team-leader of the dispensary had difficulty getting approval for several sessions to be organised as the hospital dispensary was running a busy rota. As it was quite difficult to organise a group session during their working hours, the only feasible time and place they could converge as a group were during lunch break at the hospital pharmacy dispensary canteen. Since model-building is also a process of learning where mental models of the participants are changed, it was important to include methods that allowed interactions and discussion in every session, in order to improve existing mental models and to clarify the problem.

Table 4.3 Top 3 contributory causes to dispensing errors listed by participants (pre-test)

<table>
<thead>
<tr>
<th>Cause</th>
<th>Ambiguity</th>
<th>Comm.</th>
<th>Fatigue</th>
<th>Final Check</th>
<th>Skill</th>
<th>Interruptions</th>
<th>Self-check</th>
<th>Sick</th>
<th>Workload</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 participants mentioned</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>13</td>
<td>4</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

The session started with participants introducing themselves. Secondly, I explained the purpose of the session and asked them to write the three top causes of dispensing errors (see Table 4.3), then finally I presented an introductory presentation on what SD is (see Figure 4.3). The three top causes of dispensing errors served a pre-test of what they perceived to be the top contributory causes of dispensing errors which will be evaluated after the model has been formulated and simulated in Section 6.2. I started with a simple conceptual diagram exercise that shows the relationship between three variables: death, population and birth and how they are interconnected. By explaining the polarities and
starting with a simple exercise, participants managed to understand the basic concept of qualitative system dynamics modelling.

After introducing SD, an hour was spent talking about the simple preliminary model, which variables to add or subtract and reach consensus on a group model. The preliminary model started with two state variables, ‘Tendency for Errors’ which leads to ‘Errors’ (see Figure 4.4). We engaged the participants through plenary dialogue, hands-on activities, and interaction with the preliminary SD model. I chaired the session with support from my colleagues. Participants actively supported model development when they created sketches of the important elements that influence dispensing errors. The themes captured by these images served as the foundation for updating the preliminary model into a working model. We continued engaging the model's structure level. Participants evaluated the information captured in the model and made suggestions for further refinement by adding group-contributed variables that they view as critical to the contribution of dispensing errors.

The broad aim of these sessions was to convey the focus of the study (and model) and present the model in a comprehensible form so that their views of the model could be elicited. The importance of checking each stage for errors and promoting a degree of model ‘ownership’ was emphasised, and these meetings were presented as part of this process. It was also explained that, although the model would be calibrated to the experiences of this particular hospital pharmacy dispensary, the aim was to produce a general model of the feedback mechanisms involved in the evolution of hospital pharmacy dispensaries. This point was made to avoid the potential pitfall that the pharmacists would be ‘blinkered’ by their personal experiences. Finally, the session was audio recorded, and relevant pictures were taken of participants engaging with the model.

Figure 4.3: (a) Participatory modelling (b) Final output
4.2.5 Causal-loop Qualitative Diagram

4.2.5.1 Subsystem and their interrelationships

In the session, four subsystems were selected by the group (see Figure 4.5). The relationships amongst the subsystems arrived during the first session. These subsystems and their interrelationships are the building modules of the conceptual model and stock-
and-flow diagram for the hospital pharmacy dispensary. The subsystems fit the dispensary system boundary. The four subsystems are as follows:

- The interruptions (questions) subsystem influences the staff, production and the performance subsystems and is influenced in return by the production, staff and performance subsystem.
- The staff (workload capacity) subsystem influences the interruptions, production and performance and is influenced in return by the interruptions, production and performance.
- The production (dispensing) subsystem influences the interruptions, performance and staff and is influenced in return by the staff, performance and interruptions.
- The performance (fatigue) subsystem influences the interruptions, production and staff and is influenced in return by the production, staff and interruptions blocks.

![Simulation model subsystems](image)

**Figure 4.5: Simulation model subsystems**

4.2.5.2 Refine Causal Diagram

SD models can be used either to explain the occurrence of a policy problem or to suggest ways to mitigate the problem or both. Policy in this context could be defined as a broad rule for decisions. In general, SD models facilitate the analysis of long-term implications of policies and structures in a system. As stated earlier, identification of cause-effect relationships constituted one of the most critical and earliest steps in the model development process, as it plays a central role in SD. In our SD model, identification of causal relationships and policy structures were not restricted to availability of quantitative data. As Forrester (2007) urged, “powerful small models”, can be used to communicate
the most crucial insights of a model to the public, who may not have the in-depth knowledge about the subject.

Further, many small SD models are capable of capturing vital, often counter-intuitive insights of a complex problem. These small models will enable policy-makers to understand complex issues easily. From its inception, much effort was taken to keep our model to a “small model”, whilst keeping it generic in nature. Keeping the model generic will enable it to be used to address similar policy issues, which in turn will help to enhance the value of the model.

During the model development process, the aim was to construct structures not only to illustrate or depict historical patterns but also to remain valid under extreme conditions. The purpose of this was to make the model robust enough to encounter unexpected extreme situations. Furthermore, during model development, causal-loop diagrams, flow diagrams and mathematical equations were kept as simple as possible. The purpose here was to make the various study objectives transparent and easily understood. When developing this model, more emphasis was paid to the structure than to the parameter values.

A causal-loop conceptually reveals the dynamic process in which the chain effects of a cause are traced through a set of related variables back to the original cause. This conceptual model in a causal-loop diagram, as shown in Figure 4.6 is comprised of four major feedback loops. Out of these four feedbacks, two are positive (i.e. R1 and R2), and the other two are negative (i.e. B1 and B2). The behaviour of the hospital pharmacy dispensing system is defined through the dynamic interactions between these feedback loops.

Figure 4.6: Refined qualitative diagram
Loop B1 shows the dynamic behaviour of staff management. It can be noted that having less qualified staff allows them less time to process or dispense prescriptions which in turn forces to increase the propensity of committing more errors which in turn leads to more undetected errors. After a long delay, it can convert into patient harm. Such unstable behaviour can be avoided by finding the proper balance in assigning correct staffing levels to accommodate the workload and give them greater amount of time to dispense the prescriptions.

The reinforcing feedback loop R1 shows one of the side feedback effects for staffing management process of reducing the balancing effect of loop B1 to stabilise staffing levels oscillations. The higher the workload, the less time to self-check which leads to more detected errors being committed. This forces staff to redo the work which in turn creates backlog and workload is subsequently increased. Loop B2 shows the dynamic behaviour caused by interruptions, specifically questions from trainees. Interruptions force labellers to redo the work which contributes to the time to process or dispense prescriptions. As they have to rush, it increases the propensity for committing errors and doing rework. By introducing an offset of qualified labellers to answer the questions of trainees, it balances the number of interruptions that qualified staff receive. The reinforcing feedback loop R2 displays the affect interruptions have on the performance of the staff. The more staff are interrupted on a regular basis, the stress it induces, the more stress the staff have to deal, the more fatigue is introduced. This will have an impact on the number of errors committed, and this can only be mitigated by having proper staff levels to reduce the number of interruptions.

4.2.6 Stock and Flow Quantitative Diagram
The model purpose outlines the broad aims of the study, the target audience, the policy levers of interest and the desired outcomes. In formulating a formal simulation model from the informal conceptual model, a clear purpose is essential. It provides a clear focus on what should be included and what should be excluded from the simulation model (Richardson et al., 1981). Without it, the model may become cluttered with unnecessary detail thus undermining the ability to seek useful policy insight.

The second phase of an SD simulation study involves the conversion of the informal conceptual model into a formal simulation model. This is referred to as the formulation phase. It is followed by an experimental phase, which aims to provide insight into the base case behaviour and, by conducting policy analyses, obtain insight into how more
desirable behaviour may be achieved. In practice, the different modelling phases are iterative. A process of model testing and refinement is embedded within the SD approach. This produces iterations as models are constructed gradually and undergo a series of revisions. The model output is analysed for sources of insight into the relationship between behaviour and structure and the existence of model errors. The model structure is refined, and analyses are rerun on the revised model.

After identifying the major variables affecting the hospital pharmacy system, their interrelationships are defined and quantified mathematically (see Appendix C for model code). The conceptual model in Figure 4.6 is then converted into a stock-and-flow diagram by using the Vensim PRO software described in the sections below. Many essential details are added through the converting process to the conceptual model to enable simulation quantitatively. Prior to performing quantitative simulation and analysis, quantification of majority of the variables has been accomplished by collecting data from University Hospitals of Leicester dispensary databases.

In total, all values of the quantitative variables were obtained from the participatory group sessions and database data from the hospital dispensary databases.

Despite the fact that the causal relationships for the following SD models are generated from the validated causal-loop diagram, it is important to note that the appearance and arrangement of variables within the sub-models will differ from those shown the causal-loop diagrams. This can be explained thus:

- Different symbols (i.e. levels, rates, auxiliary, and constants) will be used at this stage, and they require a different logical arrangement.

- The variables are linked together by relationships that are governed by equations; therefore, the variables should be shown together to be able to create the equations.

- The whole model and its variables are interactive in a very dynamic way, so its location within the model is not essential. For clarity and a fluent description of the model, a small number of variables is shown together.

Once the stock-and-flow model was created in Vensim PRO software, the UHL hospital pharmacy dispensaries were revisited to collect data from participants and NHS databases on the number of incoming prescriptions, outgoing prescriptions, the number of daily interruptions, number of minimum staff and detected and undetected dispensing errors.
First were the incoming urgent and non-urgent prescriptions received per hour by each hospital pharmacy dispensary. The urgent prescriptions have priority over the non-urgent, and this is simulated in the model. Second was the number of staff required to effectively (lean) run a hospital dispensary depending on the number of machines available. This includes the maximum capacity of each staff group when it comes to dispensing the prescriptions. This was obtained from the UHL hospital pharmacy dispensaries. Third was the errors data showcasing the number of errors committed by each practitioner allowing us to fine-tune the model.

On the next page, the stock-and-flow quantitative diagram is displayed (see Figure 4.7). Due to its large size, it is difficult to decipher the text, and as a result, I will closely explain the sections compromising the stock-and-flow diagram. A larger version of the simulation model is shown in Appendix D.

Section 4.2.6 will look at the factors of the developed simulation model based on the subsystems, as defined in Figure 4.5.

In 4.2.7 the scenarios are defined, and in 4.2.8, the model is validated with participants.
Figure 4.7: Quantified Stock-and-Flow diagram

See Section 4.2.6.1

See Section 4.2.6.2

See Section 4.2.6.3

See Section 4.2.6.4
4.2.6.1 Factors affecting the production (dispensing) subsystem

In a typical hospital pharmacy dispensary system, incoming prescriptions are separated into a plethora of categories. For the purpose of this model, prescriptions were separated into two distinct categories based on the expected turnaround time. They are urgent prescriptions and non-urgent prescriptions. Urgent prescriptions have to be dispensed within 4 hours upon receiving.

For this study, the hospital pharmacy dispensary model is used to define productivity in the following form: productivity is affected by incoming prescriptions, rework, number of staff and capacity. If there is a change in the scope of the work, the productivity is considered to decrease due to the factors of continuous high workload, fatigue, reduced staff, and interruptions. Incoming prescriptions are the hourly prescriptions that the administrator/receptionist receives, placing them in their respective trays based on their level of urgency. Urgent prescriptions have priority over non-urgent prescriptions, and this is reflected in the model where urgent prescriptions are first labelled and dispensed before urgent non-urgent prescriptions are considered. Once urgent prescriptions are received, they accumulate in an unlabelled stock and are processed. The labelling rate of urgent/non-urgent unlabelled prescriptions is affected by the number of errors found by labellers. The error rate increases the workload by a degree equivalent to the error rate as the labeller has to relabel prescription with the error. The labelling rate formula below signifies the correct labelled medications:

$$\text{Labelling rate of urgent prescriptions} = (\text{Capacity assigned for urgent labelling}) \times (1 - \text{Delayed effect of labeller error ratio})$$

Labellers find a certain percentage of detected errors during the self-checking process which is the first phase of rework. Based on the data from hospital pharmacy dispensary, each labeller picks up two corrections per hour at 70% workload capacity. The delayed effect of staff error ratio indicates that the effects of workload increase/decrease are delayed by 1 hour. Based on the validation and verification discussions with the labellers and checkers, they concluded that they were able to work for an hour under increased workload and with standard efficiency of making acceptable labelling error (n = 1).

$$\text{Urgent prescriptions with labelling errors} = (\text{Capacity assigned for urgent labelling}) \times (\text{Delayed effect of labeller error ratio})$$
The labeller error ratio is dependent on the workload. It is based on the actual error rate and the success rate of labellers finding their own errors. The parameters were derived from observations, interviews and data from databases. This rate increases when workload increase. If the workload is at a constant 100% per hour for more than an hour, the amount of labelling errors increases to 40% which is based on the incoming prescriptions and existing backlog (see Figure 4.8a). The labeller error finding success rate measures how many of labelling errors the labeller finds after self-checking (see Figure 4.8b). This rate decreases with workload increase. With 100% uninterrupted workload of more than one hour, they can only detect 50% of their errors. For a labeller that works at a capacity of 70% workload, the self-checking success rate stands at 93%.

\[
\text{Labeller error ratio} = (\text{Labeller actual error ratio}) \times (\text{Labeller self check ratio})
\]

![Figure 4.8: (a) actual labeller error rate (b) labeller error finding success rate](image)

The second phase of rework is errors found by the checkers in the final checking stage. These are the undetected errors that labellers made and contribute to the total rework workload. The relabelling of medications found by checkers and brought back to the labellers is calculated as:

\[
\text{Urgent prescriptions assigned to relabel rate} = (\text{Capacity assigned for urgent checking}) \\
\times (\text{Delayed effect of undetected labelling errors ratio}) \\
\times (\text{Delayed effect of labelling error rate found checking})
\]

The checker’s ability to find errors depends on the existing workload. We arrived at the rates from observations, interviews and data from databases. By continuous 100% workload, checkers detect 80% of labelling errors which means that 20% will be undetected errors that will eventually contribute to patient harm. The total urgent dispensed medications (see Figure 4.9) include relabelled medications whose errors have been detected and rectified as well as medications that still contain errors but could not be detected.
**Chapter 4: Model Formulation**

*Urgent prescriptions checked rate*

\[
U_{\text{urgent}} = (\text{Capacity assigned for urgent checking}) \times (1 \quad - \quad \text{Delayed effect of undetected labelling errors ratio}) \\
+ (\text{Capacity assigned for urgent checking}) \\
\times (\text{Delayed effect of undetected labelling errors ratio}) \times (1 \quad - \quad \text{Delayed effect of labelling error rate found checking})
\]

Finally, undetected errors not found by checkers and which eventually make it to the patients is illustrated in the following formula which calculates:

*Undetected error rate*

\[
U_{\text{undetected}} = \text{Labeller actual error ratio} \times (1 - \text{Labeller self - check ratio}) \times (1 \quad - \quad \text{Checker check success ratio})
\]

Figure 4.9: Incoming prescription to outgoing medication workflow

Figure 4.10: Capacity priority allocation flow
For capacity, the total capacity of labellers per hour is calculated. The model contains a
capacity allocation (see Figure 4.10) that prioritises urgent prescriptions over the non-
urgent prescriptions. It first calculates capacity needed to relabel existing prescriptions
that were found to contain errors as they are the highest priority for labellers. After
relabelling, the remaining capacity is calculated for the rest of labelling. This builds the
importance of the task chain as the labeller starts with urgent relabelling then urgent
labelling, then non-urgent relabelling and then finally non-urgent labelling. This goes for
checking process as well.

\[
\text{Capacity assigned for urgent relabelling} = \min\left(\frac{\text{Urgent prescriptions with errors}}{\text{TIME STEP}}, \frac{\text{Total labellers capacity per hour}}{\text{TIME STEP}}\right)
\]

\[
\text{Capacity assigned for urgent labelling} = \min\left(\frac{\text{Urgent unlabelled prescriptions}}{\text{TIME STEP}}, \frac{\text{Capacity left after urgent relabelling}}{\text{TIME STEP}}\right)
\]

\[
\text{Capacity assigned for urgent checking} = \min\left(\frac{\text{Urgent labelled and relabelled}}{\text{TIME STEP}}, \frac{\text{Total checkers capacity per hour}}{\text{TIME STEP}}\right)
\]

Backlog along with dispensing errors are the metrics used to make the practitioners be
familiar with the model and understand its behaviour. The backlog was calculated using
two stocks, the first stock is the sum of both non-urgent and urgent prescriptions waiting
to be labelled and the second stock is the sum of both non-urgent and urgent prescriptions
that have been labelled and re-labelled and are waiting to be checked.

\[
\text{Backlog} = \max(0, \text{Total unlabelled prescriptions} - \text{Total labelled unchecked prescriptions})
\]

4.2.6.2 Factors affecting the staff (workload capacity) subsystem

The model has two staff groups: labellers and checkers. Both groups form the core staff
group that runs the hospital dispensary. Each staff group is regulated by a stock which
adds and removes labellers and checkers depending on the level of incoming
prescriptions.

Given that both staff groups’ stocks have similar formulas, only the labeller group stock
will be explained below (see Figure 4.11). The labeller stock starts with an initial number
of labellers. It has an incoming and outgoing rate. They are added labellers rate and
removed labellers rate.

The added labellers rate uses an IF THEN ELSE statement to calculate the number of
labellers added per hour. If total unlabelled prescriptions are greater than total labellers’
capacity per hour and a maximum number of labelling staff available is greater than current labelling staff, it automatically adds labellers. The rate works conservatively as it is activated when there is even a small shortage of capacity. That shortage can be less than one worker capacity.

\[
\text{Added labellers rate} = \text{IF THEN ELSE}((\text{Total hourly labellers' capacity} < \text{Total unlabelled prescriptions/TIME STEP}) : \text{AND}: (\text{Number of labellers} < \text{Maximum number of labellers}), \text{MIN(INTEGER}((\text{Total unlabelled prescriptions} / \text{TIME STEP}) – \text{Total hourly labellers capacity}) / \text{Current hourly capacity of average labeller}, (\text{Maximum number of labellers – Number of labellers})/\text{TIME STEP}), 0)
\]

Similarly, if total labellers capacity is greater than total unlabelled prescriptions and the current number of labelling staff is greater than the minimum number of labellers, the remove labeller rate is applied.

\[
\text{Removed labellers rate} = \text{IF THEN ELSE}((\text{Total hourly labellers capacity} > \text{Total unlabelled prescriptions/TIME STEP}) : \text{AND}: (\text{Number of labellers > Max no of labellers}), \text{MIN(INTEGER}((\text{Total labellers capacity per hour} / \text{Current hourly capacity of average labeller}), (\text{Number of labellers – Max no of labellers})/\text{TIME STEP}), 0)
\]

Figure 4.11: Staffing level add/remove system
Both pharmacist groups have different capacity capabilities. It is recognised that different pharmacists have different abilities and may perform different quantities of work more efficiently and safely than others. However, there is an optimum workload that pharmacists may perform, after which, the potential for increasing errors rises. Based on the data from the hospital pharmacy and literature, a median of 150 was nominated as the maximum number of prescriptions that can be safely dispensed per 9-hour shift day which is 17 prescriptions per hour (Peterson et al., 1999). The maximum capacity at 100% workload for labellers at UHL hospital pharmacy dispensary is 20 prescriptions per hour. Utilising Rasmussen’s safety envelope (Rasmussen, 1997) in determining the safety boundaries of acceptable workload, the formula was as follows:

\[
Acceptable\ work\ load = \frac{17\ prescriptions\ per\ hour\ (safe\ capacity)}{20\ prescriptions\ per\ hour\ (maximum\ capacity)}
\]

Which indicates that the safe threshold to safely dispense prescriptions without a rapid increase in errors is 85% of maximum capacity. The total capacity of labellers per hour of the hospital dispensary is calculated as:

\[
Total\ capacity\ labellers\ per\ hour = \text{Current capacity of average labeller} \times \text{Number of labellers}
\]

4.2.6.3 Factors affecting the interruptions subsystems

Interruptions play a huge role in the typical hospital pharmacy dispensary. Trainees interrupt qualified pharmacists with questions based on the incoming prescriptions. To incorporate this into the model, the level of interruptions is depended on the incoming prescriptions and the capacity cost which is to answer trainee question. As a result, labellers lose a certain capacity (see Figure 4.12).

The user has the option to set the percentage of prescriptions queried by trainees. Based on the interviews conducted in UHL Glenfield around 20% of all incoming prescriptions are queried per hour. The capacity cost set as the default is 3. So, capacity cost 3 indicates that to answer trainee question labeller loses the time to label two prescriptions and the trainee loses the time to label one prescription, so the total capacity of staff is incrementally reduced by three prescriptions per question. If they answer five questions per hour, they dispense ten prescriptions less which has an effect on their total capacity and is automatically deducted from the total capacity.

\[
All\ questions\ capacity\ cost\ per\ hour = \text{Number of questions per hour} \times \text{Capacity cost per question}
\]
4.2.6.4 Factors affecting the performance (fatigue) subsystem

The performance subsystem is affected mainly by the workload and the pharmacists’ average capacity (see Figure 4.13). As noted in 4.2.6.2, the maximum prescriptions that a labeller can dispense are 20 prescriptions per hour whilst checkers’ capacity is much higher at 86 prescriptions per hour. This is due to their level of experience and skill level, and that final checking is a relatively faster job than actually dispensing it.

The current capacity of one labeller is the sum capacity of the capacity restoration rate and the capacity depletion rate.

\[
\text{Current capacity of average labeller} = \text{Labeller capacity restore rate} - \text{Labeller capacity fatigue depletion rate}
\]
The capacity depletion rate of the average labeller is interlinked with the workload. If the average labeller encounters persistent workload of over 85% for more than 2 hours, the fatigue depletion rate kicks in, gradually decreasing its capacity by an hourly 5%.

\[
\text{Labeller capacity fatigue depletion rate} = \text{IF THEN ELSE}(\text{Workload ratio of labeller} > 85, \text{MAX}(0, \text{(Current capacity of average labeller} - \text{Maximum capacity of average labeller per hour})/2) \times \text{Labeller fatigue depletion percentage})/\text{TIME STEP, 0})
\]

This means that if labeller workload is above 85% of current capacity, then it reduces current capacity by 5% of available capacity over the minimum capacity of the average labeller. This is an hourly reduction if the workload is still high. The minimum capacity is equal to half of maximum capacity = 10 prescriptions per hour. If there is no fatigue (depletion rate = 0), then the labeller’s capacity is restored by 5% of missing maximum value up to maximum capacity value.

\[
\text{Labeller capacity restore rate} = \text{IF THEN ELSE}(\text{Labeller capacity fatigue depletion rate} = 0, \text{(Maximum capacity of average labeller per hour} - \text{Current capacity of average labeller}) \times \text{Labeller capacity restoration percentage})/\text{TIME STEP, 0})
\]

The workload ratio of labeller is measured from 0% to 100%, where 0% equals no workload, and 100% equals full workload. If the workload increases and persist for several hours, the labellers/checkers find fewer errors when self-checking and the number of errors that they make increases.

\[
(\text{Group}) \text{Workload ratio of labellers} = \frac{\text{Used hourly capacity of total labellers}}{\text{Total labellers' capacity per hour}} \times 100
\]

4.2.7 Model Scenarios

4.2.7.1 Base Model
We developed a preliminary conceptual model (causal-loop diagram) of the relationship amongst staff ratio, interruptions and fatigue over a period of 24 hours. This development commenced with a systematic review of the literature, then involved a series of semi-structured interviews. The final qualitative model was finally developed using a group model-building session and was articulated in terms of a causal-loop diagram. Its mathematical representation was constructed in Vensim PRO.

The mathematical expression of the causal-loop diagram was an SD model structured as 13 stocks and flows modules connected by auxiliary information to form an
interdependent set of co-flows. The primary outcomes of the model that were of interest in this study were the workload, interruption and fatigue trade-off impacting system performance and effects of system changes. We calculated measure output in terms of backlog and dispensing errors where backlog is the number of incoming prescriptions waiting to be labelled and dispensed and dispensing errors is the number of detected and undetected errors made by the staff.

The three main loops (see Figure 4.14) can be summarised as follows:

- **Loop 1:** Increase in workload, decrease time to self-check for errors, increase in dispensing errors, increase in rework done, increase in backlog, increase in workload (reinforcing loop) – See Figure 4.14A.

- **Loop 2:** Decrease in qualified staff, increase in questions from trainees, increase in interruptions, decrease in time available to dispense prescription, increase in dispensing errors, increase in undetected errors, increase in patient harm, increase in qualified staff (balancing loop) – See Figure 4.14B.

- **Loop 3:** Increase in workload, increase in stress, increase in fatigue, increase in dispensing errors, increase in undetected errors, increase in patient harm, increase in staff, decrease in workload (balancing loop) – See Figure 4.14C.

Figure 4.14: (A) Loop 1 (B) Loop 2 (C) Loop 3
We developed the three model scenarios based on inputs from the participants. We used exogenous and endogenous inputs for the model parameters extracted from a series of interviews and group sessions with practitioners, pharmacy databases and literature. Verification performed included logical tests, sensitivity analysis, and face validation from the stakeholders. Validation of the model was undertaken for each scenario for which sufficient quality data were available from the hospital pharmacy dispensaries.

We created variants of the base model for the scenarios based on a generic hospital dispensary. We customised the model to each hospital pharmacy dispensary allowing them to change the model’s baseline values to match their respective hospital pharmacy dispensary such as the number of incoming prescriptions per hour, the number of staff and the number of prescriptions queried. Once the base model and variants were developed, we performed a simulation for each dispensary to establish outcomes for the simulation period and how this affects system performance. For all simulations, the dispensary boundary was considered the scope of the model.

4.2.7.2 Model Assumptions

During the simulation experiments, some fundamental assumptions are made. Because the quantitative model reflects the hospital pharmacy dispensary process and covers many variables, assumptions are made in order to simplify the simulation situation and to reduce time and resources.

- Assumption 1: The non-urgent incoming prescriptions are grouped. The non-urgent prescriptions are composed of CD bookings, day cases, external day cases, homecare and inpatient medication requests. They are not treated as urgent and have similar turnaround time. As a result, they are grouped under one category. The urgent prescriptions are mainly the TTO/Discharge prescriptions which are always treated as urgent.

- Assumption 2: Even though administrator/clinical checkers are part of the dispensing process, we do not include it in this model as their task is mainly restricted to initial verification and to make sure that the prescriptions are correct before it is labelled and dispensed.

- Assumption 3: During this simulation, dispensing errors discovered by nurses or patient after final checking is not included.
• Assumption 4: We assume that all the staff groups start at the same time every day which is 9 AM.

• Assumption 5: Once checkers detect labelling errors and they are relabelled, we assume that the second relabelling is 100% correct. This is to prevent endless loops.

• Assumption 6: Malfunctions of the automatic dispensing unit (robot) is not included. We assume that the robot operates at 100% uptime.

• Assumption 7: Because of unreliable data on undetected errors, only the detected dispensed medication errors collected by the dispensaries were used as dummy data.

• Assumption 8: Due to reliable solid data, we deduced, based on answers from interviewees, the number of prescriptions queried per hour by trainees.

4.2.7.3 Scenario 1: Number of Staff on Production and Safety
Scenario 1 (see Figure 4.15) examines the impact of staffing level on efficiency (production) and thoroughness (safety). It analyses how a number of different types of staff can have an impact on production and errors (safety). The web interface is composed of four different tabs, namely incoming prescriptions, outgoing prescriptions, workload of staff, staff changes and backlog. The incoming prescriptions tab illustrates the number of urgent and non-urgent prescription requests received per hour. The outgoing prescriptions tab shows the number of dispensed medications free from detected errors per hour. The workload tab reveals how relabelling (rework) affects the workload of labellers. The staff changes graph shows the number of additional staff brought in per hour to tackle any growing backlog and when it is reduced once the backlog subsides. The backlog tab shows the backlog and the number of errors (self-check errors and errors caught by checkers).
4.2.7.4 Scenario 2: Interruptions on Efficiency and Safety

Scenario 2 (see Figure 4.16) is a screenshot of Forio web interface of the model. It displays outputs of how effect interruptions (questions from co-workers and trainees) have an effect on the level of efficiency. Interruption is calculated on the percentage of incoming prescriptions that are queried by trainees and co-workers. Every query is equivalent to three prescriptions that could have been dispensed, one prescription that could have been dispensed whilst answering the query and one that indicates restarting the dispensing of the existing prescription and one that the trainee could have dispensed instead of querying it. The user can play with the percentage of prescriptions queried by trainees and see how that impacts performance. The web interface has four tabs: Workload, Outgoing Prescriptions, Interruptions/Capacity (labeller) and Backlog. The workload tab illustrates a line chart indicating how interruptions have a bearing on the workload. It is displayed using two series, one variable (green) shows the workload without interruptions, and the other (purple) reveals workload with interruptions. The second tab presents the dispensed prescriptions free from detected errors, revealing to the user when the last batch is dispensed. The interruptions/capacity tab shows the performance loss labeller deals with when answering the questions. This is deducted from the capacity of the labeller. The backlog tab shows the metrics of existing backlog and how interruptions affect it.

Figure 4.15: Forio Web interface for Scenario 1 – see Appendix E.1 for a larger version
4.2.7.5 Scenario 3: Fatigue on Efficiency and Safety

Scenario 3 (see Figure 4.17) examines and analyse how the level of workload affects fatigue and eventual burnout which in turn has on capacity and errors. The model takes into account that 85% and above workload can be maintained for a number of hours before fatigue kicks in, this has been validated through interviews. Once the continuous high workload is maintained over a number of hours, the dynamic fatigue formula kicks in, and an hourly reduction of capacity by 5% is applied until the workload downsizes to below 85% which usually happens when additional staff is brought in to reduce the workload or backlog is decreased, and number of incoming prescriptions is reduced. Capacity depletion rate reaches 50% which is the base. Once that happens, an hourly fatigue recovery restoration rate of 5% is applied until full capacity is restored. The graphs reveal that once fatigue kicks in, the number of errors committed shoots up exponentially until it stabilises.
The outputs of Scenario 3 will be presented in combination with Scenario 1 and 2 respectively.

4.2.8 Building Confidence in the Hospital Pharmacy Dispensary Model

In 2000, Sterman (2000) summarised the level of tests form of a list of assessments for dynamic model testing in practice in the classic textbook on business dynamics. Several of these tests were conducted in a group environment whilst others were conducted behind-the-scenes.

(1) Historical Behaviour:

This is one of the most common and important tests, which sets the inputs to the model at their historical values to see if the outputs match history. In order to examine whether the model can replicate the observed behaviour, the incoming prescriptions, average labeller capacity and total outgoing prescriptions variables were selected. The full model worked under historical conditions driven by the statistical data series belonging to 2016 of both UHL Glenfield and Royal Infirmary hospital dispensaries.

(2) Boundary Adequacy:

Model boundaries were discussed at the beginning of the model construction. The model focuses on hospital pharmacy dispensary only. It contains key factors from the literature and the main phases of the dispensing process. The model is reviewed again, and the boundary is deemed to be appropriate.
(3) Structure Assessment:

Because performing structure assessment whilst developing the model is highly recommended (Swanson, 2002), structure assessment of the SD model has been carried out whilst constructing the model. Specifically, the approaches adopted include acquiring information from the literature and obtaining feedback from pharmacists. Labellers and checkers, as well as management, provided feedback on the correlation of system variables, and then the model is transformed according to the dispensing process, during which urgent and non-urgent prescriptions are separated into different flows in order to highlight errors and to observe the outcomes of checked medications. Results show that the model clearly illustrates the case flows from incoming prescriptions to dispensed medications. Moreover, the model structure has passed the “model check” provided by the software Vensim PRO, and there is no flow failure or structure failure.

(4) Dimensional Consistency

There is no arbitrary scaling factor involved in the model. All variables keep the dimensions consistent. The model equations keep the consistent use of units. The units in the model have passed the “units check” provided by the software Vensim PRO.

(5) Parameter Assessment

Parameters in the model have real-life meaning. Parameters are estimated according to published literature or from estimates made by pharmacists. Some of the following parameters were assessed:

- Incoming prescriptions per hour/day -> The urgent and non-urgent ratio and what intervals (quiet, busy)
- The number of total dispensed medications per day
- The level of interruptions (number of questions checker/labellers gets asked) based on ballpark figure
- How many prescriptions can a labeller label in an hour (capacity)
- How many checking can a checker do in an hour (capacity)
- The min number of checkers in the dispensary
- The min number of labellers in the dispensary
• The number of labelling errors done (collectively) – based on the self-check error forms

• The number of checking errors done (collectively)

• The number of undetected errors (in percentage) – based on how many incorrect medications are dispensed and reach patients (old data)

• The average time it takes to dispense regular and non-regular medication

(6) Integration error tests:

Their integration method adopted in the previous simulation is the “Euler” integration method. However, there are a total of three integration methods: Euler integration, Difference integration and Runge-Kutta integration.

• Euler integration assumes that the rates in the model, which are the input and output arrows for the integrated variables, computed at a given time are constant through the time interval or one-time step (Vensim, 2018).

• Difference integration is similar to Euler integration, but it records the value results before the new rates have been computed instead of recording values after determining the levels of the integrated variables. In other words, Euler integration reports levels and the values that result from those levels, whereas difference integration reports the level and the values that resulted from those levels (Vensim, 2018).

• Runge-Kutta integration is an extension of Euler integration. It steps into the time interval, evaluates derivatives, and then provides more accuracy without imposing a severe computational burden (Vensim, 2018).

The other two integration methods were tested. When the model interpretation setting is changed to “Difference” or “RK2 Auto”, the outputs of system variables are compared with previous “Euler” integration outputs, it turns out that no model behaviour changes are observed.

(7) Extreme-Condition Test


One of the most revealing tests is to make a major change in the model parameters and see if the models' response is plausible. Extreme condition testing can be facilitated by the software, in this case by use of the "reality checks" feature in the Vensim PRO
software. Each reality check test consists of a test input coupled to expected behaviour. They take the form, "If test input A is temporarily replaced with a given extreme input, then behaviour B will result".

The reality check test of Vensim PRO only refers to behaviour; this feature matches the requirement of a validity test as explained by Barlas (1996); “In behaviour validity tests, emphasis should be on pattern prediction rather than point prediction because of the long-term orientation of the model”. In other words, the emphasis of validity tests is placed on trends rather than on the precision of the simulated outcomes. Chapter 5 illustrates these tests.

Even though the validity tests were important in terms of building trust in the model, it is worth emphasising that it is impossible to correctly predict the behaviour of a chaotic system based on observation of the system's past (Hannon and Ruth 1996). This means that the output of the model should be taken as indicative under specified scenarios only rather than as a definitive statement of real future events.

(8) Face-Validity Test

A face validity test can be used when simulation models are applied to operational problems. In this test, experts evaluate the closeness of the model and its outcomes to the real system (Zebda, 2002). One such test of ‘plausibility’ was the responses of the group sessions’ participants when presented with model outputs, and the conclusions that resulted from those outputs. At a minimum, the model passed the ‘face validity’ test in that the results were not dismissed as implausible. Instead, they engaged the experts in reflecting on their own issues and picking on aspects of model behaviour that reflected and provided insights into issues they were facing. Further discussion on face validation of the model is discussed in section 6.2.

Finally, as mentioned before, the process of building confidence in a model is an ongoing, iterative process that is embedded in the SD approach. It does not rely upon a single test or performance measure. Confidence in the model develops as the number of tests it withstands increases. Furthermore, the model has to be acceptable to both the modeller and the target audience (Barlas, 1996; Richardson et al., 1981; Senge and Forrester, 1980). The model was constructed and tested with synthetic parameters initially in order to provide some illustrative model output to present to the collaborators. This was deemed very useful as they had not been exposed to SD modelling before. This also facilitated the
discussion of the face validity of the model structure and the process of calibrating the model.

4.3 Summary

Many modellers/researchers emphasise that adequate preparation at the initial stage determine the success or failure of any modelling project (Forrester, 1961; Sterman, 2000; Stave, 2003; Voinov et al., 2016). In this case, the preliminary individual interviews held with practitioners to create a preliminary model for the group model building session proved to be useful. Whilst these interviews enabled me to obtain background information about the system and the stakeholders, appreciate the magnitude of the problems, and accordingly, define the scope and boundary of the model; it was also an important vehicle for building trust and strong relationships with the stakeholders. Considering that there exists a culture of blame in NHS, the individual interviews for developing the preliminary model allowed me to convince potential participants that the model would not focus on individuals but the system as a whole.

Moreover, given the limited time allocated to me to hold a GMB session, the preliminary model significantly reduced the time needed if I started building a model from scratch. Thus, an important take-home lesson is that holding a preliminary interview prior to a GMB session can result in saving crucial time for both modeller and participants by creating a preliminary model, anticipating problems and building trust between participant stakeholders and scientific modellers. This experience further indicates that preliminary individual interviews can avoid costly mistakes, wasted time and efforts, and more importantly, establish a trust that will aid the co-construction of a shared model.

When developing the preliminary model, I made it sure to keep it basic and incomplete. During the group model building session, the participants critically analysed the preliminary model and contributed to the discussion to significantly expand the model and claim ownership to the model. Initial differences were recorded on what variables to put there, but after deliberate discussions, a consensus was reached on which variables were appropriate to adopt into the model thereby contributing to mental alignment of the participants. Three main loops were identified in the shared group model: 1) staff workload 2) interruptions from trainees and 3) capacity depletion when fatigue is induced. The group model offered interesting insights on how staff workload, interruptions and fatigue affect the backlog and dispensing errors. This set the stage for the number of scenarios that the model will offer based on the input from the participants.
However, one possible disadvantage of the qualitative group model was that it does not present the data flow of the system and cannot reflect the quantitative changes of the system when changing model variables or mapping possible strategies into the system. In other words, it can only demonstrate which are the affected variables and routes, and it does not show how much the affected variables can change. Thus, a quantitative model was required to be developed to present the data flow of the hospital pharmacy system, then make up for the drawback of the qualitative model for deeper understanding of the system behaviours. Given that it was difficult to arrange another group session to convert it to a quantitative diagram, I had to develop the stock-and-flow diagram behind-the-scenes and on my own and consult the interface design of the web interface with several practitioners including the Chief Pharmacist of UHL.

I transferred the factors and relations of the qualitative group model into the structure of the quantitative model. In order to present the number of flows with or without errors during the dispensing process and to keep the consistency of quantitative variables, I modified the relations and factors in the qualitative group model according to the dispensing process. In the end, the quantitative model structure presented different flows as well as relevant factors. It illustrated the phases of the dispensing process, and the pharmacy flows during the dispensing process as well as different dispensing outcomes. I applied inflow cases and outflow cases to present current system scenarios based on the inputs received from participants. Moreover, relevant key factors linked with the scenarios were mapped into the model.

We created and implemented a quantitative SD simulation model to demonstrate the possible outcomes of factors in the form of metrics (backlog and dispensing errors) that influence hospital pharmacies dispensary safety such as high workload and inadequate staffing levels, whilst providing different scenarios to intervene in order to improve the worst-case settings using measurements of dispensing backlog and errors. For a model to be insightful, only necessary and sufficient number of components should be included (Sterman, 2004). We validated and verified the simulation model based on the data that we received from the databases and group sessions that we conducted. Finally, the final model is uploaded to an interactive web platform (Forio Stimulate) where appropriate scenarios are devised.

One of the challenges when conducting GMB session in healthcare is that building a model in healthcare can trigger awareness that a larger enquiry is necessary; as the work progresses the model boundaries can be extended. Nevertheless, a group must resist the
temptation to model everything in great detail, and I made sure that was reflected in the sessions. The best models focus on a specific problem and work out from it. I reminded the participants that setting a scope is important as we cannot model the periphery of the hospital pharmacy system. To avoid the “groupthink” where the group adopts a particular interpretation that becomes the received wisdom, I made sure to invite a mix of practitioners from different backgrounds (labellers, checkers and trainees). These challenges in healthcare can be overcome by proper planning and establishing report with the participants before one conducts the sessions.

Finally, the evidence indicates that the simulation model is a suitably proper account of reflecting reality to provide insights on safety performance within the hospital pharmacy dispensary. The sensitivity analysis tests recognise and identify the leverage points in the hospital dispensary system, allowing decision-makers to acknowledge them when decisions affecting the system are made.

The next chapter looks at the simulation output of the formulated simulation model and the web-interface scenarios developed in Forio Simulate.
5 SIMULATION OUTPUT

In the previous chapter, a hospital pharmacy SD was constructed based on the participatory SD approach. The model was validated in a series of group discussions with experts. The results of the simulation model are reported in this chapter. Presented firstly are the baseline results, followed by different key scenarios outputs based on different key parameters such as winter pressure (increased prescriptions), staff changes, interruptions from trainees. System behaviours are observed under different scenarios. Finally, a summary of the results is then presented lastly.

5.1 Details of the Model

Table 5.1 represents two main scenario options with four sub-scenarios for each scenario whilst Table 5.2 details important parameter values used in the SD Model along with the data sources. The results reveal how the level staffing ratio, interruptions, workload and subsequent fatigue have an impact on safety and performance of the pharmacy dispensary as a whole. The results were presented to pharmacy managers/staff using learning based interactive dashboard (Forio Stimulate). The web interface dashboard presents three scenarios, allowing pharmacy staff to interactively change inputs to see how it impacts the performance and proactively interpret the results.
Table 5.1 Scenarios testing values

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Prescriptions/Interruptions parameters</th>
<th>Staff parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1: Impact of staffing level on efficiency (production) and thoroughness (safety)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 1.1: Baseline</td>
<td>Pre-winter incoming prescriptions</td>
<td>Fixed staffing levels: 5 labellers</td>
</tr>
<tr>
<td>Scenario 1.2: Winter pressure</td>
<td>Winter pressure incoming prescriptions (150%)</td>
<td>Fixed staffing levels: 5 labellers</td>
</tr>
<tr>
<td>Scenario 1.3: Dynamic staffing levels</td>
<td>Winter pressure incoming prescriptions (150%)</td>
<td>Dynamic staffing levels depending on backlog and capacity</td>
</tr>
<tr>
<td>Scenario 1.4: Fixed staffing levels derived from scenario 3</td>
<td>Winter pressure incoming prescriptions (150%)</td>
<td>Fixed staffing levels derived from scenario 1.2: 8 labellers</td>
</tr>
<tr>
<td>Scenario 2: Impact of interruptions (trainees) on efficiency and safety</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 2.1: Baseline</td>
<td>No trainees</td>
<td>Fixed staffing levels: 5 labellers and 0 trainees</td>
</tr>
<tr>
<td>Scenario 2.2: 20% percent interruption</td>
<td>20% of incoming prescriptions are queried by trainees</td>
<td>Fixed staffing levels: 4 labellers and 1 trainees</td>
</tr>
<tr>
<td>Scenario 2.3: 40% percent interruption</td>
<td>40% of incoming prescriptions are queried by trainees</td>
<td>Fixed staffing levels: 3 labellers and 2 trainees</td>
</tr>
<tr>
<td>Scenario 2.4: 60% percent interruption</td>
<td>60% of incoming prescriptions are queried by trainees</td>
<td>Fixed staffing levels: 2 labellers and 3 trainees</td>
</tr>
</tbody>
</table>

Table 5.2 Details of some important parameter values used in the SD Model along with the data sources

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Variable</th>
<th>Initial values used (unit)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td>Incoming urgent prescriptions</td>
<td>Prescriptions</td>
<td>Royal Infirmary UHL Hospital</td>
</tr>
<tr>
<td></td>
<td>Incoming regular prescriptions</td>
<td>Prescriptions</td>
<td>Royal Infirmary UHL Hospital</td>
</tr>
<tr>
<td></td>
<td>Total dispensed medications</td>
<td>Prescriptions</td>
<td>Royal Infirmary UHL Hospital</td>
</tr>
<tr>
<td>Staff</td>
<td>Number of labellers</td>
<td>5 (minimum)</td>
<td>Royal Infirmary UHL Hospital/ Glenfield UHL</td>
</tr>
<tr>
<td></td>
<td>Number of checkers</td>
<td>2 (minimum)</td>
<td>Royal Infirmary UHL Hospital/ Glenfield UHL</td>
</tr>
<tr>
<td>Performance</td>
<td>Labeller actual error ratio</td>
<td>Prescriptions</td>
<td>Royal Infirmary UHL Hospital/ Glenfield UHL</td>
</tr>
<tr>
<td></td>
<td>Checker actual error ratio</td>
<td>Prescriptions</td>
<td>Royal Infirmary UHL Hospital/ Glenfield UHL</td>
</tr>
<tr>
<td></td>
<td>Capacity of average labeller</td>
<td>Prescriptions</td>
<td>Royal Infirmary UHL Hospital/ Glenfield UHL</td>
</tr>
<tr>
<td></td>
<td>Capacity of average checker</td>
<td>Prescriptions</td>
<td>Royal Infirmary UHL Hospital/ Glenfield UHL</td>
</tr>
<tr>
<td></td>
<td>Undetected errors</td>
<td>Prescriptions</td>
<td>Royal Infirmary UHL Hospital/ Glenfield UHL</td>
</tr>
<tr>
<td>Interruptions</td>
<td>Percentage of trainee questions per prescription</td>
<td>Questions</td>
<td>Royal Infirmary UHL Hospital/ Glenfield UHL</td>
</tr>
<tr>
<td></td>
<td>Capacity cost per question</td>
<td>Prescriptions</td>
<td>Royal Infirmary UHL Hospital/ Glenfield UHL</td>
</tr>
</tbody>
</table>
5.1.1 Impact of Staffing Level on Efficiency (Production) and Thoroughness (Safety)

The baseline scenario 1.1 (see Figure 5.1) is based on the existing make of the hospital pharmacy dispensary case study. It consists of five qualified labellers and two checkers. Figure 5.1a indicates the incoming prescriptions per hour whilst Figure 5.1b illustrates the outgoing prescriptions per hour, revealing that all outgoing prescriptions are cleared around 7 PM with such staff arrangement. Figure 5.1c shows the percentage of workload that includes rework for labellers. As indicated, workload is substantially increased once the incoming prescriptions pick pace and mistakes are made forcing labellers to relabel the medications. However there is no reduction in their level of capacity. Finally, Figure 5.1d illustrates the backlog of the dispensary. The number of errors (self-check errors and final checking errors) pickup once backlog is detected and it is for this reason that workload is slightly increased. However, with a base staff ratio of five labellers and two checkers, no additional staffing is needed for this level of incoming prescriptions as backlog is substantially low and under control by the base number of staff.
Scenario 1.1: Winter pressure using baseline values

Winter pressure forces incoming prescriptions to exponentially increase and using the same level of staffing to accommodate workload is not feasible. This is shown in the following scenario (Figure 5.2) where incoming prescriptions are increased by 150% using the same level of fixed staffing levels. This indicates that at times, the dispensary receives more than 100 prescriptions per hour. Figure 5.2b shows that the outgoing prescriptions with the standard staffing levels continue way into the next morning. Figure 5.2c indicates that the degree of rework is increased which has an impact on the workload. The workload with rework stays at 100% all the way to 1 AM. Moreover there is a sharp reduction in the capacity of labellers as fatigue is induced due to the continuous workload. The capacity is gradually restored once the workload hits below 85%. Figure 5.2d shows the backlog and the number of errors committed by staff. As the backlog surpasses a certain level, the number of mistakes committed stabilises at the maximum number of errors that can be committed by the staff.
Scenario 1.3: Dynamic staffing levels

Figure 5.3: Results from Scenario 1.3 - dynamic staff levels

When the dynamic staff levels switch is enabled in the model, it calculates the number of staff needed to counteract the growing backlog and reduce the high workload (See Figure 5.3). Between 12 PM and 2 PM, when the backlog starts proliferating, 12 additional backup staff are added to reduce the backlog, which results in 17 dedicated pharmacists being brought in. Once the backlog is significantly reduced, the staff is once again reduced at 3 PM to nine labellers and 4 PM to the base staff level.

This is based on the algorithm of the number of capacity needed to dispense the prescriptions at a normal workload pace sufficiently. However, as the backlog grows again, additional backup staff is recalled from the wards, and the model calculates that a total of 15 labellers’ capacity is needed to manage the growing backlog (see Table 5.3). Once the backlog is down at 5 PM until at 8 PM, the base staff level remains. Although increased staff can significantly reduce the backlog and workload, the number of detected self-check errors made is increased due to number of available resources. It is, therefore, crucial to know when to call the additional resources and when to reduce them in order to achieve a balanced trade-off. Furthermore, the model calculations takes into account the time delay involved when calling additional staff, therefore accurately revealing that without taking into account the delay to counteract the growing backlog, it will expedite the problem.
Table 5.3 Dynamic staff levels for workload for scenario 1

<table>
<thead>
<tr>
<th>Time (Hour)</th>
<th>9 AM</th>
<th>10 AM</th>
<th>11 AM</th>
<th>12 PM</th>
<th>1 PM</th>
<th>2 PM</th>
<th>3 PM</th>
<th>4 PM</th>
<th>5 PM</th>
<th>6 PM</th>
<th>7 PM</th>
<th>8 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>No of Labellers</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>17</td>
<td>9</td>
<td>5</td>
<td>15</td>
<td>7</td>
<td>7</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

**Scenario 1.4: Fixed average staffing levels**

![Graphs showing incoming and outgoing prescriptions, staff workload, and backlog metrics.]

Figure 5.4: Results from Scenario 1.4 - fixed average staff levels

The previous scenarios automatically incorporated delay to calling the required number of staff needed to reduce the backlog and once backlog is reduced, it recalibrates the number staff needed. The scenario above (Figure 5.4) applies a more feasible approach by using the average number of staff needed to maintain the same results. The average of the dynamic staff levels for workload in previous scenario (total staff/number of hours) is calculated and incorporated it in scenario 1.3 to analyse impact. Figure 5.4 reveals that output is steadied once the eight labellers are used throughout the dispensing timeline so is the level of workload and their total capacity. What does not change is the level of backlog, though variation is minuscule, and no dispensing errors are made after 7 pm. In contrast to scenario three which in total calls up to 30 additional staff throughout the day to combat any impending backlog, scenario 4, on the other hand, finishes dispensing prescriptions 9 minutes earlier, with a more stabilised workload throughout and with the same level of rework and backlog. Table 5.4 collectively list the output of subscenarios within Scenario 1.
Table 5.4 Quantitative output of scenarios within Scenario 1

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Incoming urgent prescriptions</th>
<th>Incoming regular prescriptions</th>
<th>Staff</th>
<th>Time finish</th>
<th>Highest backlog (unlabelled prescriptions)</th>
<th>Self-check errors detected by labellers</th>
<th>Errors detected by checkers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>47</td>
<td>298</td>
<td>5 labellers</td>
<td>8:01 PM</td>
<td>35</td>
<td>38</td>
<td>4</td>
</tr>
<tr>
<td>1.2</td>
<td>118</td>
<td>723</td>
<td>5 labellers</td>
<td>01:02 AM</td>
<td>219</td>
<td>153</td>
<td>156</td>
</tr>
<tr>
<td>1.3</td>
<td>118</td>
<td>723</td>
<td>5 – 17 labellers</td>
<td>8:17 PM</td>
<td>89</td>
<td>139</td>
<td>70</td>
</tr>
<tr>
<td>1.4</td>
<td>118</td>
<td>723</td>
<td>8 labellers</td>
<td>8:08 PM</td>
<td>88</td>
<td>118</td>
<td>35</td>
</tr>
</tbody>
</table>

5.1.2 Impact of Interruptions (Trainees) on Efficiency and Safety

Figure 5.5: Results from baseline scenario of impact of interruptions on efficiency and safety

Figure 5.5 illustrates the base scenario for interruptions from trainees within the hospital pharmacy and the level of impact it has on the performance (rework) of qualified labellers. The base scenario 2.1 displays five different graphs. They are compartmentalised in five
different sections: hourly incoming prescriptions, hourly outgoing dispensed prescriptions, hourly workload of labellers, hourly backlog generated and how that impacts the number of errors committed and the capacity loss caused by the interruptions. The graphs show the default baseline obtained from the hospital pharmacy which is based on a ratio of five qualified labellers, two checkers and no trainees and as a result, no incoming prescriptions are queried. The workload does not exceed 70%, there is relatively low amount of backlog (highest: 35), and the number of errors committed is par standard vis-a-vis historical data (8 labelling errors).

Scenario 2.2: Twenty percent of incoming prescriptions are queried

For every prescription queried by trainees, the time required to do three prescriptions is lost. By being interrupted by the trainees, the labellers have to allocate time to answer the query and restart the labelling process whilst the trainee has to spend extra time querying the prescriptions.

When there are four labellers and one trainee who queries 20% of all incoming prescriptions with the more qualified labellers, there is a significant increase (20%) in
workload. This is attributable to labellers restarting their work mid-way after tending the interruption from the trainees and the trainee losing time querying a number of prescriptions. The graphs reveal that in total 207 prescriptions could have been labelled if no interruptions occurred. The 20% increase in interruptions from the trainees contributes to a 21% increase in labellers self-detecting labelling errors. However, there is a 175% increase in errors that they miss which are eventually detected by checkers in the final checking process. The trade-off is manageable as the labellers finish the same time in comparison to the base scenario. There is no reduction in capacity and output reveals that with a slight increase in interruptions, the base staff are able to dispense satisfactorily without significant pressure. The number of questions queried per hour is reflected in Table 5.5.

Table 5.5 Interruptions/Time lost – Scenario 2.2

<table>
<thead>
<tr>
<th>Time (Hour)</th>
<th>9 AM</th>
<th>10 AM</th>
<th>11 AM</th>
<th>12 PM</th>
<th>1 PM</th>
<th>2 PM</th>
<th>3 PM</th>
<th>4 PM</th>
<th>5 PM</th>
<th>6 PM</th>
<th>7 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of questions</td>
<td>2</td>
<td>7</td>
<td>5</td>
<td>12</td>
<td>8</td>
<td>5</td>
<td>8</td>
<td>10</td>
<td>10</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Prescriptions that could have been processed</td>
<td>6</td>
<td>21</td>
<td>15</td>
<td>36</td>
<td>24</td>
<td>15</td>
<td>24</td>
<td>30</td>
<td>30</td>
<td>6</td>
<td>0</td>
</tr>
</tbody>
</table>

Scenario 2.3: Forty percent of incoming prescriptions are queried

Figure 5.7: Results from scenario 2.3
impact of interruptions on efficiency and safety with a 40% increase in interruptions
In Scenario 2.3 (Figure 5.7), when there are two trainees and three qualified labellers, a 40% increase in interruption by trainees against the backdrop of the lean base staff is performed. Several parameters are affected such as the staff workload, a significant increase in labelling errors being picked up in the final checking stage and the time finished. The graphs reveal that 411 prescriptions could have been labelled if no interruptions occurred from the two trainees and this is reflected in the workload where labellers are battling continuous high workload as their capacity is severely reduced on account from interruptions. The 40% increase in interruptions from the trainees contributes to a 30% increase in labelling errors being detected during the self-check process by labeller. However, there is a 400% increase compared to the previous of labelling errors going undetected during the self-checking process and being detected by checkers during the final checking stage. Furthermore, on account of the aforementioned factors, labellers finish an hour later (see Table 5.6) in comparison to the two previous scenarios scenario. There is a reduction in capacity throughout the day which is connected to the continuous high workload as fatigue is introduced.

Table 5.6 Interruptions/Time lost – Scenario 2.3

<table>
<thead>
<tr>
<th>Time (Hour)</th>
<th>9 AM</th>
<th>10 AM</th>
<th>11 AM</th>
<th>12 PM</th>
<th>1 PM</th>
<th>2 PM</th>
<th>3 PM</th>
<th>4 PM</th>
<th>5 PM</th>
<th>6 PM</th>
<th>7 PM</th>
<th>8 PM</th>
<th>9 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of questions</td>
<td>4</td>
<td>14</td>
<td>10</td>
<td>24</td>
<td>16</td>
<td>11</td>
<td>17</td>
<td>19</td>
<td>19</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Prescriptions that could have been processed</td>
<td>12</td>
<td>42</td>
<td>30</td>
<td>72</td>
<td>48</td>
<td>33</td>
<td>51</td>
<td>57</td>
<td>57</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Scenario 2.4: Sixty percent of incoming prescriptions are queried

(a) incoming prescriptions

(b) outgoing prescriptions

(c) staff workload

(d) backlog metrics
(e) capacity/errors

Figure 5.8: Results from scenario 2.4
impact of interruptions on efficiency and safety with an 60% increase in interruptions

When there are three trainees in the dispensaries, and the number of interruptions is increased to 60%, significant changes are recorded, affecting workload, backlog, and time finished. The graphs reveal that 624 prescriptions could have been labelled if no interruptions occurred. This is a 62% increase compared to the previous scenario which has an impact on the dispensing process as the capacity of labellers is shifted to answering queries. The highest peak of backlog detected is 222 unlabelled prescriptions, a 192% increase compared to the previous scenario. This has a critical effect on the workload (Figure 5.8c) as labellers experience continuous high workload throughout the day. This, in turn, reduces their total capacity as fatigue is introduced (Figure 5.8e) around 11 AM, showing a gradual decline of capacity and an increased surge of dispensing errors, particularly from 4 PM to 8 PM. This increased continuous workload and high backlog affect their finishing time, which in comparison to the first two scenarios went from 8 PM to 11 PM.

Table 5.7 Interruptions/Time lost – Scenario 2.4

<table>
<thead>
<tr>
<th>Time (Hour)</th>
<th>9 AM</th>
<th>10 AM</th>
<th>11 AM</th>
<th>12 PM</th>
<th>1 PM</th>
<th>2 PM</th>
<th>3 PM</th>
<th>4 PM</th>
<th>5 PM</th>
<th>6 PM</th>
<th>7 PM</th>
<th>8 PM</th>
<th>9 PM</th>
<th>10 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of questions</td>
<td>7</td>
<td>20</td>
<td>16</td>
<td>36</td>
<td>25</td>
<td>16</td>
<td>25</td>
<td>29</td>
<td>29</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Prescriptions that could have been processed</td>
<td>21</td>
<td>60</td>
<td>48</td>
<td>108</td>
<td>75</td>
<td>48</td>
<td>75</td>
<td>87</td>
<td>87</td>
<td>15</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5.8 Quantitative output of scenarios within Scenario 2
<table>
<thead>
<tr>
<th>Scenario</th>
<th>Incoming urgent prescriptions</th>
<th>Incoming regular prescriptions</th>
<th>Staff (labellers and trainees)</th>
<th>Time</th>
<th>Highest backlog</th>
<th>Self-check errors by labellers</th>
<th>Errors detected by checkers</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>47</td>
<td>298</td>
<td>5 labellers</td>
<td>8:01 PM</td>
<td>35</td>
<td>38</td>
<td>4</td>
</tr>
<tr>
<td>2.2</td>
<td>47</td>
<td>298</td>
<td>4 labellers and 1 trainee</td>
<td>8:01 PM</td>
<td>35</td>
<td>46</td>
<td>11</td>
</tr>
<tr>
<td>2.3</td>
<td>47</td>
<td>298</td>
<td>3 labellers and 2 trainees</td>
<td>9:03 PM</td>
<td>76</td>
<td>60</td>
<td>56</td>
</tr>
<tr>
<td>2.4</td>
<td>47</td>
<td>298</td>
<td>2 labellers and trainees</td>
<td>11:07 PM</td>
<td>222</td>
<td>61</td>
<td>63</td>
</tr>
</tbody>
</table>

### 5.2 Summary

To summarise, we have presented the baseline results of two scenarios: 1) impact of staffing level on efficiency and thoroughness and 2) impact of interruptions on efficiency and safety followed by different key scenarios outputs based on different key parameters such as winter pressure (increased prescriptions), staff changes and interruptions from trainees (see Table 5.9 for summary of all scenarios). System behaviours were observed under the different scenarios. The scenarios were conceptualised based on the interviews from practitioners, literature review and the developed simulation models.
### Table 5.9 Summary of all scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Incoming urgent prescriptions</th>
<th>Incoming regular prescriptions</th>
<th>Staff</th>
<th>Time finish</th>
<th>Highest backlog</th>
<th>Self-check errors detected by labellers</th>
<th>Errors detected by checkers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>47</td>
<td>298</td>
<td>5 labellers</td>
<td>8:01 PM</td>
<td>35</td>
<td>38</td>
<td>4</td>
</tr>
<tr>
<td>1.2</td>
<td>118</td>
<td>723</td>
<td>5 labellers</td>
<td>01:02 AM</td>
<td>219</td>
<td>153</td>
<td>156</td>
</tr>
<tr>
<td>1.3</td>
<td>118</td>
<td>723</td>
<td>5–17 labellers</td>
<td>8:17 PM</td>
<td>89</td>
<td>139</td>
<td>70</td>
</tr>
<tr>
<td>1.4</td>
<td>118</td>
<td>723</td>
<td>8 labellers</td>
<td>8:08 PM</td>
<td>88</td>
<td>118</td>
<td>35</td>
</tr>
<tr>
<td>2.1</td>
<td>47</td>
<td>298</td>
<td>5 labellers</td>
<td>8:01 PM</td>
<td>35</td>
<td>38</td>
<td>4</td>
</tr>
<tr>
<td>2.2</td>
<td>47</td>
<td>298</td>
<td>4 labellers and 1 trainee</td>
<td>8:01 PM</td>
<td>35</td>
<td>46</td>
<td>11</td>
</tr>
<tr>
<td>2.3</td>
<td>47</td>
<td>298</td>
<td>3 labellers and 2 trainees</td>
<td>9:03 PM</td>
<td>76</td>
<td>60</td>
<td>56</td>
</tr>
<tr>
<td>2.4</td>
<td>47</td>
<td>298</td>
<td>2 labellers and 3 trainees</td>
<td>11:07 PM</td>
<td>222</td>
<td>61</td>
<td>63</td>
</tr>
</tbody>
</table>

Scenario 1.1 and 1.2 reveal how using the minimum number of staff and an increase in incoming prescriptions can have a detrimental effect on workload, dispensing errors, backlog and the time finished. As scenario 1.2 reveals, using the standard five labellers to combat winter pressure forces labellers to finish around 1 AM. In scenario 1.3, as the staffing resources are continually overstretched, and dispensaries are working with lean staffing levels (five labellers) to reduce costs, pharmacy managers only recall extra staff when an imminent backlog is detected, and labellers are maintaining a high workload that ultimately has a detrimental effect on their total capacity. When the extra staff from ward arrives, more labelling errors have been committed resulting in a greater number of reworks to be done. This influences the backlog, and the number of additional staff needed to reduce the workload as illustrated in section 5.1.1, scenario 1.3. By introducing a fixed adequate staffing level (calculating the average staff number of scenario 1.4) throughout the day, pharmacy managers have the ability to balance the efficiency and thoroughness demands, by being sufficiently efficient (finish dispensing earlier) and thoroughness (reduce dispensing errors/rework). Constant high workload pressure can be
effective initially but has the effect of reducing capacity and self-checking once it persists in the long run. This causes the overall capacity of the staff to be reduced, signalling backlog and increased detected errors. Furthermore, it creates a bottle-neck between the workflow of labellers and checkers, thereby reducing the number of outgoing prescriptions.

Scenario 2 reveals that operating the hospital pharmacy with a number of trainees who are not overshadowed and tend to interrupt labellers with questions regarding prescriptions can severely disrupt the hospital pharmacy at a certain percentage. This is reflected in scenarios 2.1 which does not employ trainees and scenario 2.2 which employs a limited number of trainees. There is little difference in the time finished albeit there is a slight increase of number of labelling errors detected by checkers during the final stage. Scenario 2.3 is based on the premise where 40% of incoming prescriptions are queried by a number of trainees. Whilst number of self-detected labelling errors have increased, a closer look at errors detected by checkers indicate that labellers’ success finding rate of their own errors is dramatically decreased as they are frequently interrupted. As a result, they finish an hour later. The tipping point is crossed in scenario 1.3 where 60% of incoming prescriptions are queried by trainees. As indicated in Table 5.9, whilst number of self-detected labelling errors and detected errors by checking do not significantly increased in comparison to 1.2, it, however, induces a backlog as labellers have to dedicate their time in answering questions whilst dispensing medications. As a result, they finish 2 hours later as compared to where 40% of incoming prescriptions are queried.

The results reveal how the simulation model highlights the structural/organisational characteristics of healthcare work systems, such as labellers’ workload, winter pressure, incorrect staffing levels and interruptions from trainees can affect dispensing (backlog) and patient safety (dispensing errors).

Overall, the model results presented in this research are likely to play an important role in supporting hospital pharmacy management in deciding the staffing level management issue in hospital pharmacy dispensaries.
Chapter 6: SD Practicality As A Learning Tool In The Hospital Pharmacy Setting

6 SD PRACTICALITY AS A LEARNING TOOL IN THE HOSPITAL PHARMACY SETTING

This chapter discusses the evaluative outcomes of the model, gathered from group discussions and survey questionnaires, and highlights participatory SD’s real impact on hospital pharmacy management practices. In doing so, this chapter integrates the results from Chapter 5 and relates them back to the original research questions identified in Chapter 1 which is to evaluate the applicability, utility and usability of how participatory SD can enhance group learning. This will specifically look at i) what kind of benefits (or drawbacks) in knowledge will pharmacy decision-makers gain by applying the SD approach, ii) how easy is it to use (in terms of modelling, analysis and result interpretation) the SD approach is to improve group learning, iii) How applicable is the participatory SD approach in the healthcare environment?

Section 6.1 to 6.5 describes the analysis that is performed on the group session discussion when evaluating the model and questionnaire output. Section 6.6 describes the feasibility of applying SD modelling approach to safe and efficient staffing level management within hospital pharmacies and looks at the utility and usability of participatory SD modelling approach as a group learning method.

From the questionnaire survey with two different groups consisting of practitioners and managers, 21 questionnaires were obtained from both groups, eight from practitioners group and 13 from management group (see Appendix D for participants’ profile). The two groups were mixed, and there was no clear division of both labellers and checkers in the practitioners’ group and senior management members from diverse pharmacy departments in the management group. In the first group, around 62.5% were checkers, having previously been labellers. Checkers have the skill to do dispensing as well as checking whilst the remaining 37.5% were labellers. The most experienced checker...
interviewed thus far has over 30 years of experience whilst the most experienced labeller has three years of experience. In the management group, the most experienced senior manager interviewed thus far has over 31 years of experience whilst the least experience has ten years of experience. None of the respondents had ever used simulation in any form before.

6.1 Model Understanding and Complexity

Section 2 of the survey questionnaire included a series of statements regarding the respondents’ understanding of both the conceptual and simulated model. Question 2.4, which highlights factors that aid model understanding, asked the user to rank in order of importance the factors that helped them understand the simulation model better: conceptual diagram, web interface of the model and simulation. The conceptual diagrams are the causal-loop diagrams of the three scenarios. The web interfaces are the indicators and tables that aid the model understanding.

Table 6.1 According to the level of importance, which of the following factors, helped you understand the model?

<table>
<thead>
<tr>
<th>Factor by model type</th>
<th>Important (%)</th>
<th>Very Important (%)</th>
<th>Most Important (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conceptual Diagrams</td>
<td>Practitioners</td>
<td>50%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>Management</td>
<td>23%</td>
<td>31%</td>
</tr>
<tr>
<td>Web Interface</td>
<td>Practitioners</td>
<td>25%</td>
<td>75%</td>
</tr>
<tr>
<td></td>
<td>Management</td>
<td>38%</td>
<td>62%</td>
</tr>
<tr>
<td>Simulation</td>
<td>Practitioners</td>
<td>25%</td>
<td>25%</td>
</tr>
<tr>
<td></td>
<td>Management</td>
<td>38%</td>
<td>8%</td>
</tr>
</tbody>
</table>

Table 6.1 is the results of importance in model type based on a ranking of 1 to 3. Practitioners and management equally selected conceptual diagrams and simulation as their most important types to understand the model. Understanding deals with overall model understanding, understanding of the relationship between variables, understanding of the model structure, and understanding of how to use the model and interpret the model outputs. Furthermore, several follow up questions on the model understanding (a1 to b3 – see Appendix B for the questionnaire template) were presented to the users. The level of understanding for each of these items is measured on a Likert-type scale of 1 to 5, where one means ‘very little’ and five means ‘very well’. The aim is to measure the participants’ perceived understanding of the models.
The question regarding the factors that help model understanding asked the user to rank in order of importance the factors: conceptual diagram, visual interface of the model and simulation of the model runs. The results from Section 2a reveals that the majority of management (54%) and practitioners (92%) identified the simulation model as the most important factor in aiding model understanding.

Figure 6.1: How well do you feel you understand how the Conceptual model works?

Figure 6.2: How well do you feel you understand how the Simulation model works?
Participant P5 gave his answer for preferring the simulation over the conceptual diagram:

“It gave me a clearer picture, and you could see it as it went throughout the day whereas, with the conceptual diagrams, you have to follow the variables and look at the polarities to make sense of it. You could not stare at it as a full picture whereas, with the graph, you can automatically see where it goes up and down, and visually it gave me more information in a snapshot whilst with the conceptual diagrams you have to stare it for quite some time and read it to get some insight. With the conceptual diagrams, looking at all those closed groups is information overflow. With the graphs, you can see an increase in workload, increase in errors, and decrease in staff and so on.”

Concerning the level of detail of the dispensary model, a Likert-type question asked the user to rate the dispensary model where 1 represents ‘very comprehensive’ and 5 ‘very abstract’. Around 75% of the practitioners mentioned that the model was quite comprehensive whilst merely 13% stated that it was ‘quite abstract’ and one another 13% took a middle approach of ‘neither too abstract nor too comprehensive’. In general, the practitioners perceived the dispensary model as relatively comprehensive in its reflection of the actual generic dispensary that is not specific to a particular dispensary. The management group, however, were equally divided as 38% cited that it was neither comprehensive nor abstract whilst 31% mentioned that was quite abstract and quite comprehensive respectfully. Managers should have perceived the SD model as comprehensive due to the fact that all the components of the SD model are explicitly presented on screen, however, this can be explained that given assorted participants in the management belonged to different backgrounds and ran different departments, each had a subjective view of what level of detail the model should encompass.

6.2 Model Validity

The users were asked to provide their opinions to the extent they find the hospital dispensary model representative of the actual dispensary and the outputs realistic. They were asked to rate their level of confidence in the model. Of the practitioners, majority (67%) rated ‘quite much’ indicating that they were satisfied with the validity of the model. The model was initially constructed through iterative discussions with the practitioners, modelling it in a way that it reflects reality and work-as-done. This contributes to ownership of the model, thereby indicating the high confidence rate of the model’s validity amongst practitioners. However, with management, over 28% chose ‘rather little’ and were unsure whether it reflects reality and 44% stated took a middle balance of
‘somewhat’. They argued that the level of error reporting require further validation. The practitioners highlighted how there are various bottlenecks and increased errors being reported and the existing Root-Cause-Analysis (RCA) forms are quite linear, allowing them to list causes and thereby only treating the symptoms. When validating the model, participant R4 made mention of the dynamics of the staff workload management of the hospital pharmacy dispensary is reflected in the model, allowing them to understand how certain factors impact high workload better: “the staffing levels have always been the same, but the workload has increased. Just because we are doing the work doesn’t mean we are not suffering from high workload. If they increase capacity on the ward let’s say they add 30 patients, we don’t have the immediate resources to cope with it and then we are asked to do extra, and that is where problems start, and we are continuously stretched, and it never changes... So, the model shows that incoming prescriptions, interruptions and fatigue all impact us at the same time which makes sense, especially the impact on workload.”

Figure 6.3: To what extent do you feel the simulation model is representative of the dispensary system?

6.3 Perceived Model Usefulness

Section C of the questionnaire dealt with users’ opinion regarding the usefulness of the dispensary simulation model, three Likert-type questions and two open-ended questions were employed. The three Likert-type questions asked users to express their opinions as to whether the use of the model enhanced their learning and whether it helped them think strategically about dispensing errors and if it facilitated communication of ideas.
To aid the answers to the Likert-type questions on the model's capacity to enhance learning; the open-ended questions asked the users to identify other contexts similar simulation model might be used and based on what you have learned and how it would impact their current practice. These questions aimed to identify whether after using the hospital pharmacy dispensary simulation model, users could transfer the knowledge gained to other similar systems or apply it in their current hospital pharmacy dispensary. ‘Knowledge transfer’ can be used as an indicator of the learning achieved (Morecroft and Sterman, 1994).

![Figure 6.4: To what extent do you feel using the dispensary simulation model enhanced your learning about causes of dispensing errors?](image)

Majority of practitioners (67%) responded that the model was useful whereas 41% of management thought it was useful. Given that 72% of management did not though the model was valid, as discussed in the previous section, a significant portion (n=7) thought it was still useful to gain insights about the hospital pharmacy system. When practitioners were asked based on what they have learned thus far and how it can impact their current practice, they stated that the model can change the reductive and reactive way of approaching issues in the dispensary. Participant P8 wrote: “having a visual representation of workload/time and its effect would enable proactive approach”. Around 49% of management considered the perceived model usefulness as ‘somewhat’ whilst 31% had the same opinion as the majority of practitioners. The source for this and which has been echoed by the labellers is that the model is missing a key part which is the skill mix element. Currently, the model takes into account a generic average capacity of one type of labellers group which process at 100% capacity of around 20 prescriptions.
per hour as devised from literature and observations. Taking into account the capacity of trainees, starters, pre-registration pharmacists and so on would enable them to play with different types of skills set in order to determine how that impacts backlog and errors. Participant M6 stated: “...seem to be having a big issue with training. It is quite difficult to capture an individual’s performance. Everyone in the dispensary different and has various levels of training, various levels of experience, and everyone works at different speeds...if you split your labellers down into different groups, trainees might get an increase in the number of questions being asked whilst skilled staff don’t. If you add those groups, it might give you a different result and perhaps allows us to see a greater efficiency if we change which the number of groups of staff that we can utilise.”

The most mentioned answer from practitioners on what they have learned and how they can be applied in their current dispensary using the application of holistic thinking and system thinking was that model enabled them to utilise holistic thinking in a more proactive way. Participant M7 writes: “It allowed me to see the whole level of complexity”. He further added in the discussions how the model enabled him to perceive things in a more systematic way: “... thing that can contribute to backlog is not having things in stock. It causes delay, and we have to take extra steps to get those prescriptions thereby losing time where we could process 1 or 2 prescriptions. But also, if you think about it, and this is related to the model. If you add several other subsystems like the ward or the store and it could be that they have staffing problems which can affect us. It’s for this reason why we need a holistic approach where we look at the full picture, and this model made me think about it in a more systematic way. You got think from all the areas, ward to store to dispensing team. You can exceptionally expand the model and its scope. For instance, if you have storekeepers working below the capacity, how will that affect the dispensary.”

In regard to the different context a similar model might be used, both practitioners and management had a disparate number of answers. Some of these answers were: measuring workload for pharmacists/nurses working at the wards, measuring workload in aseptics and imaging, measuring pharmacy warehouse/distribution workload capacity and how this affects pharmacy dispensary and staff workflow with processing prescriptions.

One particular area that the model does not take into account, as mentioned by the participants is that the number of staff is constrained by the number of equipment. In Scenario 1 of the simulation game, one plays with the number of labellers and checkers one can place in the hospital pharmacy dispensary and analyse how this affects incoming

Mohammed Ibrahim Shire - September 2018
prescriptions and existing workload. It does not take into account the number of computers that are present in the hospital pharmacy dispensary. Presently, there are five computers that labellers work on and if there is an impending backlog and one adds more staff to reduce the backlog, clearing the backlog will operate at the same speed as the number of the machines that are available. Practitioner P6 remarks: “...thing that is missing is equipment, you can add ten labellers but only have five computers, and you will soon find out that the equipment is causing delay and that there are not enough computers for the number of staff.”

On highlighting how the model might be useful in their respective dispensary, participant M10 stated that: “…only notice we ever get of an impending backlog is that there is going to be a bed crisis but most of the time is that we have 100 prescriptions in the tray and we need help rather than anticipating it. And it’s an area where we fall short considering that we do not capture in real time. We can’t see an increase or delay, all we see is the piece of paper on the tray. Only when that increases do we get a sense that we will be busy. But if we had a graph like the one you showed us, that allows us to play around with the number of incoming prescriptions and see where backlog might occur, we can anticipate better. I like the part where it shows the incoming and outgoing which is quite helpful. Coupled with that showing the level of workload and where we cross the red line will be very useful. If we can predict the number of staff that we need to be coupled with which type of stuff, it would be extremely helpful, and this model, for the most part, shows that. Instead of analysing and sending down five more staff which causes delay where they only might need three staff.”

Participants found it useful on how to experiment with the model using the buttons provided to change the variables. Participant M1 stated that: “I like the fact that I can simply manipulate one or two variables and instantly visualise their implication on the overall system. It’s a useful policy-making tool. I like it.”

The management group highlighted several answers when asked how the model might impact their respective department. Several managers mentioned that the SD model might be useful in adjusting the level of staff against workflow by proactively managing the level of capacity and demand. Others stated that by considering the number of staff, additional workers could be pulled through the dispensary in anticipation in order to and make the best use of skilled workforce. Others voiced that the simulation model requires more scenarios in order to arrive at the level impacts it can have on their departments.
6.4 Participants’ interpretation of results

The questions in Section d of the questionnaire dealt with participants’ opinions about model results and their interpretation. The three aspects involved in the interpretation of model results in a type of learning achieved, the level of difficulty and considerations made about the behaviour of model results. The questionnaire results show that almost the same proportion of checkers and labellers found the tables and graphs to understand the model indispensable. The majority of them mentioned that the tables helped them follow the graphs and when asked what the main learning point was from the graphs, majority specified the non-linearity aspect and how ‘manipulation of variables in our control can have significant impacts.’

Finally, they were asked how they saw the interpretation of results. The practitioners revealed that it was very straightforward whilst the majority of management group (62%) mentioned that it is was neither straightforward nor difficult. Only 31% of management agreed that it was quite straightforward revealing a difference in attitude between the two groups in how they interpret the simulation results.

![Figure 6.5: How did you find the interpretation of the results?](image)

Participant M12 mentioned that “the simulation only focused between the relationship within the dispensary and would be easier to interpret if it included all the flows such as warehouse, wards, and such that connect to the pharmacy dispensary.” I mentioned that, whilst feasible, overcomplicating the model by including every aspect of the pharmacy workflow will confuse the user more, forcing the user to be unable to see the behavioural structure. It is for this reason that scope needs to be set, and boundary established and
include the necessary components of the dispensary. Finally, none of the participants mentioned that it was difficult to interpret the results, thereby revealing the relative straightforwardness in understanding the model results. Participant M9 mentions that: “…biggest thing that I got from this is the proactive approach and showing that even if your working at full capacity and you add one or two members, there is still a level of delay that is factored before it takes effect and that could add to 4 to 5 hours of your finish time, and it has given me that impact. The workload increasing, and decreasing is very useful, and the model does a good way of showing it.” One manager finally mentioned that the results were easily interpreted through the “visual factors that show the relationships and the projection of results in simulation.” It allowed him to think more proactively about the current relationships and feedback loops in his department.

6.5 Pre-and Post-Modelling Results

I have instructed the participants, prior to building the group model and before conducting group discussions for validation and evaluation of the model, to list the top three causes that contribute to detected dispensing errors (see Figure 6.6). Out of 21 respondents, 32% mentioned in their top three causes that interruption was the top contributing factor, followed by high workload at 17% and incorrect self-checking at 13%. The group discussions mention that lack of (proper) self-checking which includes rushed self-checking because of high workload and incorrectly self-checking because of lack of experience. When it comes to high workload, participants mentioned that this includes prolonged high workload involving the same intensity of more than 2 to 3 hours. It does not come as a surprise as these causes remain most frequently mentioned causes in the literature (Keers et al., 2013).

![Figure 6.6: Pre-and post-test - Top causes of dispensing errors](image-url)
After model testing and evaluation, the same question was posed to same participants to list once again the top three contributory causes to dispensing errors (see Figure 6.6). This was to measure attitudes after the simulation case study and whether there has been any change in their attitudes. Surprisingly, no significant change was reflected apart from high workload overtaking interruptions as the top contributory cause of dispensing errors. The top three contributory causes to dispensing errors listed by participants are still high workload (36%), interruptions (33%) and lack of self-check (10%).

6.6 Discussion
The results indicate that model provides a learning experience for decision-makers to identify and take into account the number of factors (workload, interruptions, total capacity, number staff, incoming prescriptions, rework and dispensing errors) that contribute to the total backlog and decide better staffing levels needed to effectively and efficiently reduce the backlog without wasting additional resources.

The following sections will evaluate the utility and usability of the SD approach in the hospital pharmacy.

Section 6.6.1 will look at the utility of participatory SD approach in the hospital pharmacy sector and will analyse the utility of causal-loop diagrams (conceptual), stock-and-flow diagrams (simulation) and GUI web interface. Feedback from group discussions and questionnaires as discussed in section 6.6.2 will be utilised as well as the researcher’s experiences. Finally, recommendations for good practices of using participatory SD approach in health is discussed.

6.6.1 Utility of SD Approach in the Healthcare
This study demonstrates that poor performance of hospital pharmacy dispensary can be traced to the inefficiency of existing methods and tools used to examine them. Whilst the hospital pharmacy dispensary system is complex and dynamic, the approaches and heuristics influencing decision-making in the hospital dispensary system do not realise sufficiently the properties of the most essentials in the system and their interrelatedness resulting in their observed under-performance. This can be addressed by adopting the key principles of SD to frame, simulate, and study the system.

The research objectives provided a focus for the model purpose. Several steps of the study were established in order to address the first objective and validate the model. The first step was to offer a framework in which to investigate the effects and factors of staff
workload management in the hospital pharmacy dispensary and how factors such as staff levels, interruptions and workload impacts safety (dispensing errors) and performance issues (backlog). The second step was to study the sensitivity of different aspects of performance within the hospital dispensary to changes in staffing levels, capacity constraints and interruptions from trainees. The third step was to calibrate the model to the experiences of UHL hospital dispensaries. The final step was to evaluate the utility and usability of the SD modelling approach as a learning tool.

The target audience for this study were primarily pharmacists at the strategic level of decision making, given the strategic nature of SD. The broad audience for the study also encompassed other interested groups, such as the managers of other healthcare departments struggling with performance and safety issues. The following two subsections will discuss the utility of the qualitative and quantitative aspects of participatory SD approach in health.

6.6.1.1 Utility of Conceptual Diagram

Participant responses regarding the utility of conceptual diagrams yielded positive and constructive feedback regarding the modelling process and the complexities that it revealed, as well as the output and how it can be applied in other areas. Participants emphasised the importance of applying the conceptual diagrams in assessing and disseminating the shared factors in their RCA (Root-Cause-Analysis) reports. They emphasised that it should really be conceptual models that can continuously be improved and expanded so that they can learn more about it. When asked to rank the utility of the conceptual model, the majority of practitioners and managers ranked it highly.

Participants mentioned how the conceptual diagram illustration of high workload, number of staff, interruptions and fatigue practically affects other factors that can make a problem get much worse. This reveals how the conceptual diagram itself is a tool that can be used to visualise influences and reveal factors affecting the staff workload management issue.

When it came to the top-ranked loops that the conceptual diagrams revealed, participants mentioned how the conceptual diagram illustrates the capacity of labellers and checkers and how they drive the dispensing flow and how in turn other factors affect their capacities. Factors such as incorrect staff levels, interruptions, fatigue, backlog and workload factors greatly influence the dispensing process, both directly and indirectly.

Participants revealed how conceptual diagrams allows them to better envision the role of multiple key factors in a larger context.
Therefore, our results indicate that the signs of system thinking were largely evident in the perceptions of the responding pharmacy dispensaries and operational pharmacy managers, it was not utilised it. This was also seen in their responses to the structured statements. Both practitioners and managers still, to some extent, have the individual-centred approach to medication safety but analysing the conceptual diagrams showed them that the individual-centred approach can have a detrimental effect when it comes to safety within the hospital pharmacy.

6.6.1.2 Utility of Simulation

Simulation modelling allows pharmacy managers to capture separate dynamics in the model and show the relationship between staff and backlog. The strength of the simulation model is that it allows pharmacy managers to test the impact of organisational decision-making impacting safety. They can change assumptions and see its impact, and without simulation, these calculations are incredibly complex and time-consuming. It is never possible to test a range of assumptions in real life as the time periods required to get results are prohibitively long and the consequences of bad decisions disastrous. The simulation allows assumptions, some of which may be purely speculative but potentially useful, to be tested in a matter of seconds.

One key insight that popped up according to the participants is how bringing additional staff from wards can reduce backlog, but that simulation revealed that it can contribute to more errors and that having a correct static staff throughout has a much better impact. Whilst calling additional staff during impending backlog are needed to reduce the backlog, participants realised that having a fixed adequate staffing level throughout can be more advantageous in combatting backlog, keeping workload steady and dispensing errors low.

Many of the explicit observations made by the groups pointed to the model being more suitable tool for either demonstrating the effects of staff workload pressure and its contributory factors and for helping people to learn more about the staff workload management. There was an acknowledgement that the simulation would still be of value in learning or even policy-making when set in an abstract context, although there was a greater appreciation of the model in its present real-world form. Much of the underlying discussion pointed towards using the model to assist with decision-making. Suggestions were made concerning the introduction of other parameters into the model and extending it to include systems or extrapolate it to different healthcare units with similar problems.
The results of the experiments that the groups conducted were certainly pertinent to the discussion. Staffing levels, interruptions from trainees and workload were identified as the model policy able to exert either a virtuous or vicious effect on the whole systems’ performance. The model had allowed the participants to appreciate this result and much debate had followed as to how such factors can be mitigated.

It was evident from the discussion on simulation result interpretation that the managers were particularly interested in using the model at a lower level for learning, and at a higher level for policy analysis. They did not offer blind faith in the model but suggested that they were prepared to follow the policies that the simulation showed to be desirable whilst monitoring how accurately the predictions of behaviour were.

To make sense of simulation results, a number of participants had several follow-up comments that do go beyond SD modelling, such as modelling based individuals’ characteristics and capacity as opposed to aggregated staff groups. I had to remind them that SD approach is based on an aggregation philosophy.

With respect to the simulation, most participants thought that the use of the simulation model was an important system tool to represent and simplify complex hospital pharmacy dispensary issues. Participants also felt that the developed models represent the reality on the ground. Overall, there were strong feelings amongst the stakeholders that the developed models were credible, relevant, and consistent, and may potentially be used to enhance learning and facilitate decision-making within the hospital pharmacy dispensary. Understanding the correlation between high workload, staff capacity, backlog, incoming prescriptions, errors and delay allow stakeholders to comprehend the outcomes of their choices better when calling for additional resources or determining the correct staffing levels.

6.6.1.3 Utility of Web Interface

When it comes to the results interpretation of the hospital pharmacy dispensary model, a wide range of views was put forward by the participants, all possessing varying degrees and types of knowledge of hospital pharmacy dispensing process. The common thread that can be teased out of the discussion is that the model in its present form was found to be helpful and easy to interpret by the stakeholders for viewing and deciding the staff workload management issue by considering the impact of staff levels, interruptions and workload on safety (dispensing errors) and performance (backlog). This was aided through the web interface. Participants mentioned how both the conceptual and
simulation model clearly illustrates how everything relates to each other and the importance of each other. They added how the web interface undoubtedly aided to visualise the complexity and made it easier to understand what was happening.

The participants found the key indicators outlined in the web interface such as the data derived from the tables and graphs made understanding the model indispensable. The Forio Simulate web-interface aided in providing the necessary tools to adequately illustrate model results in a clear-to-understand manner. Conversely, using a complex stock-and-flow diagram to participants with a little background in SD would have been confusing and difficult to interpret and having a clear easy-to-understand user-friendly web-interfaces simplified the complexity involved in the stock-and-flow diagram.

6.6.2 Usability of SD Approach in the Hospital Pharmacy Sector

One of the many factors that determine the usability of a method is its ease of use. However, the weight placed upon this factor will be very subjective. Some might reject a method that has various practical difficulties as being useless whilst others might accept these challenges as an inevitable part of the process of deriving important insights - a ‘no pain, no gain’ attitude. SD modellers argue that the benefits of participatory SD modelling can be considerable since they claim that the linkage between the structure of a system and its behaviour is the key to long-term success or failure. As stated in Section 1.2, the assessment of the ease of use is on the basis of the qualitative, quantitative aspects of participatory SD approach, the stakeholder involvement requirements and the need to modify the SD paradigm. These factors are dealt with in turn.

**Usability of participatory SD Approach**

The usability of the participatory will look at the qualitative (conceptual) and quantitative (simulation) aspects of the SD approach. By building structures in front of or with participants tend to teach participants more about the basics of conceptual model building. Teaching stakeholders the basics of the conceptual model building may accomplish two factors important to the process. First, it helps establish trust in the model and software and an appreciation of model transparency. Established groups who have trust in one another may have less need for hands-on modelling. Second, it helps stakeholders to understand systems thinking. Those who are accustomed to viewing the world in a linear manner may benefit from this system thinking exercise.
Most evaluated participants found the simulation easy to understand. The primary reason for this is the web-interface design that aided the ease of use aspect. The design of these interfaces is critical to the transparency of the model. A well-designed interface will provide the information and the tools for effective simulation model. It should also be an effective tool to encourage exploration of the model map, parameters and relationships of those parameters. This is especially important with larger models that may appear at first to be “black boxes”.

Participants, more specifically managers, who were not part of the original group model building sessions and the formulation of the conceptual model found it more difficult to understand claim ownership as opposed to participants who were part of the early sessions. Furthermore, participants in small-sized groups who were not part of the original group model building session found it much easier to comprehend and use the completed model as opposed to participants in large groups and who were absent from the initial sessions. Participants remarked that by being in small-sized groups and playing with the model allowed them to ask useful questions to comprehend the model and have the ability to play around with it whereas participants in large groups did not have that option.

Conducting simulation model exercise in small-sized groups tend to be more effective in healthcare and incorporating and engaging participants from the get-go will allow them to understand the model building process much easier.

All participants indicated that they have learned from the co-modelling process and the different interpretations that their co-participants had. Several participants felt that the modelling process and accompanying discussions added greater value and insight to their knowledge and expertise because they knew better where it fit into their decision-making process. Some participants stated that, seeing the model outputs helped them to understand the complexity of the staff workload problem.

Overall, the participants’ experience and perception of the modelling process and the resultant outputs were largely very positive. Consequently; all participants expressed appreciation for the opportunity to discuss staff workload problems in a structured manner, reflecting on their knowledge, opinions, views, values, perspectives, and interests. Many expressed their willingness to participate in future SD participatory modelling efforts within healthcare.
Stakeholder Involvement

In modelling studies, effort also needs to be devoted to gaining the stakeholders’ confidence in the model and securing their participation in the study. Without stakeholders’ confidence, the analysis becomes pointless, as the policy recommendations will be ignored. Stakeholders’ participation ensures that the analysis maintains relevance. There are well-established guidelines for securing stakeholders’ confidence and participation. However, in SD, there is a particular difficulty as the aggregated, deterministic modelling perspective, which is a characteristic of the SD paradigm, could conflict with stakeholders’ desire for detail, especially in healthcare.

Moreover, this conflict could undermine their confidence in the model and discourage their participation in the study. Healthcare stakeholders would be expected to be particularly demanding given the emphasis in healthcare on individual detail. The SD modelling perspective is adopted for a specific purpose. The aggregated view aims to isolate the feedback structure whilst the deterministic view emphasises causality rather than randomness. Furthermore, the exclusion of unnecessary and confusing detail avoids the model becoming cluttered and obscuring the dynamic elements of interest (Forrester, 1961; Richardson, 1991).

Being a facilitator is not the only task of the modeller. Building the model and suggesting the recommendations that lead to changes in the system requires some knowledge of the main characteristics of the system. Even the best possible model created in such a process is useless if stakeholders are not ready to listen and accept the results. It is therefore important to know whom exactly we are serving and who will follow up on the changes that are suggested as a result of the process. If those who can drive the required changes are not cooperating, there is no justification to keep on with the process.

If there are no obvious stakeholders’ alternatives, or if there are competing management alternatives how do decisions get made? What is it that decision-makers need to develop and choose between management alternatives effectively? They need to understand the system and its underlying structures. They need to understand the implications of decisions in advance so that they may better understand the pros and cons of different alternatives. Then theoretically, the alternative with the most positive and lease negative attributes would be chosen.

SD models are helpful in these situations. The point is not to have a model that precisely predicts but rather to have one that helps us better understand alternatives and the
complexities that created them. This is difficult to tease out of the messy problems inherent to healthcare systems. Participatory SD modelling can be used to help decision-makers and stakeholders investigate a variety of alternatives in an effort to find the “most positive”.

The measures that were taken to involve the stakeholders in this study were described in chapters 3, 4 and 6. The stakeholders did not object to the modelling perspective of SD. They accepted the focus on aggregate dispensary flows rather than individual staff member processes. This was perhaps due, to some extent, to the fact that the practitioners involved were strategic decision makers.

It is important that stakeholders own the process or are led to believe that they have ownership to it. In particular, the issue of low model impact (no action is taken) even when practitioners are involved, can be overcome through increased practitioners’ involvement in the modelling process. ‘Action’ results from practitioners’ commitment to act which is preceded by ownership of and involvement in the process (Scholl, 2004). In other words, understanding the modelling process by practitioners regarding their contribution to modelling and benefits from involvement leads to action.

One of the most common criticisms of participatory processes is that the stakeholders become disengaged with the process. This is because they either feel their participation in the process is tokenism (Voinov and Bousquet, 2010) or they find the situation too scientifically complex to effectively contribute (Newig et al., 2008). The survey questionnaire results at the end of the process showed that all of the stakeholders enjoyed the process and they believed their input was valued. This finding suggests that the SD participatory approach was successful in achieving a ‘meaningful’ participatory approach.

Furthermore, the evaluation results and feedback from stakeholders suggest that group model-building process and its outputs (i.e., the models) are important vehicles for enhancing social learning, participation, and facilitating a shared and better understanding of complex problems within hospital pharmacies. Social learning is generally understood as a process in which participants are involved in a dialectic exchange of information and ideas in a structured group situation, leading them to learn from each other and develop a deeper and collective understanding of a complex issue and its possible solutions (Akkermans and Vennix, 1997; Rouwette, 2011; Scott et al., 2015). Also, having stakeholders stating that they now perceive the problems differently indicates that group
model-building can be a powerful tool for changing current paradigms and mental model of how complex healthcare systems functions.

What is also apparent from the evaluation results is that the process has succeeded in building stakeholders’ knowledge, capacity and skills regarding the interpretation of the SD model. This finding supports the notion that in certain situations, a model is considered valuable not for the accuracy of its predictive power, but for other outcomes, such as workforce and capacity-building, as well as the educational functionality that it conveys to stakeholder groups or users who benefitted by taking part in the modelling process.

Participants highlighted how the simulation model could be useful in many other settings. The participatory SD and the simulation model can be useful and extended to other applications such as another pharmacy, healthcare services where the differences in variables are minimalistic, and thus could benefit from the knowledge generated by dynamic analysis of this abstract model such as such as pathology labs and aseptic dispensing units and finally applications where safety-efficiency trade-offs needs utilisation.

All participants reported that the modelling project was valuable as a learning experience and that they learned from both the process rather as well as interpreting the output. Most reported that the experience helped them gain a better understanding of one another, the hospital pharmacy dispensary system, and how incorrect staffing levels, workload, interruptions and fatigue has an impact on the well-being of the hospital pharmacy dispensary. Modelling the problem together seemed to have created a sense of participant ownership in the simulation model. Labellers and checkers who represent the sharp-end of the system expressed confidence that the simulation model reflected their mental model of the hospital pharmacy dispensary system.

6.6.3 Recommendations for Participatory SD modelling Good Practices within Healthcare

In this section, I am recommending good practices of the participatory SD approach within healthcare based on my experience. I will discuss the modeller's time and skill requirements needed to conduct and facilitate an effective participatory SD model session in healthcare. I will review details about building the model drawing from Vennix (1996) and other guidelines. I will also review additional elements that I used and will explain
what can be learned from my own experience on how to improve the group modelling process.

Vennix’s process of group model-building includes four stages. During the first stage, the modeller/researcher has to decide whether to use qualitative or quantitative model. Regardless of the goals and the resources required for developing the model, Vennix argues that the use of a qualitative or quantitative model depends on the participants’ inclination. If they tend to be analytical thinkers, they should use a qualitative approach, and if they lack the ability required for analytical thinking, then a formalised model is preferable. In this research, the participants lacked the ability required for analytical thinking, so I started with a qualitative model and converted to a quantitative model. My conclusion from this experience is that whether the audience involved in the modelling effort is more analytical or not, the decision to use a quantitative model depends mainly on the ultimate goal of the modelling effort rather than on the inclination of the audience but using a combination of these two approaches is preferred as it demonstrates to the audience the evolution of their model, and it allows them to reclaim ownership.

During the second stage, one has to decide how many participants should be involved in the model building sessions. Vennix suggests the number of five participants in a group model-building process as the best size from his experience; however, each case needs to be dealt with specifically. The larger the size of the group the more structured the sessions needs to be. In this research, the total number of participants based on the hospital pharmacy dispensary was 21. The group diversity according to Vennix (1996) is advantageous to the model’s quality but might create more tension within the group. There were no substantial tensions, but it was observed during the non-management sessions, trainees tend not to contribute much or highlight deficiencies, as their seniors were there observing them. Therefore, the facilitator has to be very skilful at problem-solving when such environments are introduced and making sure that participants feel ease to talk. Otherwise, the process of building the model might fall apart.

During the third stage, one has to decide whether to start with a preliminary model. According to Vennix (1996), starting without a preliminary model is effective in terms of time because no interviews have to be scheduled. In the process of building the model, I used interviews before the sessions for two reasons: (a) to understand the problems of the hospital pharmacy dispensary and be able later to present a preliminary model and build from there and (b) to be acquainted with the potential participants for the group-modelling
process. It also helped me, later on, to get in touch with staff members who were not part of the group and who were helpful in providing information and data.

Vennix’s fourth stage of the group model-building process deals with the preparation of sessions. On the other hand, I was limited when using the five essential roles encouraged by Richardson and Andersen (1995), Vennix (1996) and Andersen and Richardson (1997). In my study, the group participants were not interested in taking on a specific role. Finally, three issues that I find important to point out are:

a) Assuming that the members in the group have no SD background, I deemed it important to introduce to the group, during the initial first meeting, the concepts of system thinking, SD and explain what feedback loops are. In order to practice systems thinking, I also gave them some posters to be hung at the dispensary showing example models related to the hospital pharmacy dispensary

b) Since the group was larger than recommended and their time schedules were varied, I found it useful to split them into groups of three, with different skill-mix. That way, communication can flow clearly, and the model can be validated extensively.

c) Participation in a group building-model requires a high level of communication. I found it essential to introduce to the group some concepts on better communication.

In general, although it is preferable to plan each session in detail, it is important to be flexible during each session, to listen to the participants’ intents and desires as the participants are the facilitator’s customers.

The skill requirements and time requirements will discuss in detail some of the good practices of applying the participatory SD approach in healthcare.

6.6.3.1 Skill requirements for the participatory SD approach

Applying participatory SD modelling is a non-trivial process. Given the availability of user-friendly purpose-built SD software that can produce a useable simulation model in a matter of minutes, it is tempting to assume that building an SD model is a straightforward process. However, this is not true as the underlying assumptions can be easily violated and the inexperienced analyst can easily succumb to a number of possible modelling pitfalls. Therefore, a certain level of skill is required to ensure that SD is applied correctly and that the model adheres to good modelling practice. Specialist
knowledge of SD would not be necessary if a completed and validated SD model was
delivered to the organisation as an ongoing policy analysis tool, known in SD as a
microworld. However, given that this was a participatory approach, some level of
prerequisites is needed to facilitate group sessions and model on the spot. Furthermore,
the necessary skills were available because basic skills in SD were acquired prior to the
study and these skills developed during the course of the study.

In terms of the necessary skill requirements for conducting group sessions, the facilitator
within healthcare is supposed to guide the group rather than being a participant. She/he
has to be aware of the problem that is being tackled but should concentrate on the process
and structure rather than on the content (Phillips and Phillips, 1993). To facilitate
successfully requires separation of information, thoughts and emotions through the
process of modelling. This kind of separation might sometimes create conflicts that are
likely to harm the process and adversely affect quality outcomes.

The role of the facilitator cannot be fully predetermined and may have to be adapted
according to the idiosyncrasies of the group. The diversity of the group members and their
interrelationships, as well as the facilitator's style, necessitate the need to understand the
group's life by being flexible and accommodating to the needs of the group members
(Phillips and Phillips, 1993). The facilitator needs to improve through a learning process
that can turn him/her into a more mature and experienced guide who can fully understand
the needs of the group members. The ongoing learning is a natural path that may lead to
a better understanding of behaviours and issues that might arise within the group.

Assuming a continuous improvement and better experience through reflection and
internalising of the group's needs, the facilitator may use various tools to obtain important
feedback from the group members in order to improve the modelling process. In the
process of this research I deemed it necessary, as I explained earlier, to distribute a
questionnaire survey form during the sessions and learn what and how to improve the
process. The following are the important issues that I have learned from the group
members’ feedbacks:

• Starting the first session with a lengthy introduction (even if topics are important
like explaining what SD is) is boring for the participants, as they expect to discuss
the problem.
A meeting’s schedule is very important but needs to be flexible and resilient. The schedule is valuable in the process of working with a group. Attention should be given more to the group participants rather than rushing to meet the set goals.

- It is useful to reintroduce the same scenario but using different settings so that they can understand the behaviour.
- Having participants from diverse backgrounds can strengthen the shared vision and enrichen the group model.
- It is important to use variable names that do not contribute to the existing blame-culture prevalent in healthcare and highlight beforehand that blaming people is not the objective of the group sessions.

Last but not least, the model (as all models in general) is only an attempt to represent the reality. It is never reality, or as Sterman (2002) emphasised: “all models are wrong….all models, mental or formal, are limited, simplified representations of the real world.” (p. 846). In any case, our mind has its own peculiar mental model of the reality; therefore, there are many difficulties and limitations involved in building an accurate model. I assume that any other researcher might come up with different results following the group modelling process for a different organisation; however, the behaviour of variables as a result of the relationships amongst them will most likely be the same.

Computer modelling helps us understand complexities that are beyond the capacity of our own minds. SD adds to computer simulation by helping us capture feedback and time lags that are inherent to many complex problems. Computers are so effective at performing these tasks that Meadow and Robinson (2002) have referred to them as “electronic oracles”. However, computer models are only as good as their designers. Many modellers and participants may be inclined to include everything in a model. The ease of which software can be used aggravates this situation. Careful consideration of the problem and the use of output data generated by complex research models can help simplify the requirements of an SD model. It also helps to remember why SD was originally designed.

6.6.3.2 Time requirements for the participatory SD approach

Participatory processes are often considered to be significantly time (and resource) intensive. This was found to be particularly true in this participatory SD process (GMB) when it came to the qualitative analyses of the data. Working face-to-face with several groups of stakeholders and repeating the process each time, took a significant amount of time, mainly from participants as they had to adhere to a strict schedule. In this study, due
to the nature of the sessions taking place in groups and the researcher’s familiarity with the process, an hour of audio took approximately 10 hours to transcribe and then at least 4 hours to code using thematic analysis. Furthermore, it is important to be flexible and adjust the methodology depending on how the methods worked with the stakeholders. For example, in the model assessment session, it was much easier and manage to split groups into 3 (mix of labellers and checkers) and test the model with them. It proved to be much convenient for the dispensaries team leaders as not a huge number of staff were absent to engage in these sessions.

Another important notion about collecting information should be considered whilst building the model. Measuring soft variables like interruptions requires the use of interviews and observations. The modeller has to be sure that management will confirm the use of such questionnaires which require some time investment on behalf of the employees.

Therefore, the participatory SD process should not be overly concerned with adapting the process to allow for changes in conditions or identified improvements

An early discovery in the research was that developing a quantitative diagram and designing the interface is also extremely time and resource intensive, and in this project, it has taken around 18 months to date. This resulted in the need to engage with the stakeholder groups throughout this period in order to keep them engaged in the project. However, this led to another issue; there is a fine line to tread between over-burdening stakeholders with questions and information and taking a less-involved approach. People can easily become frustrated if they receive too much communication, causing them to disengage or ignore the information. Taking a less involved approach, however, can have the opposite effect of making a group feel disconnected.

6.7 Summary

Evaluating the participatory SD approach within group discussions was constructive. Many opinions about the uses of the SD approach were offered. Most comments appeared to consist of valid observations and suggestions. According to the practitioners and managers, the simulation model could be just as easily used as an aid to understanding the structure and behaviour of hospital pharmacy dispensary system in assisting strategic decision-making. The interviewees also introduced the idea of using the model in a demonstrative capacity.
Regarding the process, a majority of participants thought the modelling process was a good method for planning and management; and that the process has helped improve their understanding of the complex problems within the staff management issue; open and transparent, and that it was useful to them as their views were represented in the final model.

Some stakeholders indicated that the modelling process was successful in empowering them, in that, they learned to stand up and express their views in the presence of more senior stakeholders. However, many of the stakeholders reckoned that the time allocated for the entire process was inadequate. This was particularly the case during the validation of the model as they required more time but were unable because of the hectic hospital pharmacy dispensary schedule. However, they noted that patient and impartial facilitation was instrumental in keeping them motivated and that their perception changed after seeing the completed GMB qualitative model.

As indicated by participants’ perception that their values, opinions or positions have been represented, the decisions made herein, can be viewed as legitimate (Fokkinga et al., 2009). This means that the results have the potential of being used or extrapolated in a different setting. Further, the declaration that the process was inclusive, open and transparent, as well as the desire to be involved in future efforts are also important insights worth noting, as they imply model use and uptake.

The discussions also revealed a miss-match between the Work-As-Imagined (WAI) and Work-As-Done (WAD) paradigms. WAI is what work should look like if everyone follows procedures, it is based on what designers, managers, regulators, and authorities believe happens or should happen whilst WAD is what workers have to do to get the job done in the actual situation (Erik Hollnagel, David D. Woods, 2006). The management was of the opinion that the model does not entirely reflect their mental model and was more prone to dispute it whilst the labellers attested to its accuracy and reflection of the actual pharmacy dispensary system. The gap between WAI and WAD is viewed as a danger to safety since real working processes remain undescribed and poorly understood (Anderson et al., 2016). SD modelling has the potential to narrow the gap between WAI and WAD as it allows WAI to be updated to match with WAD.

The utility of the participatory SD approach proved to be useful in conducting scenario testing to contribute to group learning and fostering meaningful discussions with participants. The usability of the participatory SD approach highlighted how it is crucial
to involve stakeholders with the initial model development so that ownership can be claimed and that conducting model experiments in small-sized groups are more beneficial for ease of understanding as opposed to large groups.

Overall, the participants’ experience and perception of the modelling process and the resultant outputs were largely very positive. This insight is consistent with experience from recent participatory modelling experiments (Scott et al., 2016).

There were glaring challenges in conducting the participatory SD approach; the most obvious challenge was the time constraint in conduction multiple group sessions. The quantitative adoption of the qualitative model had to be formulated by the researcher as participants did not have the required time to participate in additional model building sessions. As a result, a strong focus was dedicated to making sure that the evaluative sessions were conducted to validate and evaluate the model and maintain ownership of the model. Finally, it proved to be a challenge in keeping communication open with necessary stakeholders for continuous model development.
7 CONCLUSION

This chapter summarises and highlights the key findings and the key contributions of this study to existing knowledge, review the research objectives that have been addressed, considers the implications of these findings for participatory SD research and identifies areas for future research.

The motivation to research the pharmacy staff workload management issue and its interrelated factors stemmed from the lack of research in the literature concerning these relationships.

This study investigated how the SD framework can help hospital management to view and make decisions about the staff workload management issue by supporting them to better consider the impact of staff levels, interruptions and workload on safety (dispensing errors) and performance (backlog). The proposed SD framework is based on the theory of systems thinking, and it has employed the participatory SD approach: Group Model Building (GMB). The SD approach enables the understanding of the dynamic relationship amongst the various variables in the hospital pharmacy dispensary when linking staff levels, interruptions and workload on safety. The proposed framework provides the basis for learning and for hospital pharmacies to adapt to change as required by their present realities.

7.1 Research Questions and Research Findings

As stated in the introduction, SD has been widely used in modelling across a range of applications from socio-economic to engineering systems, but its potential has not yet been fully realised as a tool for understanding trade-offs dynamics between safety and efficiency in healthcare. Moreover, with increasingly complex systems like healthcare being developed and managed, there is a need for a tool that allows us to understand their complexity, design better strategies and guide effective change. SD has the potential to provide balanced and trustworthy insights into strategic decision making in determining the best trade-off between safety and efficiency. Participatory SD modelling and learning is particularly important in healthcare since problems in healthcare are difficult to comprehend due to complexity, the involvement of multiple stakeholders in decision
making and fragmented structure of delivery systems. Participatory SD modelling triangulates stakeholder expertise, data and simulation of implementation plans prior to attempting change. It provides decision-makers with an evaluation and learning tool to analyse impacts to changes and determine which input data is most likely to achieve desired outcomes. Based on this aim, two distinct research objectives were formulated and, subsequently, addressed:

1. To investigate how the SD framework can help hospital pharmacy management to view and make decisions about the staff workload management issue by supporting them to consider the impact of staff levels better, interruptions and workload on safety (dispensing errors) and performance (backlog).
2. Evaluate the applicability, utility and usability of how participatory SD can enhance group learning:
   - What kind of benefits (or drawbacks) in knowledge will pharmacy decision-makers gain by applying the SD approach?
   - How easy is it to use (in terms of modelling, analysis and result interpretation) the SD approach to improve group learning?
   - How applicable is the participatory SD approach in the healthcare sector?

This study has addressed these objectives as follows.

Objective 1 was successfully addressed by creating a full-fledged SD simulation model using the participatory SD approach that looks at how the impact of staff levels, interruptions and workload contributes to safety (dispensing errors) and performance (backlog). Using the preliminary interviews, an initial conceptual model was first developed, facilitating a better understanding of the feedback structure and function of the hospital pharmacy dispensary system. The preliminary conceptual model was further refined and improved in a series of group model-building sessions with relevant stakeholders. The conceptual model indicated that the hospital dispensary system is governed by several feedback processes, including two balancing (negative) feedback loops and two reinforcing (positive) loops. These feedback loops revolve around the issues of staff workload, interruptions from trainees, fatigue, and dispensing errors.

Consequently, the main parts of the conceptual model were translated into an SD simulation model to gain an insight into the dynamic behaviour of the hospital pharmacy dispensary in a 24-hour time horizon. The simulation model consisted of four interacting
constituent sub-models: production sub-model, performance sub-model, interruptions sub-model and staff sub-model, with backlog and errors used as metrics. Finally, the model was uploaded on to a web platform (Forio Simulate), and online interface scenarios were created reflecting several scenarios. Structural and behavioural pattern tests, and extreme conditions test were used to evaluate and validate the performance of the model. The results showed that the simulated outputs agreed well with the observed reality of the system.

Besides business-as-usual scenario, which suggests an unsustainable trajectory when it comes to winter pressure, two main policy scenarios were simulated to assess their impact on workload, backlog, fatigue and errors: Impact of staffing level on efficiency (production) and thoroughness (safety) (scenario 1) with three sub-scenarios: winter pressure using baseline values, dynamic staffing levels and best fixed average staffing levels. The second scenario is based on the impact of interruptions (from trainees) on efficiency and safety. Scenario 2 which includes four sub-scenarios: no trainees, twenty (1 trainee), forty (2 trainees) and sixty (3 trainees) percent increase in trainees interrupting. The results from both scenarios showed the knock-on impact rework has on dispensing errors, which is often missing from the traditional linear model-based approaches. This potentially downward-spiral knock-on effect makes it more challenging to deal with demand variability, for example, due to hospital winter pressures. The results provide pharmacy management with in-depth insights into potential downward-spiral knock-on effect of high workload and potential challenges in dealing with demand variability. Results and simulated scenarios reveal that it is better to have a fixed adequate staff number throughout the day to keep backlog and dispensing errors to a minimum than calling additional staff to combat growing backlog; and that whilst having a significant amount of trainees might be cost efficient, it has a detrimental effect on dispensing errors (safety) as number of rework done to correct the errors increases exponentially and contributes to the growing backlog. Furthermore, capacity depletion initiated by continuous high workload (over 85% of total workload) has a significant effect on the amount of rework.

SD has provided pharmacy management with the ability to capture separate dynamics of the hospital pharmacy dispensary, its effect on safety and the relationships between workload, interruptions (from trainees), fatigue and error. The feedback and evaluative discussions with pharmacy management revealed how the adopted simulation model can be used as a suitable tool for demonstrating the effects of staff workload pressure and its
contributory factors and for helping people to learn more about the staff workload management. There was an acknowledgement that the simulation would still be of value in learning or even policy-making when set in an abstract context, although there was a greater appreciation of the model in its present real-world form. The discussions with the pharmacy management pointed towards using the model to assist with decision-making, with a specific focus on the lower level for learning, and at a higher level for policy analysis.

Objective 2 was successfully addressed by evaluating the applicability, utility and usability of how participatory SD can enhance group learning. Objective 2 had three sub-objectives: 2A What kind of benefits (or drawbacks) in knowledge will pharmacy decision-makers gain by applying the SD approach? Moreover, 2B: How easy is it to use (in terms of modelling, analysis and result interpretation) the SD approach to improve group learning? 2C: How applicable is the participatory SD approach in the healthcare environment?

One of the key benefits of participatory SD modelling is participants learning about system connections and feedback and about other participants’ opinions. Incorporating all relevant stakeholders in the initial model building sessions has a more significant impact on participants to claim ownership to the model and promotes more engagement with the model. The participatory SD approach is more effective and beneficial when model experiments are conducted in small-sized groups. This will produce more engagement and allow participants to understand the model building process much more comfortably. Participants found both the qualitative (conceptual) and quantitative (simulation) aspects of the SD approach equally useful and easy to understand. Introducing a web-interface (Forio) aided their understanding and learning from of the results.

The point is not to have a model that precisely predicts but rather to have one that helps us better understand alternatives and the complexities that created them. This is difficult to tease out of the messy problems inherent to healthcare systems. Participatory SD modelling can be used to help decision-makers and stakeholders investigate a variety of alternatives in an effort to find the “most positive”.

As discussed in the previous chapter, the participatory SD process demonstrated how it is useful in building stakeholders’ knowledge, capacity and skills regarding the interpretation of the SD model. This reinforces the notion that a model is considered
valuable not for the accuracy of its predictive power, but for other outcomes, such as workforce and capacity-building, as well as the educational functionality that it conveys to stakeholder groups or users who benefitted by taking part in the modelling process.

Modelling the problem together seemed to have created a sense of participant ownership in the simulation model.

This research has addressed the applicability of the participatory SD approach in healthcare by suggesting good practices in implementing GMB in a healthcare environment (see Section 6.6.3). The frameworks highlighted by Richardson and Andersen (1995) and Andersen and Richardson (1997) identify five roles to be represented within the group modelling support team: (1) the facilitator, who acts as a group guide and knowledge elicitor; (2) the modeller, or reflector, who focuses on the model that is being formulated by the group and the facilitator; (3) the process coach, who focuses on the dynamics of individuals and subgroups within the team; (4) the recorder, whose task is to write down or sketch the important elements of the group proceedings; (5) the gatekeeper, who is usually a person within the “client” group who carries responsibility for the modelling project and initiates it. These five roles that have to be represented in any group modelling support team are well accepted in the GMB literature (Andersen and Richardson, 1997; Carter et al., 2014; Richardson and Andersen, 1995).

However, for a solo researcher, it is feasible to conduct GMB stages without the need for a team. By conducting preliminary interviews and developing a preliminary model, solo research can eliminate the time needed to model a model from scratch during the GMB sessions. Furthermore, once a qualitative model is developed with the participants, it is imperative to convert the conceptual model to a simulation model during the behind-the-scenes stage. Given that hospitals are busy and high-stress environment and the difficulty in organising multiple sessions, the ability to convert the qualitative model to a quantitative model downsizes the time needed to conduct further sessions that can potentially prolong the research study. By using graphical web interfaces to base your scenarios upon will reduce the time needed to explicitly explain the concept of the stock-and-flow diagram, allowing the participants to immerse with a user-friendly interface to understand the complexity of the model better. During the evaluation stage, conducting the validation/testing/experimenting sessions is best done in small group sizes. This enables the solo researcher to be flexible and manage the sessions with the sessions as opposed to conducting large group sessions.
Secondly, this research has used an interactive web-based interface, accessible via any standard web browser, to present user-friendly scenarios.

The platform used was Forio Simulate software which allows building and sharing simulations and making them interactive using an interface design tool. Interactive web-based simulations have been used in the SD literature to teach key ideas in business and strategy (Martínez-Moyano et al., 2005; Sterman, 2014) but their level of interactivity is significantly limited and mostly sequential. Furthermore, aiding the group interactions with the web-interface by using questionnaire contributed to rich discussions on the applicability, utility and usability of this approach within healthcare. A questionnaire survey is a widely used method in social science research, involving a list of questions, which serve as an instrument for the measurement of data regarding attitudes, opinions, etc (Hair, 2007; Oppenheim, 1968). One limitation in the SD literature argues that post-modelling output is rarely evaluated (Größler, 2007). To incorporate that into the post-modelling evaluation sessions helped probe respondents to elaborate on their answers and get enrich the discussions and how suitable the approach is. Whilst these facilitated processes have been applied in the facilitated DES literature (Franco and Montibeller, 2010; Kotiadis et al., 2014; Tako and Kotiadis, 2015), the aforementioned approach has never been extended to the participatory SD approach.

Finally, the evaluation results and feedback from stakeholders suggest that participatory modelling process and its outputs (i.e., the interactive models) are important instruments for enhancing social learning, participation, and promoting a shared and better understanding of complex problems within healthcare. Overall, the model results could help inform planning and policy decisions within the hospital pharmacy sector to enhance correct staffing levels, improve cost-benefit analysis, and proactively reduce dispensing errors and backlog.

However, it was noted that implementing a participatory SD process is not trivial. Consequently, several challenges and lessons, which can guide future work were highlighted as outlined in section 6.6.3. These include: the importance of preliminary interviews, being aware that the modelling objective could be changed and dictated by stakeholders, involving a manageable number of participants, keep the model output as generic as possible, and devoting enough time for model quantification and simulation.
7.2 Contributions of This Research

This work has produced several contributions. The first contribution is a new application of participatory SD approach to safe and efficient staffing level management within hospital pharmacies. Before this study was conducted, incorrect staffing levels, workload problems and dispensing errors processes within the pharmacy sector had been discussed (Aldhwaihi et al., 2016), but there were no means for investigating the causal-effect relations and quantitative relations between the variables that impacted staff level management within hospital pharmacy. This study has provided the interrelation structure of the variables in the hospital pharmacy dispensary model and has identified quantitative relations between the variables. Simulation results of the model show that the SD model of hospital pharmacy dispensary can help to understand safe staffing levels, workload and the factors relating to causes of rework. It has provided a way of observing model behaviours whilst one or more factors are varied. The second contribution is to the field of GMB by offering a new approach that requires fewer analysts and facilitators, allowing solo researchers to conduct GMB sessions without the need to follow the multiple-actors script.

The third contribution is to the facilitation literature by developing a web-based interface to facilitate group sessions and using a questionnaire after the sessions to support group interactions.

Finally, the results of this study have contributed significantly to the advancement of participatory SD modelling approach within healthcare by evaluating its applicability, utility and usability as a learning method, which until recently, has been dominated by the linear reductionist approaches. Methodologically, this is one of the few studies to apply participatory SD approach as a modelling tool for understanding trade-offs dynamics between safety and efficiency in healthcare. Practically, this research provides stakeholders and managers, from pharmacists to managers the decision support tools in the form of a web-based platform showcasing the integrated conceptual and simulation model for staffing level management in hospital pharmacy. This model integrates what the researcher and the system stakeholders view as the important issues, processes, and complex dynamics that operate within the hospital pharmacy dispensary over time. The overall goal of the research was to examine the feasibility of applying participatory SD modelling approach to safe and efficient staffing level management within hospital pharmacy and evaluate the utility and usability of participatory SD modelling approach
as a learning method. This has been achieved through the application of a contemporary approach – systems-based/systems thinking approach and its concomitant tools: group modelling, causal-loop diagrams, and SD simulation modelling approach. This research was conducted with the understanding that a flawless research design or model rarely exists. However, if a research project is carefully designed and executed, whilst acknowledging weaknesses and limitations, the research can achieve its intended purpose. Finally, this research includes detailed records about its context, including information about the physical environment, social factors and the process of group model building sessions. This will help other researchers to draw conclusions about the extent to which its findings might be generalisable to other situations (Leedy and Ormrod, 2010).

7.3 Recommendations for Decision Makers
This research demonstrates the importance of the decision makers in hospital pharmacy sector, in leading a system with the understanding of the relationship amongst the safety factors of staff workload, staff levels, dispensing errors, interruptions and fatigue. Most of the decision makers’ efforts should be aimed at improving safety in healthcare, which includes amongst others: management based on facts in order to be able to understand safety trends, cause and effect, and interrelations amongst variables which are too complex to be evident without such data collection and analysis. Understanding the correlation between high workload, staff capacity, backlog, incoming prescriptions, errors and fatigue allow stakeholders to comprehend the outcomes of their choices better when calling for additional resources or determining the correct staffing levels. Dispensing backlog can be averted or substantially diminished using the correct number of staff, by considering the total staff capacity needed vis-a-vis the current workload. Furthermore, it is critical for decision-makers to understand the delay involved between releasing and recalling extra staff to counteract growing backlog. Premature releasing extra staff and calling additional staff from wards without taking into account the lag involved can have a significant impact on backlog. Once backlog is significantly reduced, incorporating a two hours window for the additional staff from wards are on call can prove to be useful combating the sudden resurgence of backlog. Finally, having an best-fixed staff resources throughout the workday is more efficient than recalling and reducing additional staff. Interruptions from trainees have a significant detrimental effect on backlog and workload as opposed to dispensing errors and it is important to take that into account when recruiting trainees.
7.4 Research Limitations

According to Beall and Thornton (2016), “we must realise that we can never solve all our problems and challenges, we move from solution to the next challenge”. Also, Hannon and Ruth (1994) argued that “modelling is a never-ending process – we build, revise, compare and change models”. Accordingly, some limitations that present opportunities for further research can be identified because of this research study. First, hospital pharmacy dispensaries have several external subsystems that rest on its dispensing process. However, due to time and logistical constraints, this study only focused on the staffing levels and dispensing process conducted by labellers and checkers. Thus, the scope boundary of the model could be expanded to include key problematic issues that affect the dispensary, with a concentration on developing a greater-hospital pharmacy SD model that includes processes (i.e. wards, robots, pharmaceutical companies) that directly impact the dispensing process and capacity of the different types of staff. This also includes including a greater skill mix by adding the varied capacity of technicians and clinical pharmacists to truly reflect the diverse staff operating within the dispensary. Indeed, the model equations, graphical functions, and data sources may act as a template for such efforts.

Second, a noteworthy point to mention when discussing modelling relates to uncertainties. This is because uncertainty is accepted to be an integral aspect of any effort to manage and understand healthcare problems, including modelling (Coyle, 2000; Fone and Hollinghurst, 2003). Walker et al. (2003) characterised uncertainty in model development by its level along the spectrum from determinism to total ignorance; and its nature (epistemic, stochastic or ambiguity uncertainty). Walker et al. (2003) categorised as: input uncertainty, model structure uncertainty, parameter uncertainty, model technical uncertainty. Indeed, this research does not rule out the presence of all these forms of uncertainties in the model. However, the drawback to draw attention here relates to parameter uncertainty (i.e., the uncertainties concerning parameter values) (Walker et al., 2003). For example, in developing and parameterising the simulation model, some assumptions and inferences were made based on the researcher’s and stakeholders’ best judgment and their understanding of the hospital pharmacy problems and challenges. Also, some variables and issues, which may be relevant, have been omitted to keep the models simple and comprehensible. Furthermore, in this study, great efforts were made to obtain the best data available, but it was not possible to fully assess quality and exactness.
Third, one apparent limitation is that the study was based on the model of one case study which is the UHL pharmacies (Glenfield and Royal Infirmary). There was a real challenge in finding other hospital pharmacy dispensaries outside Leicester who wanted to be part of the process. Initially, several hospital pharmacies were potentially interested such as Imperial College Healthcare NHS Trust and Oxford University Hospitals NHS Foundation Trust; however, due to management changes, momentum loss and time constraints, it proved to be difficult to extend the process to these dispensaries.

Fourth, given the finite time with participants who were adhering to a strict busy schedule, there was no full participation in the whole process. For instance, developing the web-interface of the scenarios was done behind-the-scenes instead of in a participatory manner. This was attributed due to lack of time to arrange further sessions with participants.

Finally, it is vital to acknowledge that there are no models that can represent the ‘true’ or complete reality of a system, as they are only approximations of real systems (Mai, 2012). Thus, although the models developed in this study were verified and validated through standard best practice, it is imperative to note that, ideally, no model can ever be fully verified or validated (Sterman, 2001; Swanson, 2002). This is because “all models are wrong; all models, mental or formal, are limited, simplified representations of the real world” (Swanson, 2002). Indeed, many SD modellers recognise the “impossibility” of perfect model validation (e.g., Goh et al., 2012a; Keers et al., 2013; Woo, 2015). For instance, Cave and Willis (2016) argue that models will never provide an answer by themselves to the “best solution” for a healthcare problem; models only provide input to a decision in the form of indications of which sources that are important or the plausible scale of the effects of a suggested measure. As such, the model developed in this study may not be the best, despite the multiple tests to establish their robustness and reliability. Hence, the results should be interpreted with caution. Nevertheless, the acceptability and the trustworthiness of the results by the system stakeholders may not be in doubt, since they took part in the model development and are, therefore, aware of the model assumptions, aware of the degree of model reliability and recognise that the model included the best available knowledge and data, and understand that there will always be inherent uncertainty in the model results (Pruyt, 2014).

There are several limitations that I will reflect on. They are: if I could do the research again, what would I change; my limitations as a researcher; how I engaged with the participants and finally how I could have explained the technical elements in hindsight.
If I could do the research again, I would have put more effort into organising further group sessions to formulate the stock-and-flow diagram. If that was not possible, I would have presented the completed stock-and-flow diagram for validation and experimentation to a group of the original participants prior to creating the web-interface scenarios. That way, they would have a greater understanding of how parts of the group conceptual model are illustrated in the simulation model.

One inherent limitation as a researcher was the longer learning curve in understanding OR modelling software. I was originally trained as a computer scientist and had no prior background in OR modelling techniques, more specifically the system dynamics approach. To get myself up to speed, I had to learn the approach from scratch, coupled with establishing a firm foundation on how to use the VenSim software. I believe, if I had a solid modelling experience prior to undertaking my research, it would have sped the process significantly.

In terms of engaging with the participants. There was significant difficulty in engaging with the participants. Without necessary persistence, it is hard to organise the sessions with varied practitioners. I spent a great amount of time chasing team-leaders in organising group-sessions to build the model. At times, I had appointments and meetings cancelled last-minute. However, establishing a solid communication with the Chief Pharmacist did contribute to meetings being materialised. It is highly important to make sure that enough planning is conducted prior to engaging participants. Modelling with a mix of participants from different backgrounds can cause people to off-topic. Making sure that the scope is established, and the session properly facilitated can reduce wasted time.

Given that the completed stock-and-flow diagram was not presented to the participants, in hindsight, I would have held several group sessions with the participants that were part of the group-model-building sessions and showed them simulated parts of the stock-and-flow diagram with the intention to validate the model.

7.5 Recommendations for Future Research

In order to address these limitations and to develop the ideas in this thesis further, future research could focus on the following areas.

First, future research should focus on expanding the scope boundary of the adopted model from the dispensing process conducted by labellers and checkers to incorporating
subsystems (i.e. wards, robots, pharmaceutical companies) that impact the dispensing process. To include more pertinent staff groups (clinical pharmacists, technicians, senior pharmacists) that are part of the dispensing process and assign them their respective capacities so that a true skill mix is generated.

Second, future research should involve collecting more objective real-time data, adding additional relevant variables where data was scarce and greatly reduce the number of assumptions by substituting them with accurate historical and observable data. Furthermore, further research should include modifying the models to fit different purposes and to provide more specific suggestions and strategies. This thesis provides a platform for future safety improvement in healthcare studies, and the model can be further modified to fit different purposes for providing more specific suggestions and strategies.

Third, future research should include expanding the adoption of the simulation model to other hospital pharmacy dispensaries. Given that the adopted model focused on a single case study with two hospital pharmacies within UHL, more case studies need to be conducted to establish the generic applicability of the simulation model to other hospital pharmacies outside Leicester.

Fourth, to achieve full participation as part of the participatory SD paradigm, future research should focus on making sure that stakeholders are part of every stage of the model building sessions. This includes conducting the group model building sessions to develop the conceptual model, build the simulation model and designing and running the scenarios. This will increase the shared ownership to the model and will increase the adoption of the model by decision-makers.

Additionally, future research includes seeking a way of merging the models in the thesis with other existing models that also focus on the process of safety improvement in healthcare delivery in order to further develop the models. Since SD modelling has been applied in different areas and systems of healthcare, it provides the opportunity for linking the SD model in the pharmacy context with other models.

Furthermore, much research remains to be done on implementations of similar system thinking approaches to safety analysis within hospital pharmacy, which will contribute to better coverage of possible factors and improvement of the quantitative modelling results. This thesis demonstrates the successful application of participatory SD modelling to safe and efficient staffing level management within hospital pharmacy. When sufficient data are available, further staff groups’ capacity can be categorised to achieve a true staff skill-
mix tool as well as greater learning can be dedicated on the types of errors committed by labellers.
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9 APPENDICES

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APPENDIX A. HFACS-EE

<table>
<thead>
<tr>
<th>External Factors</th>
<th>Regulatory Factors</th>
<th>The effects that government adopted laws, regulations and policies have on the organisation. It includes how actions of the regulator, including inspections and enforcement, affect safety. The formulation to control over hazardous processes.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Others</td>
<td></td>
<td>The effect society as a whole has on the safety including economic pressure, environmental concerns and legal pressure</td>
</tr>
<tr>
<td>Organisational Influences</td>
<td>Organisational climate</td>
<td>The working atmosphere within the organisation which includes culture, policies and structure</td>
</tr>
<tr>
<td></td>
<td>Operational process</td>
<td>This refers to organisational decisions and rules that govern the everyday activities within the organisation. This includes the establishment/use of standard operational procedures, and formal methods for maintaining oversight of the workforce.</td>
</tr>
<tr>
<td></td>
<td>Resource management</td>
<td>This encompassess organisational-level decision-making vis-à-vis the sharing and maintenance of organisational assets (such as personnel, money, equipment and facilities)</td>
</tr>
<tr>
<td>Unsafe supervisions</td>
<td>Inadequate supervision</td>
<td>The factors that supervision fails to identify a hazard, recognise and control risk, provide guidance, training and/or oversight, etc., resulting in human error or an unsafe situation</td>
</tr>
<tr>
<td></td>
<td>Planned inappropriate operations</td>
<td>The factors that supervision fails to adequately assess the hazards associated with an operation and allow for unnecessary risks</td>
</tr>
<tr>
<td></td>
<td>Failed to correct problems</td>
<td>The factors that supervision fails to correct known deficiencies in documents, processes or procedures, or fails to correct inappropriate or unsafe actions of individuals create an unsafe situation</td>
</tr>
<tr>
<td>Preconditions for unsafe acts</td>
<td>Environmental factors</td>
<td>This category encompasses a variety issues, including the design of equipment and controls, display/interface characteristics, checklist layout, task factors and automation. It also includes the operational setting (e.g. weather, altitude, terrain) and the ambient environment (e.g., heat, vibration, lighting, toxins)</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Condition of the operator</td>
<td>The conditions of an individual that can have adverse influence to perform his/her job such as mental fatigue resulting from high work-load, pernicious attitudes, and misplaced motivation. This also includes mental/physical limitations of the practitioners.</td>
<td></td>
</tr>
<tr>
<td>Personnel factors</td>
<td>Includes a variety of communication, coordination, and teamwork issues that impact performance</td>
<td></td>
</tr>
</tbody>
</table>
| Unsafe acts | Human errors | Decision errors: These “thinking” errors represent conscious, goal-intended behaviour that proceeds as designed, yet the plan proves inadequate or inappropriate for the situation. These errors typically manifest as poorly executed procedures, improper choices, or simply the misinterpretation and/or misuse of relevant information.  
Skill-based errors: Highly practiced behaviour that occurs with little or no conscious thought. These “doing” errors frequently appear as breakdown in visual scan patterns, forgotten intentions, and omitted items in checklists. Even the manner or technique with which one performs a task is included.  
Perceptual errors: Medication errors resulting from sound alike, look-alike drugs or the use of decimal point or abbreviations |
| Violations | Routine violations: Often referred to as “bending the rules,” this type of violation tends to be habitual by nature and is often enabled by a system of supervision |
and management that tolerates such departures from the rules.

*Exceptional violations:* Isolated departures from authority, neither typical of the individual nor condoned by management.
APPENDIX B. SURVEY QUESTIONNAIRE

Survey Questionnaire

I. Personal details
1. What is your role in the dispensary? Please specify whether you are a student or not.

☐ Dispenser  ☐ Checker
☐ Other (Please specify):

2. What is your level of experience (in years)?

3. Have you ever used a simulation model before?

☐ Yes (Please specify):

☐ No

II. Opinion about the dispensary simulation model

a. Model understanding & complexity
Please answer the following questions based on your experience of running the dispensary simulation model in the group. The aim of this set of questions is to assess how comprehensive the model provided was.

1. How well do you feel you understand how the non-animated model works?

Understand very little  □ 1 □ 2 □ 3 □ 4 □ 5 Understand very well

2. Please specify to what extent you feel you understand the following parts of non-animated the model?
   a. The relationship between variables

Understand very little  □ 1 □ 2 □ 3 □ 4 □ 5 Understand very well

   b. The structure of the model

Understand very little  □ 1 □ 2 □ 3 □ 4 □ 5 Understand very well

3. Please specify to what extent you feel you understand the following parts of animated the model?
   a. How to use the model

Understand very little  □ 1 □ 2 □ 3 □ 4 □ 5 Understand very well

   b. Model outputs/results

Understand very little  □ 1 □ 2 □ 3 □ 4 □ 5 Understand very well

4. According to the level of importance, please rank from 1 to 3, where 1 is most important and 3 least important, which of the following factors, helped you understand the model?

a. Non-animated description of model (Casual Loop)

b. Visual interface of the model (Web Interface)

c. Animation as the model runs (Web Interface)

5. How would you rate the level of detail of the dispensary model?

Very comprehensive  □ 1 □ 2 □ 3 □ 4 □ 5 Very abstract
### Appendices

#### b. Model validity

*This section deals with your opinion about the credibility of the dispensary simulation model.*

1. To what extent do you feel the simulation model is representative of the dispensary system?

<table>
<thead>
<tr>
<th>Very little</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Very much</th>
</tr>
</thead>
</table>

2. To what extent do you feel the model generates realistic outputs?

<table>
<thead>
<tr>
<th>Very little</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Very much</th>
</tr>
</thead>
</table>

3. How confident would you feel in using this model for decision making?

<table>
<thead>
<tr>
<th>Very little</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Very much</th>
</tr>
</thead>
</table>

#### c. Model usefulness

*Please answer the following questions with respect to the dispensary simulation model. The aim is to identify the trade-off about the usefulness of the dispensary simulation model.*

1. To what extent do you feel using the dispensary simulation model enhanced your learning about causes of dispensing errors?

<table>
<thead>
<tr>
<th>Very little</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Very much</th>
</tr>
</thead>
</table>

2. To what extent do you feel using the dispensary simulation model helped you think strategically about dispensing errors?

<table>
<thead>
<tr>
<th>Very little</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Very much</th>
</tr>
</thead>
</table>

3. In what other contexts might a similar model be used? Please name a few. Why is it relevant?

To what extent do you feel the dispensary simulation model facilitated the communication of ideas and suggestions throughout your group discussion?

<table>
<thead>
<tr>
<th>Very little</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Very much</th>
</tr>
</thead>
</table>

4. Based on what you have learned, how would you impact current practice?

#### d. Opinion about the simulation results

*In this section, we intend to derive your opinion about the results of the dispensary simulation model.*

1. How did you find the interpretation of results?

<table>
<thead>
<tr>
<th>Very straightforward</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Very difficult</th>
</tr>
</thead>
</table>

Any further comments? *(Please specify):*

2. a. On a scale from 1 to 5, how useful did you find the tables?

<table>
<thead>
<tr>
<th>Very little</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Very much</th>
</tr>
</thead>
</table>

b. What was the main learning point from the tables?

3. a. On a scale from 1 to 5, how useful did you find the graphs?

<table>
<thead>
<tr>
<th>Very little</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Very much</th>
</tr>
</thead>
</table>

b. What was the main learning point from the graphs?

#### e. Overall opinion about the simulation model

1. Would you like to make any other comments about the dispensary simulation model?
APPENDIX C. MODEL CODE

**Added checkers rate**= IF THEN ELSE((Total checkers capacity per hour < Total labelled unchecked prescriptions/TIME STEP) :AND: (Number of checkers < Maximum number of checkers), MIN(INTEGER((Total labelled unchecked prescriptions/TIME STEP - Total checkers capacity per hour)/Current capacity of average checker) +1, (Maximum number of checkers-Number of checkers)/TIME STEP) , 0)

Units: Persons/Hour

This is the number of checkers added per hour if total labelled unchecked medications are greater than total checkers capacity per hour and maximum number of checkers is greater than current checkers, add checkers. Rate works conservatively - adding activates even when there’s even small shortage of capacity. That shortage can be less than one checker capacity.

**Added labellers rate**= IF THEN ELSE((Total labellers capacity per hour < Total unlabelled prescriptions /TIME STEP) :AND: (Number of labellers < Maximum number of labellers), MIN(INTEGER((Total unlabelled prescriptions/TIME STEP-Total labellers capacity per hour)/Current capacity of average labeller)+10, (Maximum number of labellers-Number of labellers)/TIME STEP) , 0)

Units: Persons/Hour

This is the number of labellers added per hour if total unlabelled prescriptions is greater than total labellers capacity per hour and maximum number of labelling staff is greater than current labelling staff, add labellers. Rate works conservatively - adding activates when there’s even small shortage of capacity. That shortage can be less than one worker capacity. This can be adjusted by changing IF statement to ratio.

**addalllabelling errors**= Total labelling errors found by checkers+Total Selfcheck errors

Units: Prescriptions/Hour

**All questions capacity cost per hour**= Number of questions per hour*Capacity cost per question

Units: Prescriptions/Hour

Capacity cost in prescriptions per hour. It equally affects both labellers and checkers. It reduces their total capacity per hour as they are interrupted by questions from trainees/colleagues
Average labelled unchecked prescriptions = ZIDZ( Culminating total labelled + Total labelled unchecked prescriptions \* TIME STEP, Time-INITIAL TIME)
Units: Prescriptions

Average lbl actual error ratio = ZIDZ( Culminate lbl actual error ratio + Percentage lbl actual error ratio \* TIME STEP, Time-INITIAL TIME)
Units: 1

Average lbl self-check ratio = ZIDZ( Culminate lbl selfcheck ratio, Time )
Units: 1

Average no of questions = ZIDZ( Culmination no of questions + Number of questions per hour \* TIME STEP, Time-INITIAL TIME)
Units: Question/Hour

Average total checkers capacity = ZIDZ( Culmination of total checkers capacity per hour, Time )
Units: Prescriptions/Hour

Average total labellers capacity = ZIDZ( Culmination of total labellers capacity per hour, Time )
Units: Prescriptions/Hour

Average undetected error rate = ZIDZ( Culminate undetected error rate + Undetected error rate \* TIME STEP, Time-INITIAL TIME)
Units: 1

Average unlabelled prescriptions = INTEGER(ZIDZ( Culminating total unlabelled + Total unlabelled prescriptions \* TIME STEP, Time-INITIAL TIME))
Units: Prescriptions

Average workload of labeller = ZIDZ( Culminate workload of labeller + Workload ratio of labeller \* TIME STEP, Time-INITIAL TIME)
Units: 1
Capacity assigned for regular checking = MIN(Capacity left after urgent checking, Regular labelled and relabelled / TIME STEP)

Units: Prescriptions/Hour

Capacity of checkers used to check regular medications. This task is lowest priority

Capacity assigned for regular labelling = MIN(Regular unlabelled prescriptions / TIME STEP, Capacity left after regular relabelling)

Units: Prescriptions/Hour

Capacity that labellers use for labelling regular prescriptions.

Capacity assigned for regular relabelling = MIN(Regular prescriptions with errors / TIME STEP, Capacity left after urgent labelling)

Units: Prescriptions/Hour

Capacity of labeller that is used to relabel prescriptions that contained errors. This has priority over regular labelling of unlabelled prescriptions.

Capacity assigned for urgent checking = MIN(Urgent labelled and relabelled / TIME STEP, Total checkers capacity per hour)

Units: Prescriptions/Hour

Checkers capacity used to check urgent prescriptions for errors. This task has priority over regular rechecking.

Capacity assigned for urgent labelling = MIN(Urgent unlabelled prescriptions / TIME STEP, Capacity left after urgent relabelling)

Units: Prescriptions/Hour

Capacity of labellers used to label urgent unlabelled prescriptions. This task has priority over regular relabelling.

Capacity assigned for urgent relabelling = MIN(Urgent prescriptions with errors / TIME STEP, Total labellers capacity per hour)

Units: Prescriptions/Hour

Capacity of labeller used to relabel urgent medications that contain errors. This task has priority over urgent labelling.

Capacity cost per question = 2
Appendices

Units: Prescriptions/Question

The number of prescriptions that could have been processed in an hour if no questions were asked

**Capacity left after regular relabelling** = Capacity left after urgent labelling - Regular relabelling rate

Units: Prescriptions/Hour

After regular relabelling is done, capacity left for regular labelling

**Capacity left after urgent checking** = Total checkers capacity per hour - Urgent checked rate

Units: Prescriptions/Hour

Capacity left after urgent checking is done and prepared for regular rechecking

**Capacity left after urgent labelling** = Capacity left after urgent relabelling - Labelling rate of urgent meds

Units: Prescriptions/Hour

Capacity left after urgent labelling is done and prepared for regular relabelling

**Capacity left after urgent relabelling** = Total labellers capacity per hour - Urgent relabelling rate

Units: Prescriptions/Hour

Capacity that is left after urgent relabelling is done

**Checker capacity fatigue depletion rate** = IF THEN ELSE(workload checker ratio > 85, MAX(0 , (Current capacity of average checker - Maximum capacity of average checker per hour / 2) * Checker fatigue depletion percentage)/TIME STEP , 0)

Units: (Prescriptions/Person)/Hour

If checker workload is above 85% of current capacity, then this reduces current capacity by 5% of available capacity over minimum capacity of average checker. This is an hourly reduction if workload is still high. Minimum capacity is equal to half of maximum capacity. Fatigue kicks in

Checker capacity restoration percentage = 0.05

Units: Dmnl
10% capacity restoration

**Checker capacity restore rate** = IF THEN ELSE(Checker capacity fatigue depletion rate = 0, (Maximum capacity of average checker per hour - Current capacity of average checker) * Checker capacity restoration percentage / TIME STEP, 0 )

Units: (Prescriptions/Person)/Hour

*If there is no fatigue (i.e. depletion rate = 0) then checker capacity is restored by 10% of missing maximum value up to maximum capacity value.*

**Checker check success ratio** = WITH LOOKUP (workload checker ratio, ([(0,0.8)-(100,1)],(0,1),(10,0.98),(20,0.96),(30,0.94),(40,0.92),(50,0.88),(60,0.86),(70,0.84),(80,0.82),(90,0.8),(100,0.8) ))

Units: Dmnl

*The checker’s ability to find errors made by labellers. If workload is 0%, checker finds 100% of all errors, and as workload decreases, their ability to find errors made by labellers decreases. 1 is finding 100% success. Lowest it can go 0.8 which is 80% success rate of finding it 0 - 100 = workload 1 - 0.8 = success rate of error detection This rate decreases with checker workload increase.*

Checker fatigue depletion percentage = 0.05

Units: Dmnl

*Percentage of fatigue depletion rate 5%*

**Current capacity of average checker** = INTEG (Checker capacity restore rate-Checker capacity fatigue depletion rate, Maximum capacity of average checker per hour)

Units: Prescriptions/Person

*Average capacity of checker at current hour.*

**Current capacity of average labeller** = INTEG (Labeller capacity restore rate-Labeller capacity fatigue depletion rate, Maximum capacity of average labeller per hour)

Units: Prescriptions/Person

*Average capacity of labeller at current hour.*

**Delayed effect of labeller error ratio** = DELAY FIXED (Labeller error ratio, 1, 0)

Units: Dmnl
Effects of workload increase/decrease is delayed by 1 hour. It is natural for person to be able to work for an hour under increased workload and with standard efficiency. This period might be even longer.

Delayed effect of labelling error rate found checking= DELAY FIXED (Checker check success ratio,1,1)

Units: Dmnl

Effects of workload increase/decrease is delayed by 1 hour. It is natural for person to be able to work for an hour under increased workload and with standard efficiency. This period might be even longer.

Delayed effect of undetected labelling errors ratio= DELAY FIXED (Undetected labelling errors ratio,1,0)

Units: Dmnl

Incoming regular prescriptions rate= multiplier*New regular prescriptions per hour

Units: Prescriptions/Hour

Incoming regular prescriptions

Incoming urgent prescriptions rate= multiplier*New urgent prescriptions per hour

Units: Prescriptions/Hour

Labeller actual error ratio= WITH LOOKUP (Workload ratio of labeller,\([(0,0.004),\((101,0.9))\],(0,0),(10,0.05),(20,0.075),(30,0.1),(40,0.125),(50,0.15),(60,0.175),(70,0.2),(80,0.25),(90,0.3),(100,0.4)\))

Units: Dmnl

Labeller actual error rate. This rate measures how many errors does labeller makes. This rate increases when workload increase.

Labeller capacity fatigue depletion rate= IF THEN ELSE(Workload ratio of labeller > 85, MAX(0,(Current capacity of average labeller - Maximum capacity of average labeller per hour / 2) * Labeller fatigue depletion percentage)/TIME STEP, 0)

Units: (Prescriptions/Person)/Hour

If labeller workload is above 85% of current capacity, then this reduces current capacity by 5% of available capacity over minimum capacity of average labeller. This is an hourly
reduction if workload is still high. Minimum capacity is equal to half of maximum capacity = 10 prescriptions per hour. Fatigue kicks in

**Labeller capacity restoration percentage** = 0.10

Units: Dmnl

**Labeller capacity restore rate** = IF THEN ELSE(Labeller capacity fatigue depletion rate = 0, (Maximum capacity of average labeller per hour - Current capacity of average labeller) * Labeller capacity restoration percentage / TIME STEP, 0)

Units: (Prescriptions/Person)/Hour

*If there is no fatigue (depletion rate = 0) then labeller capacity is restored by 10% of missing maximum value up to maximum capacity value.*

**Labeller error ratio** = Labeller actual error ratio * Labeller self-check ratio

Units: Dmnl

*Error ratio after labeller has self-checked for own error*

**Labeller fatigue depletion percentage** = 0.05

Units: Dmnl

*Percentage of fatigue depletion rate 5%*

**Labeller self-check ratio** = WITH LOOKUP (Workload ratio of labeller, 
([(0,0) - (100,1))],(0,1),(10,0.98),(20,0.98),(30,0.96),(40,0.95),(50,0.91),
(60,0.86),(70,0.8),(80,0.71),(90,0.61),(100,0.5))

Units: Dmnl

*Labeller error finding success rate. This rate measures how many of labelling error the labeller finds after self-checking. This rate decreases with workload increase. By 100%, they can only detect 70% of their own errors. This is based on real data that by 70% capacity they can detect around 2 errors and 1 goes undetected which is 93% success rate.*

**Labelling rate of regular medications** = Capacity assigned for regular labelling * (1 - Delayed effect of labeller error ratio)

Units: Prescriptions/Hour

*Labelling rate of regular unlabelled medications that are labelled correctly.*
**Labelling rate of urgent meds** = Capacity assigned for urgent labelling*(1-Delayed effect of labeller error ratio)

Units: Prescriptions/Hour

*Labelling rate of regular/urgent unlabelled prescriptions. It is affected by errors found by labellers. Error rate increases workload by degree equivalent to error rate - labeller has to relabel prescription with the error.*

**Max no of Checkers** = GAME (Initial checkers)

Units: Persons

**Max no of labellers** = GAME (Initial labellers)

Units: Persons

**Maximum capacity of average checker per hour** = 86

Units: Prescriptions/Person

*Max number of prescriptions an average checker can check per hour when there is low workload and checker is fresh. Safe checking levels is between 60 to 70 prescriptions per hour*

**Maximum capacity of average labeller per hour** = 20

Units: Prescriptions/Person [1,30,1]

*Maximum number of prescriptions an average labeller can label per hour when workload is, and labeller is fresh. Safe filling area is 14 prescriptions (70%) to 17 (85%)*

**Minimum number of labellers** = 5

Units: Persons

multiplier= 2.5

Units: 1 [1,100]

**New regular prescriptions per hour** = WITH LOOKUP (Time, [(0,0)-(11,100)],(0,9),(1,30),(2,21),(3,54),(4,37),(5,23),(6,36),(7,41), (8,40),(9,7),(10,0),(11,0 ))

Units: Prescriptions/Hour

**New urgent prescriptions per hour** = WITH LOOKUP (Time, [(0,0)-(10,100)],(0,2),(1,4),(2,5),(3,6),(4,4),(5,4),(6,6),(7,7),(8,8),(9,1),(10,0 ))
Units: Prescriptions/Hour

**Number of checkers** = INTEG (Added checkers rate-Removed checkers rate, Max no of Checkers)

Units: Persons

**Number of labellers** = INTEG (Added labelers rate-Removed labelers rate, Minimum number of labellers)

Units: Person

**Number of questions per hour** = Percentage of trainee questions per prescription/100*Total incoming prescriptions

Units: Questions/Hour

Percentage of trainee questions per prescription = GAME (20)

Units: Questions/Prescriptions [1,100]

*20% of incoming prescriptions are questioned. Estimate - query.*

**Regular assigned to relabel rate** = Capacity assigned for regular checking*Delayed effect of undetected labelling errors ratio *Delayed effect of labelling error rate found checking

Units: Prescriptions/Hour

*Rate of labels that contain errors found by checkers. Labels are assigned to relabel.*

**Regular checked rate** = Capacity assigned for regular checking*(1-Delayed effect of undetected labelling errors ratio)+Capacity assigned for regular checking*Delayed effect of undetected labelling errors ratio*(1-Delayed effect of labelling error rate found checking)

Units: Prescriptions/Hour

**Regular labelled and relabelled** = INTEG (Labelling rate of regular medications+Regular relabelling rate-Regular checked rate-Regular assigned to relabel rate, 0)

Units: Prescriptions

*Stock of labels that have been self-checked and relabelled.*
**Regular prescriptions with errors** = INTEG (Regular assigned to relabel rate + Regular with labelling errors - Regular relabelling rate, 0)

Units: Prescriptions

*Stock of labels that need to be relabelled*

**Regular relabelling rate** = Capacity assigned for regular relabelling

Units: Prescriptions/Hour

*Relabelling rate of labels that have been found to contain errors.*

**Regular unlabelled prescriptions** = INTEG (Incoming regular prescriptions rate - Labelling rate of regular medications - Regular with labelling errors, 0)

Units: Prescriptions

*Incoming regular prescriptions*

**Regular with labelling errors** = Capacity assigned for regular labelling * Delayed effect of labeller error ratio

Units: Prescriptions/Hour

*Labels found to contain errors by labellers self-checking process.*

**Removed checkers rate** = IF THEN ELSE((Total checkers capacity per hour > Total labelled unchecked prescriptions / TIME STEP) :AND: (Number of checkers > Max no of Checkers), MIN(INTEGER((Total checkers capacity per hour - Total labelled unchecked prescriptions / TIME STEP) / Current capacity of average checker), (Number of checkers - Max no of Checkers) / TIME STEP) , 0)

Units: Persons/Hour

*Number of checkers removed from current checking staff per hour. If total checkers capacity is greater than total labelled unchecked medications and current number of checkers is greater minimum number of checkers remove checkers. Rate works conservatively - removes checker only when unused capacity us higher than one checker current capacity.*

**Removed labellers rate** = IF THEN ELSE((Total labellers capacity per hour > Total unlabelled prescriptions / TIME STEP) :AND: (Number of labellers > Minimum number of labellers), MIN(INTEGER((Total labellers capacity per hour - Total unlabelled
Participatory System Dynamics Modelling Approach to Safe and Efficient Staffing Level Management within Hospital Pharmacies

prescriptions/(TIME STEP) /Current capacity of average labeller), (Number of labellers- Minimum number of labellers )/(TIME STEP), 0) 

Units: Persons/Hour

Number of labellers removed from staff per hour. If total labellers capacity is greater than total unlabelled prescriptions and current number of labelling staff is greater than minimum number of labeller, remove labellers. Rate works conservatively - removes labellers only when unused capacity is higher than one labeller's current capacity.

TIME STEP = 1

Units: Hour [0,1]

The time step for the simulation.

Total checkers capacity per hour= (Current capacity of average checker*Number of checkers)/TIME STEP - All questions capacity cost per hour

Units: Prescriptions/Hour

Total checkers capacity available in that hour minus capacity lost to questions.

Total incoming prescriptions= Incoming urgent prescriptions rate+Incoming regular prescriptions rate

Units: Prescriptions/Hour

Total labelled unchecked prescriptions= Regular labelled and relabelled+Urgent labelled and relabelled

Units: Prescriptions

Total number of labelled urgent and non-urgent medications but not checked

Total labellers capacity per hour= (Current capacity of average labeller*Number of labellers)/TIME STEP - All questions capacity cost per hour

Units: Prescriptions/Hour

Total labellers capacity for current hour minus capacity lost to answering questions.

Total labelling errors= INTEG (addalllabelling errors, 0)

Units: Prescriptions

Total labelling errors found by checkers= Urgent assigned to relabel rate+Regular assigned to relabel rate
Units: Prescriptions/Hour

**Total Selfcheck errors** = Urgent with labelling errors + Regular with labelling errors

Units: Prescriptions/Hour

**Total unlabelled prescriptions** = Regular unlabelled prescriptions + Urgent unlabelled prescriptions

Units: Prescriptions

*Total incoming prescriptions (regular and urgent)*

**Undetected error rate** = Labeller actual error ratio * (1 - Labeller self check ratio) * (1 - Checker check success ratio)

Units: Dmnl

*The undetected medications errors by checkers which might cause patient harm*

**Undetected labelling errors ratio** = Labeller actual error ratio - Labeller error ratio

Units: 1

**Unused checker capacity** = MAX(0, Capacity left after urgent checking - Regular checked rate)

Units: Prescriptions/Hour

*Capacity left after everything*

**Unused labeller capacity** = MAX(0, Capacity left after regular relabelling - Labelling rate of regular medications - Regular with labelling errors)

Units: Prescriptions/Hour

*Capacity left after everything*

**Urgent assigned to relabel rate** = Capacity assigned for urgent checking * Delayed effect of undetected labelling errors ratio * Delayed effect of labelling error rate found checking

Units: Prescriptions/Hour

*Rate of labels that contain errors found by checkers. Labels are assigned to relabel.*

**Urgent checked rate** = Capacity assigned for urgent checking * (1 - Delayed effect of undetected labelling errors ratio) + Capacity assigned for urgent checking * Delayed effect of undetected labelling errors ratio * (1 - Delayed effect of labelling error rate found checking)
Units: Prescriptions/Hour

**Urgent labelled and relabelled** = INTEG (Labelling rate of urgent meds-Urgent checked rate-Urgent assigned to relabel rate+Urgent relabelling rate,0)

Units: Prescriptions

Stock of labels that have been self-checked and relabelled.

**Urgent prescriptions with errors** = INTEG (Urgent assigned to relabel rate+Urgent with labelling errors-Urgent relabelling rate,0)

Units: Prescriptions

Stock of labels that need to be relabelled

**Urgent relabelling rate** = Capacity assigned for urgent relabelling

Units: Prescriptions/Hour

Relabelling rate of labels that have been found to contain errors.

**Urgent unlabelled prescriptions** = INTEG (Incoming urgent prescriptions rate-Labelling rate of urgent meds-Urgent with labelling errors,0)

Units: Prescriptions

**Urgent with labelling errors** = Capacity assigned for urgent labelling*Delayed effect of labeller error ratio

Units: Prescriptions/Hour

Labels found to contain errors by labellers self-checking process.

**Workload checker ratio** = (1 - Unused checker capacity/Total checkers capacity per hour)*100

Units: Dimnl

Checker workload ratio measured from 0 to 100, where 0 - no workload, 100 - full workload. Remaining capacity/Initial total capacity * 100

**Workload ratio of labeller**=(1-Unused labeller capacity/Total labellers capacity per hour)*100

Units: Dimnl

The workload ratio of labeller is measured from 0% to 100%, where 0% equals no workload and 100% equals full workload.
**APPENDIX D. PARTICIPANTS PROFILE**

<table>
<thead>
<tr>
<th>Sessions</th>
<th>Respondent</th>
<th>Role</th>
<th>Years of Experience in NHS</th>
<th>Used a simulation model before?</th>
<th>Hospital</th>
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<tr>
<td>1</td>
<td>P1</td>
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<td>UHL Glenfield</td>
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</tr>
</tbody>
</table>
APPENDIX E. WEB INTERFACES (FORIO)

Scenario 1: Number of staff on workload and errors

<table>
<thead>
<tr>
<th>Base values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Labellers: 5</td>
</tr>
<tr>
<td>Number of Checkers: 2</td>
</tr>
<tr>
<td>Max total prescriptions labelled by labeller (per hour): 20 capacity</td>
</tr>
<tr>
<td>Max total prescriptions dispensed by checker (per hour): 86 100%</td>
</tr>
</tbody>
</table>

Increase incoming Prescriptions 150%

Initial labellers 5

Initial checkers 2

Hours

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<tbody>
<tr>
<td>Incoming prescriptions per hour</td>
</tr>
<tr>
<td>Backlog</td>
</tr>
<tr>
<td>Correctly labelled but not checked</td>
</tr>
<tr>
<td>Relabelling made per hour</td>
</tr>
<tr>
<td>Checked meds per hour</td>
</tr>
<tr>
<td>Staff capacity needed per hour</td>
</tr>
<tr>
<td>Undetected errors per hour</td>
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</table>
Scenario 2: Interruptions on performance and errors

Effect of interruptions on efficiency

<table>
<thead>
<tr>
<th>Hours</th>
<th>Efficiency loss (labeller)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Base values
- Number of Labellers: 5
- Number of Checkers: 2
- Max total prescriptions labelled by labeller (per hour): 20 (100%)
- Max total prescriptions dispensed by checker (per hour): 86 (100%)

Increase Incoming Prescriptions: 150%
Initial labellers: 5
Initial checkers: 2
Percentage of questions per incoming prescription (%): 0%
Capacity cost per question (The number of prescriptions that could have been processed in an hour if no questions were asked): 2

Run Per Hour
Go to Scenario 1
Run to End
Go to Scenario 3
Reset Scenario
Back
Scenario 3: High workload effect on fatigue and errors

Workload of Staff

85% - Marginal Workload boundary
100% - Unacceptable Workload

Base values
- Number of Labellers: 5
- Number of Checkers: 2
- Max total prescriptions labelled by labeller (per hour): 20 (100%)
- Max total prescriptions dispensed by checker (per hour): 86 (100%)

Increase Incoming Prescriptions: 150%

Initial labellers: 5
Initial checkers: 2

Run Per Hour
Run to End
Reset Scenario
Go to Scenario 1
Go to Scenario 2
Back
APPENDIX F. STOCK AND FLOW DIAGRAM (A3)
APPENDIX G. PRESENTATION EVALUATION DISCUSSION (MANAGEMENT)

Impact of pharmacy staff’s workload on throughput and safety: System Dynamics simulation-based approach to pharmacy staff management

Mohammed Ibrahim Shire (PhD student)  
Human Factors and Complex Systems Research Group  
Loughborough University

Dr Thomas Jun (Supervisor)  
Professor Stewart Robinson (Supervisor)  
Loughborough University

Motivation

“Interruptions, staff shortages and workload make an important contribution to pharmacists’ job.”
Centre For Workforce Intelligence, 2011

“There is urgent need for developing methods and guidance for staffing ratios based on dynamic understanding of staff workload and scientific data.”
Berwick Review into Patient Safety, 2013
System Thinking and System Dynamics

System Thinking

- It is a science based on understanding connections and relations between seemingly isolated things.
- Based on the understanding of simple concept "feedback" which shows how actions can reinforce or counteract (balance) each other.
- Everyone shares responsibility for problems generated by a system i.e. no "one" factor is responsible for changes in a system.

System Dynamics

- System Dynamic is the practical application of System Thinking
- It is a simulation approach to understand the nonlinear behaviour of complex systems over time using stocks, flows, internal feedback loops, and time delays.

Polarities

+ means same flow, indicating that an increase in A (cause) will lead to an increase in B (effect)

- means opposite flow indicating that an increase in C (cause) will lead to a decrease in D (effect)
Causal Loop Diagram Example

More Births will lead to higher Population. The higher the Population the more Births. The higher the Population the more Deaths. The more Deaths there are the decrease in Population.

Model Building (1)

Interruptions – Fatigue – Workload
Model Building (2)
Scenario 1: Staff on Capacity

Scenario 2: Interruptions on Capacity
Scenario 3: Fatigue and Stress on Capacity

Web Interface

The NHS Dispersary Model

Start Simulation
APPENDIX H. ETHICAL APPROVAL AND CONSENT FORMS

PARTICIPATORY SYSTEM DYNAMICS MODELLING APPROACH TO SAFE AND EFFICIENT STAFFING LEVEL MANAGEMENT WITHIN HOSPITAL PHARMACIES

Participant Information Sheet

We would like to invite you to take part in our research study by participating in a short interview. Before you decide we would like you to understand why the research is being done and what it would involve for you. Ask us if anything is not clear and talk to others about the study if you wish.

What is the purpose of the study?
The aim of this research project is to look at ways to assist hospital pharmacy staff management by modelling and simulating the impact of staff workload on dispensing errors.

Who is doing this research and why?
This study is part of a PhD student research project supported and funded by Loughborough University. The research is being conducted by Mohammed Ibrahim Shire under the supervision of Dr Thomas Jun. Ethical approval for this research has been granted by Loughborough University Ethics Approval (Human Participants) Sub-Committee.

What will I be asked to do?
We will ask you to participate in a short interview to understand the processes involved in your daily role. We would like to show you a simulation model and require your input and opinion on the scenarios that we have defined and whether that is accurately reflected in the actual dispensary unit. We require your input on how to improve the model and whether it is something that will improve your understanding of the dispensary and how it operates.

How long will it take?
We anticipate that the interview will take no longer than one hour.

Will my taking part in this study be kept confidential?
Yes. We will follow ethical and legal practice and all personal information about you will be handled in confidence. Only the research team of this project will have access to the primary data. All data will be securely stored for ten years and destroyed after this time.
Will audio recording be used?

If you do take part in the interview, the interviewing researcher will ask you if you are happy to be recorded on digital audio recorder. However, if you would prefer, the researcher will make notes by hand instead. If you do agree to be audio-recorded, the recordings will be transcribed, and the transcripts will be used only by people involved in this project.

Once I take part, can I change my mind?

Yes. After you have read this information and asked any questions you may have we will ask you to complete an Informed Consent Form, however if at any time, before, during or after the sessions you wish to withdraw from the study please just contact the main investigator. You can withdraw at any time, for any reason and you will not be asked to explain your reasons for withdrawing.

What will happen to the results of the study?

The study results will be used to inform the next stages of this research project. We also hope to publish the results in reports and academic papers. Participants will not be identified in any report or publication.

What if I am not happy with how the research was conducted?

If you are not happy with how the research was conducted, please contact Ms Jackie Green, the Secretary for the University’s Ethics Approvals (Human Participants) Sub-Committee:

Ms J Green, Research Office, Hazlerigg Building, Loughborough University, Epinal Way, Loughborough, LE11 3TU. Tel: 01509 222423. Email: J.A.Green@lboro.ac.uk

The University also has a policy relating to Research Misconduct and Whistle Blowing which is available online at http://www.lboro.ac.uk/committees/ethics-approvals-human-participants/additionalinformation/codesofpractice/

Contact for further information:

If you have any questions or wish to speak to a member of the research team, please contact Mohammed Ibrahim Shire (m.ibrahim-shire@lboro.ac.uk) or Dr Thomas Jun (g.jun@lboro.ac.uk).

Thank you very much for taking the time to read this information sheet.
PARTICIPATORY SYSTEM DYNAMICS MODELLING APPROACH TO SAFE AND EFFICIENT STAFFING LEVEL MANAGEMENT WITHIN HOSPITAL PHARMACIES

Informed Consent Form

The purpose and details of this study have been explained to me. I understand that this study is designed to further scientific knowledge and that all procedures have been approved by the Loughborough University Ethics Approvals (Human Participants) Sub-Committee.  

I have read and understood the information sheet and this consent form. Yes ☐ No ☐

I have had an opportunity to ask questions about my participation. Yes ☐ No ☐

I understand that I am under no obligation to take part in the study. Yes ☐ No ☐

I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing. Yes ☐ No ☐

I understand that all the information I provide will be treated in strict confidence and will be kept anonymous and confidential to the researchers unless (under the statutory obligations of the agencies which the researchers are working with), it is judged that confidentiality will have to be breached for the safety of the participant or others. Yes ☐ No ☐

I agree to participate in this study. Yes ☐ No ☐

Your name: ..........................................................................................................................

Your signature: ..............................................................................................................

Signature of investigator: .............................................................................................