Modelling and Simulating the Performance of User Behaviour in Serious Contexts

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This work is dedicated to the memories of my father,
my family and my friends
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Abstract

Real-time experiments on healthcare procedural improvement can be infeasible due to the domain’s criticality and sensitivity. For instance, high morbidity rates and escalated patient treatment duration can, in some circumstances, be associated with medical resources exhaustion. Thus, formal methods can be an answer to lower the effects of experimenting within these healthcare domains as such an approach may be effective in deriving new insights and proposing further recommendations to the investigated domain. Specifically, performance modelling formalisms provide a rich theoretical foundation for dynamic systems, which are affected by an extensive collection of interventions, and supported by the existing formalisms tool sets. Hence, investigating healthcare system contexts involves several complex challenges. These challenges range from data collection methods and data analysis formalisms to optimising medical outcomes. This optimisation is beneficial to behaviour analysts and medical administrators.

The current thesis contributes to addressing these challenges in many different ways: (i) By presenting an improved web-based version of a sketch simulation that collects the clinician behaviour during massive bleeding scenarios. This unconventional data collection method is proposed to minimise the need to observe the interventions in person where such treatment of these medical cases are performed; (ii) The modelling of two medical scenarios using different modelling formalisms for analysis and evaluation purposes, these modelling formalisms are Performance Evaluation Process Algebra (PEPA), Collective Adaptive Resource-sharing Markovian Agents (CARMA), and Stochastic Petri nets (SPN); (iii) A proposed tool to enhance the log analysis process. Doing so required the implementation of a trace-driven simulation tool. The tool simulates a clinical behaviour that has been recorded using a sketch simulation version. (iv) Proposing different suggestions to improve the medical outcomes and to effectively reduce the cost of health resources.
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Chapter 1

Introduction

The optimisation of health systems is an ongoing research problem [7–10]. Studies of Accident & Emergency (A&E) are essential for several reasons, including high demand for healthcare, severe health conditions, patient experience, medical regulations and cost-effectiveness. An optimised health system may overcome these effects by improving the medical regulations, improving the patient’s health condition or reducing the needed medical resources. In addition, complex environments, such as emergency rooms or operation rooms, are critical from a medical point of view. Therefore, this thesis focuses on the medical interventions that are most likely to occur within these health critical environments.

1.1 Motivation and Research Problem

There have been several attempts to simulate real emergency environments so that end-users can gain better experience and have a sense of what they need to do in real situations [11, 12]. In addition, exploring end-users behaviour concerning compliance with medical codes of practice, such as medical protocols, is highly important. However, much uncertainty still exists about the relationship between these codes of practice and the performed end user’s behaviour.

One of the most critical medical contexts used in this research is massive bleeding cases, which sometimes may be called massive haemorrhage cases. These cases occur where patients suffer from colossal blood loss in a short period. This context, discussed in detail in the next chapter, usually happens rarely. Also, it is associated with a high death rate and exhausting medical resources.

This research project is interested in exploring appropriate methods to understand better the factors influencing the performance of processes or procedures in such contexts. In particular, the ability to model the impact of interventions in such complex systems based on the clinicians’ behaviour logs and how the patient responds to this behaviour is
of particular research interest. The main research questions are:

1. What is the feasibility of modelling these complex interventions in such an environment?

2. What modelling tools/techniques are most suitable to be adopted?

3. To what extent do the available analysis tools/techniques provide efficient results and deeper understanding of such contexts?

4. Using an example, what improvements, if any, could be recognised and implemented to improve cost-effectiveness?

1.2 Aim and Objectives

This project aims to explore, examine and learn the behaviours and procedures during serious incidents. These serious incidents are massive bleeding cases sometimes associated with trauma-induced coagulopathy. In particular, the aim is to study how modelling and simulating techniques can help analyse the behaviours of clinicians. These behaviours are based on interacting with massive bleeding patients according to the related medical protocols. The outcome depends on the acquisition of knowledge from these behaviours and procedures. This research produces and discovers several models that abstract clinician interactions. The following are the objectives of this research:

• Identifying and analysing appropriate modelling approaches.

• Developing a framework for data capture in a serious context.

• Developing and analysing the context models.

• Analysing data through models to evaluate alternative behaviours and processes.

1.3 Methodology

This thesis presents an open research problem that could be investigated from many different perspectives and various points of view. This section introduces the approach and the methodology we follow to perform our investigation.

Using the accumulated knowledge of other researchers and projects, we use several strategies that minimise this investigation’s limitations in many ways. For instance, due to the complex and sensitive context, we developed a sketch simulation to reduce the need to use medical resources, for example, blood products and medical staff, especially during the coronavirus pandemic when these resources were needed, available in Chapter 3.
Furthermore, in Chapters 4 and 5, we start our investigation by focusing on stochastic process algebra formalisms as a suitable method to represent the clinician behaviour demonstrated in the logs from the sketch simulation. We use different stochastic modelling formalisms: Performance modelling Process Algebra (PEPA), Collective Adaptive Resource-sharing Markovian Agents (CARMA) and Stochastic Petri Nets (SPN). Detailed discussion regarding these formalisms is available in Chapter 2.

We afterwards perform an empirical evaluation of the most appropriate formalisms to determine the most fitting formalism to model this complex scenario. After that, Chapter 6 includes our model of the investigated scenario using the described techniques to narrow the exposed limitations within each technique. Finally, we analyse the clinician’s behaviour using procedures, such as correlation analysis and pattern recognition, to name a few. The analysis process suggests many improvements to the study outcomes, available in Chapter 7.

Conducting this research involved the following steps:

- Review the available literature and identify all the contributions to the research areas involved.
- Use gaming elements that simulate massive bleeding cases to derive clinician behaviour data.
- Investigate the available modelling formalisms PEPA, CARMA and Stochastic Petri nets as well as discrete simulations.
- Conduct a comparison between the formal modelling approaches using a health-related example.
- Model the complex interventions.
- Compare the model results with the available logs.
- Analyse the clinician’s behaviour using the available logs.
- Estimate the needed resources in the simulation scenarios.
- Characterise several criteria derived from the behaviour logs, for example, treatment duration and interventions score.
- Using the above criteria we analyse and evaluate the clinician behaviours.
- Provide suggestions to improve the models and the scenario outcomes.
1.4 Contributions

This section covers the investigated aspects that have been used during this research. These aspects are highlighted in several contributions. The details of these contributions are in the following:

- Develop a web-based sketch simulation, based on an IOS application, to simulate the massive bleeding context which is used as a data collection method, in Chapter 3.

- Perform a novel and empirical review of the available formalisms to model user behaviour using a medical example. This contribution corresponds to research question number two, detailed in Chapter 4.

- In Chapter 5, we introduce the CARMA modelling formalism in a different context than its original purpose. Notably, this research used CARMA’s expressive ability to model complex medical interventions, especially how it can handle the volume of resources represented in blood products. In addition, CARMA used to describe collective adaptive systems (CAS) context and particularly the spatial structure of these contexts. Furthermore, this contribution answers research question number one.

- Aiming to provide a further answer to research question number two, we design and implement a trace-driven simulation tool using Java and a numerical modelling tool using Excel to overcome the CARMA modelling limitations, thus providing a method to analyse the behaviour from a different perspective, in Chapter 6.

- Provide the results of extensive log analysis techniques, including presenting suggestions to improve the clinician’s behaviour in a massive bleeding context, in Chapter 7. Moreover, this contribution establishes the answers to research questions number three and four.

1.5 Thesis Structure

The overall structure of the study takes the form of eight chapters, including this introduction. The presentation of these chapters are as the following:

Introduction

Chapter 1 presents the research motivation and problem. In addition, the research aim and objectives followed by the research methodology are outlined. We also summarise the research contributions, thesis structure, and related publications.
Background & Related Work

Chapter 2 covers the research areas involved in this project and discusses the related work involved in this study.

The Research Context: The Serious Web-based Sketch Simulation

Chapter 3 consists of creating a sketch of a massive haemorrhage situation and clinicians’ available actions to save the patient’s life. The sketch records the clinician’s activity using logs. Also, it allows us to understand the situation, as a data analyst, and how each intervention affects the patient health. Moreover, the sketch simulation is designed to trigger and gather the clinician’s expertise and eliminate the difficulties of conducting a study inside an operating room.

Reviewing Different Existing Modelling Formalisms

Chapter 4 includes three formal methods used for modelling and analysing systems. This investigation compares and evaluates which formalisms are suitable, and explores the differences between the investigated formalisms. We conduct this comparison using a case study of the patient journey in an A&E department.

An Approach to Model a Massive Haemorrhage Case Using CARMA

In Chapter 5, modelling the behaviour of the sketch simulation users is achieved using the available sketch simulation logs. Specifically, we use a stochastic approach represented in the CARMA modelling tool to model the clinician’s behaviour log.

Simulation and Evaluation of Massive Haemorrhage Cases

Chapter 6 presents two solutions to extend the analysis of CARMA models. These solutions are: developing a Java simulation tool based on the behaviour logs using a trace-driven simulation approach and producing a numerical model of these logs using a Microsoft Excel sheet.

Log Analysis & Experimentation

Chapter 7 deals with the available logs and uses various statistical measures to provide valuable insights into these logs. It also includes deciding which behaviour is best and improving it in this chapter.

Conclusion and Further Work

The final chapter consists of future work suggestions and the conclusion of this thesis.
Because of the progress during the development of this thesis, we present the manner of how the thesis chapters are connected together. This manner is illustrated in Figure 1.1.

Figure 1.1: The thesis flow
1.6 Related Publications


- A Alkoradees, M Harrison, N Thomas, Comparison of different modelling formalisms for a healthcare application, 35th UK Performance Engineering Workshop, 2019.

It is worth mentioning that these publications form the basis of Chapter 4 of this thesis.
Chapter 2

Background and Related Work

2.1 Introduction

This chapter is intended to provide the reader with the background details related to the medical contexts of this investigation and the performance modelling formalisms used in this research to model and analyse the clinician behaviour. First, Section 2.2 introduces two medical examples used for the research investigation. Second, Section 2.3 presents the data collection method used in this research project. Third, Section 2.4 presents the performance modelling formalisms and the choice justification for three chosen formalisms followed by other available approaches to model investigation. Lastly, Section 2.7 discusses how our research approaches compare with some related literature.

2.2 The Used Case Studies

Throughout this research, the investigation covers two medical examples. The first example is the patient flow in an Accident and Emergency department (A&E) used as a case study to evaluate three chosen modelling formalisms. The second example is a Trauma-induced Coagulopathy (TIC) scenario used to study the clinician’s behaviour during such contexts.

2.2.1 Accident and Emergency(A&E) Scenario

The main goal of the health care provider is to provide services that lower morbidity and increase life expectancy. A patient journey in a hospital involves many factors, and improving patient flow and patient clinical experience can involve many criteria, including typical start-to-end times, short waiting times at the different stages in the process, a calming environment, access to facilities and availability of crucial information. Furthermore, Accident and Emergency (A&E) is a part of any hospital where patients present
without prior appointment, possibly with critical health conditions. Therefore, analysing the patient journey in such a context is desirable to achieve the best health care experience. Furthermore, even though that does not hold for any health care directly, swift or fast-moving patient flow would lead to receiving the desired health care, which may improve patients’ health outcomes.

**Patient flow** is defined as “the ability of the healthcare system to serve patients quickly and efficiently as they move through stages of care. When the system works well, patients flow like a river, meaning that each stage is completed with minimal delay” [13]. Several consequences can follow when patient flow moves slowly. Examples include reduced patient satisfaction [14]; increased staff stress [15]; patients leaving without treatment [16]; patients wait in long queues for treatment [17]. Many factors delay patient flow in healthcare organisations [15, 18]. Derlet and Richards [15] identify the following:

- **Increased patients’ complexity and severity**: Medical development has increased the life expectancy of acutely ill patients. Therefore, it is more likely that this type of patient will come back to the hospital more often.

- **Large patient volume**: Depending on the population that the hospital serves, the patient volume will be affected due to a delayed treatment process. A large population means increased patient volumes and vice versa.

- **Lack of beds**: The number of beds available for admitting patients is limited, especially when surgical intervention is needed. The lack of beds may lead to valuable space occupied when some urgent patients need them.

- **Delays in service provided by laboratory and radiology services**: Due to medical advances and health standards, patients who need these types of tests have increased. As a result, performing these tests or services and retrieving the results would increase the time spent in the hospital.

- **Shortage of nursing staff**: This not only relates to the number of nurses but extends to the experience of the nurses in the hospital. Experienced and dedicated nursing staff positively impact patient flow because they can move patients through the system more efficiently and effectively.

- **Shortage of administrative support staff**: Telecommunications and paperwork are essential functions needed by any hospital. Insufficient staff resources for these tasks can lead to a delay in patient flow.

- **Shortage of on-call speciality consultants**: Exceptional cases or illnesses need to be examined by a specialist consultant. Lack of consultant availability will force the
hospital to transfer the patient affecting patient flow or it may delay the treatment process significantly.

- **Increased medical record documentation requirements**: Because of recent regulations, physicians spend more time documenting rather than providing patient care which may interrupt the patient flow.

- **Difficulty in arranging follow-up care**: This can occur because unregistered patients would come back to the same hospital for follow-up rather than go to general practices.

The issues mentioned above provide the background to understand the A&E scenario fully. Thus, it is clear that this context is essential and worth investigating. This issue’s importance comes from affecting the patient’s health outcomes and psychological state. Also, the listed issues above are a concern from many points of view, such as performance optimisation and resource-sharing perspectives. Therefore, this thesis will use the A&E context to analyse patient behaviour according to the above perspectives. In addition, it will evaluate the different modelling formalism approaches to decide the most suitable one to be used in the TIC scenario. The following section presents an example used to investigate the clinician behaviour observed during the TIC scenario.

### 2.2.2 Trauma-induced Coagulopathy Scenario

Trauma-induced coagulopathy (TIC) is a pathology that affects several cases of trauma patients where massive haemorrhage occurs when activated protein C (APC) is present [1]. It has many consequences, such as the injury site in the patient’s body being unable to form a clot to stop bleeding; organ failure that comes from poor blood flow; and it escalates the patient’s stay in the intensive care unit (ICU) in hospital. Eventually all these consequences could lead to increased morbidity in trauma patients [1, 19].

To shed some light on the importance of this challenging area, several kinds of research provide some critical statistics about how commonly this problem occurs. Trauma is considered one of the leading causes of death in the world and is responsible for one in seven deaths globally [19]. Also, it is notable that one-quarter of trauma patients have some signs of TIC [1]. More importantly, the total deaths related to trauma patients are much more than the total of HIV and heart diseases combined. As a result, when a patient has some signs of TIC, his/her mortality is elevated to four times that of regular trauma patients who do not have blood coagulation concerns [20].

TIC has several causes, as is presented by the literature, although this field is considered an ongoing research challenge [19, 21, 20]. There are four primary causes of TIC discussed by [19].
- Traumatic brain injury (TBI): Despite minor blood loss, APC is released from injured neurons, causing anticoagulation factors.

- Hemorrhagic shock: This cause associated with severe bleeding will activate APC to create massive coagulation to control bleeding.

- Dilution of factors: Transfusing blood to injured patients will cause the blood factors to be unbalanced. Then, this unbalanced combination will affect the coagulation factors by delaying its efficiency.

- Hypothermia/acidosis: External and continued resuscitation processes could reduce body temperature, causing hypothermia. Hypothermia is responsible for the slow forming of fragile clots. Even though acidosis is not considered to affect coagulopathy, combining hypothermia, acidosis and coagulopathy is viewed as a lethal combination and one of the significant health concerns.

Although these causes are recognised as primary causes of TIC, other authors such as Chang et al. [1] suggest including other ones, for example, pre-injury anticoagulant medication, platelet dysfunction and iatrogenic resuscitation injury. Figure 2.1 illustrates some of the causes related to TIC.

Figure 2.1: Causes of TIC developed from [1]
The most interesting aspect of Figure 2.1 is that TIC resulted from three leading causes. The first one is Platelet dysfunction, which occurs when Platelet is activated or exists but is not functioning as it is supposed to. Moreover, the second cause is Hyperfibrinolysis which comes from haemorrhage shock. Furthermore, the last one is low clotting factor activity which results from different reasons, as the previous figure shows.

Based on the cause of TIC, the treatment process differs. However, it is suggested that an early coagulation screening, including the use of VHA (Viscoelastic haemostatic analysis), is essential in patients who are injured severely [1,22]. Indeed, many researchers agree that blood transfusion is regarded as the best treatment. Therefore, they advise transfusing one packed red blood cell (PRBC) unit, one platelet unit, and one plasma unit (1:1:1) [19,23]. Another recommendation of treatment is to control the blood pressure to its minimal range to raise a patient’s health outcome [19]. Also, another recommended treatment is the use of tranexamic acid (TXA), especially in the first three hours of a patient’s arrival at the Accident & Emergency (A&E) department [11,24].

The operating room (OR) is where many activities are performed rapidly, requiring several individuals with different expertise. The consequence of failure may be catastrophic for the patient. The focus of the scenarios of interest here involves patients suffering massive haemorrhage where there is increasing potential for dangerous pathological blood coagulation [1,19,21].

There are many guidebooks in healthcare centres, usually referred to as protocols or codes, obeyed in these critical cases [25]. These guidebooks provide protocols for performing various blood tests, ordering blood products from a blood bank, infusing blood products into the patient body, and other medical procedures [25]. The related protocols in this investigation are discussed in Chapter 5.

This present research will generate fresh insight from studying the TIC context using computer aid analysis tools, such as modelling formalisms. We start this investigation by becoming more familiar with the TIC context, including its causes and treatment plan recommendations. Also, studying the clinician’s behaviour using different modelling formalisms is required to investigate it comprehensively from multiple aspects. The following sections introduce the data collection strategy and then present the performance modelling formalisms and the other concepts and materials related to this research project.

2.3 Gamification - Data Collection Approach

The gamification approach has become more popular during the last few years; however, there is little consensus about what gamification means. The term gamification is defined vaguely as enhancing non-game context by using game design techniques, game thinking, and rewards in order to increase engagement [26,27 and 28]. The concept of gamification
Chapter 2. Background and Related Work

involves achieving pleasurable activities. This pleasure is related to the way the human brain is designed to be triggered by winning, problem-solving, recognition, surprises and so on [29].

The different use cases of gamification can be listed as follows: education, business, health and social media are some to mention. Furthermore, [Hamari et al. 27] provided an extensive literature review of empirical studies on gamification. They discuss how this concept was searched in the different research databases, the studies’ psychological and behavioural outcomes, the context of gamification, and the study types among the reviewed studies. They concluded that gamification had led to positive impacts on most reviewed studies. Moreover, [Sardi et al. 28] performed a systematic review on gamification in the healthcare domain. They discussed how gamification is used in such a domain as well as the types of studies that used it alongside its advantages and disadvantages.

This research project applied the gamification features to collect the clinician behaviour data in a massive bleeding context. The reasons to include this approach and how we incorporated it are described in Chapter 3.

2.4 Performance Modelling

The general use of the term “modelling” is sometimes equated with capturing the behavioural activities of system components. Formal methods can be used to model and evaluate dynamic systems [30]. Usually, the difficulties and the cost of experimenting within such systems limit the possibility of performing an experiment that leads to new outcomes or new knowledge. Therefore, developing such models of these systems is essential [30, 31].

A complete discussion of the available modelling formalisms, which was covered in [32] and [33], lies beyond the scope of this study. However, due to the nature of the investigated context, we focused on the formalisms that support stochastic behaviour modelling. In this project, we considered three formalisms; correspondingly, a further discussion of our choice is presented in Chapter Four. Firstly, Performance Evaluation Process Algebra (PEPA) is a modelling language for creating and analysing stochastic process algebra models [34]. Secondly, another recently developed modelling language called Collective Adaptive Resource-sharing Markovian Agents (CARMA) has been used in many cases, including Ambulance deployment [30], Bicycle Sharing System [35], and Pedestrian movement [36]. Lastly, Petri nets are formalisms that can model serious context because of their wide range of types. However, due to the nature of investigated interventions and their context, we will focus on a specific Petri net called Stochastic Petri nets (SPN) [37].

There are many types of review methods a researcher could implement [38]. This thesis implements the empirical review method, which evaluates many subjects using a
case study. We performed an empirical review on the three modelling formalisms using a medical context. These formalisms have been developed to offer the capability to analyse process behaviour by developing stochastic models. The expressive power of these notations differs as well as their tools for model analysis. Also, we explored some of those differences to improve our understanding of how the choice of formalism can influence the results derived and draw conclusions. Each formalism has a different syntax that necessitates specifying the model differently. Moreover, the underlying semantics mean that specifications that appear equivalent may give rise to different numerical results. In addition, we compared these formalisms regarding the analysis type they support and the derived results they produce.

2.4.1 PEPA

PEPA is a high-level model specification language for low-level stochastic models [39]. The language can be used to study quantitative properties of models of computer and communication systems, such as throughput, utilisation and response time, as well as qualitative properties such as freedom from deadlock [34]. PEPA models are constructed by composing several components that perform actions whose duration is negatively exponential distributed. Actions can be individual (internal to a single component) or shared between components. Shared actions must occur in both components and proceed at the rate of the slowest participant. The resulting model can be used to derive a continuous-time Markov chain (CTMC) or a scalable approximation in terms of ordinary differential equations (ODEs) or Stochastic Simulation. The key features of PEPA are:

1. Compositionality, the ability to model a system as the interaction of subsystems;
2. Formality, which gives a precise meaning to all terms; and
3. Abstraction gives the ability to build up complex models from individual components and disregard the unnecessary details.

PEPA has only four combinators, prefix, choice, co-operation and hiding. Prefix is the basic building block of a sequential component: the process \((a, r).P\) performs activity \(a\) at rate \(r\) before evolving to behave as component \(P\). The choice combinator sets up a competition between two possible alternatives: in the process \((a, r).P + (b, s).Q\) either \(a\) wins the race (and the process subsequently behaves as \(P\)) or \(b\) wins the race (and the process subsequently behaves as \(Q\)). The co-operation operator requires the two “co-operands” to join for those activities which are specified in the co-operation set. In the following example, \(P \parallel^{a,b} Q\) the processes \(P\) and \(Q\) must co-operate on activities \(a\) and \(b\), but any other activities may be performed independently. The reversed compound agent theorem [40] gives a set of sufficient conditions for a co-operation to have a product form.
stationary distribution. Finally, the process $P/\{a\}$ hides the activity $a$ from view (and prevents other processes from cooperating with it).

A number of tools support model specification and analysis using the PEPA formalism, including the PEPA Workbench [41], the Imperial PEPA Compiler (IPC) [42], PRISM [43] and Möbius [44]. A summary of ready to use tools for PEPA modelling is available on the PEPA website[^1]. However, the PEPA Eclipse plug-in tool [34] is considered the primary tool used for the number of analysis types that are available to use. PEPA analysis types vary depending on the systems or models being investigated. A list of the available analysis types in the PEPA plug-in tool is given below:

- Markovian analysis allows PEPA models to be studied via the underlying Continuous Time Markov Chain (CTMC). This analysis includes state-space derivation, state-space view and steady-state analysis.

- Performance analysis that presents information concerning the throughput and the utilisation of PEPA models. This analysis supports conducting several experiments by using different values of the model parameters. A graph view is used to plot the results of these experiments.

- Scalable analysis allows PEPA models to be analysed using Ordinary Differential Equations (ODE) and Stochastic Simulation Algorithms (SSA). Both approaches support the evolution of the model over time. For example, using ODEs, it is possible to derive transient measures such as passage times.

PEPA can be used in numerous domains, especially in informatics and engineering, as well as in health contexts. For example, Chen et al. [39] claim to demonstrate the usefulness of the PEPA tool when using it to measure the performance of patient flow in a rheumatology department. Also, they compare the findings of an original model with an evolved model in this specific department. As a result, they prove that the evolved model successfully reduces waiting queues by changing the activity flow. In addition, they conclude that workflow efficiency and resource utilisation could be improved by using a dynamic scheduling policy that controls the scheduling process depending on different time slots.

Another example of how performance modelling is used in health care was discussed in [45] aiming to use formal modelling in health systems. The resulting models prove that these formalisms can capture the patient flow in such contexts. Although PEPA provides various types of analysis, population analysis is used in [45] because we want to investigate the behaviour of the total number of patients in such models and how fast they are discharged from hospital. This analysis explains how much patients can be served.

[^1]: https://www.dcs.ed.ac.uk/pepa/tools/
when a specific strategy or policy is applied. Moreover, PEPA confers the reader with an
analysis insight into where the bottlenecks in such flow are and what to do to improve or
reduce these issues.

2.4.2 CARMA

CARMA is a notation designed mainly to provide more expressive modelling features
than other stochastic process algebra formalisms, such as PEPA [35]. Although PEPA
influences CARMA, it was established to model the Collective Adaptive Systems (CAS)
paradigm. From the literature, [46–49], CAS as a broad term refers to a collection of
systems, agents or components within a system. There are several characteristics of these
components, such as large number, heterogeneous, decentralised control, local attributes
and behaviours, an irregular presence in the system, and they interact (or sometimes
compete) to achieve individual goals or global goals within an environmental setting.

CARMA offers a range of communication types, including unicast, broadcast, global
asynchronous and local synchronous communication [35]. CARMA also supports a notion
of location, which facilitates the ability to control the model environment and specify
where/how the components move. There are four types of action CARMA can perform
[35]:

input \( (\alpha[\pi](\vec{x})\sigma) \), output \( (\alpha[\pi] < \vec{e} > \sigma) \), broadcast input \( (\alpha * [\pi](\vec{x})\sigma) \), and broadcast
output \( (\alpha * [\pi] < \vec{e} > \sigma) \) where:

- \( \alpha \) is an action type;
- \( \pi \) is a predicate;
- \( x \) is a variable;
- \( e \) is an expression;
- \( \vec{\cdot} \) indicates a sequence of elements;
- \( \sigma \) is an update.

Although CARMA is a relatively recent formalism, it has been applied to several
case studies. The first one is ambulance deployment [30] where the authors measure the
behaviour of the ambulances when they respond to incidents at different times of the day.
In addition, they discuss how hospital and ambulance locations affect the movement to the
incidents locations. A second case study using CARMA is the Bicycle Sharing System [35].
In that case, the authors divide the city into four zones, and each zone has four parking
stations, then perform a simulation to measure bike users’ activities in the environment.
Finally, they conclude by showing the maximum, average and minimum number of bikes
in one city zone. As has been noted, all of these case studies have used the CARMA Eclipse plug-in \[50\] in their investigation. Furthermore, the components’ location was an integral feature in nearly all the studies that used CARMA in their investigation.

### 2.4.3 SPN

Petri nets are used to model concurrency using tokens which occupy places and move in response to transitions. Stochastic Petri Nets (SPN) are an extension to classical Petri nets where the transition happens by using a random variable to specify the delay of that transition firing \[37\]. As with PEPA, an SPN model can be used to derive a continuous-time Markov Chain (CTMC) if the random variables are all negative exponentially distributed \[51\]. More general forms of SPN include other distributions for transitions, and their models are often analysed using discrete event simulation. Formally, 6-tuples are present in every SPN model: 

\[
SPN = (P, T, I, O, W, M0)
\]

- \(P\) is a set of places.
- \(T\) is a set of transitions.
- \(I\) is a set of input arcs.
- \(O\) is a set of output arcs.
- \(W\) is the array of the firing rates \(\lambda\) which are the parameters of the exponential distribution of the delay.
- \(M0\) is the initial marking.

Unlike PEPA and CARMA, which are textual modelling languages, SPN tools allow the modeller to construct models graphically. There are a wide number of tools that support SPN\[2\], for example Cosmos \[52\], GreatSPN \[53\], Mercury \[54\], and ORIS \[55\]. We developed our SPN model using the ORIS tool in this research because its features include providing advanced performance analysis and supporting many operating environments, unlike the aforementioned tools.

### 2.5 Model Checking

This section presents a concise overview of the Model Checking concepts. An alternative approach for analysing system models is model checking. In computer science, model checking is defined as a computer-based approach for verifying that a system meets its requirements, given that this system is modelled by a state-transition system \[56\]. The

\[2\]https://www.informatik.uni-hamburg.de/TGI/PetriNets/tools/quick.html
model checking approach is needed because computer science is involved in many modern life aspects, including healthcare, transportation, finance and entertainment. Furthermore, model checking has been influenced by many computer aspects such as programming language developments, hardware designs and network inventions. In addition, in the industrial context, model checking is a process that has been used heavily to verify both hardware and software. Therefore, the developments in all of the above life aspects using the field of computer science have led to an increase interest in the “Model Checking” concepts.

An approach relevant to this thesis is stochastic model checking (SMC). SMC is an approach to determining the chance of an event to occur throughout a system execution [57]. These systems are represented as probabilistic models, which usually are types of Markov chains. There are two common types of Markov chains: discrete-time Markov chains (DTMCs) and continuous-time Markov chains (CTMCs) [57]. DTMCs are a combination of states and probability transitions array, while CTMCs are a combination of states and rate transitions array [58]. During this investigation, we will produce different stochastic models and verifying these models are behaving as they supposed to is a significant aspect. Therefore, becoming aware of these analysis approaches is fundamental. The above mentioned two types could be used in the development process in Chapters 4, 5 and 6.

There are frequently two tools used as Model Checking techniques which are more relevant to this thesis context. The first one is PRISM [3] a stochastic and statistical model checker tool that supports analysing many probabilistic models including the two above-mentioned [59]. The second one is UPPAAL [4] a statistical model checker tool designed to verify the ability to model a system as a network using several representations, such as channel synchronisation and integer variables [60].

In this research, we did not cover the aspect of model checking and, more specifically, stochastic model checking. This non-consideration is due to the small size of data we have of the medical context under investigation, detailed in Chapter 3. Furthermore, the reason to introduce this notion is to shed some light regarding other research directions, which we will discuss later in the future recommendations section of Chapter 8.

2.6 Trace-Driven Simulation

The significant advances in computer systems and the resulting logs from these systems leads to tremendous interest in trace-driven simulation. A simulation is defined as the process of imitating a system for the purposes of decision making and system evaluation.

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3[http://www.prismmodelchecker.org/]
4[https://www.uppaal.com/index.php]
More specifically, the term “trace-driven simulation” has come to be used to refer to computerised simulation that uses time-ordered records of events on a realistic system \[61\]. By definition, trace-driven simulation consist of two tasks: one is for collecting data called traces, while the other is for creating a simulation and using the collected traces as an input to the simulation. Furthermore, trace-driven simulations are primarily used for performance evaluation of an investigated system or for predicting the user behaviour in a system. Moreover, an example of a trace-driven simulation case study is applying the traces from computers implementation to analyse the energy management using a tool called HTC-Sim \[62\]. This approach is discussed in detail and could be used to complement the analysis in chapters 6 and 7 of this thesis.

Adapting a trace-driven simulation approach involves many advantages and disadvantages. Table 2.1 presents some of these characterises as the following:

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Easy to validate: compare to measurement approach</td>
<td>High complexity: need more details</td>
</tr>
<tr>
<td>High credibility: realistic events</td>
<td>Representativeness: traces change overtime</td>
</tr>
<tr>
<td>Fair comparison: different conditions with same inputs</td>
<td>Finiteness: limited to represent other trace</td>
</tr>
<tr>
<td>Less random: describe deterministic traces</td>
<td>Single point of validation: one case described</td>
</tr>
<tr>
<td>Similar to implementation</td>
<td>Traces need to be highly detailed</td>
</tr>
</tbody>
</table>

2.7 Process mining – Produce models based on an event log of system processes

Process mining has emerged to make use of the vast logs created by information systems. In addition, most processes in these systems are informal, not documented, or are used in different ways that were not expected. According to van der Aalst \[2\], the goal of process mining is to investigate, observe and upgrade any process based on event logs that are readily available in the system.

There are three types or techniques of process mining. The first technique is Discovery which aims to create a model without prior knowledge regarding the investigated situation using only an event log. The second technique of process mining is conformance checking. It is applied to check that a model corresponds to the recorded event log and vice versa. The third technique of the process mining is enhancement. It provides an upgrade or improved feature to an already available model. For example, it is possible to observe any bottlenecks, throughput times, and service levels by extending the timestamp of an event log and offering improvement suggestions. Figure 2.2 shows the different techniques of process mining.
Figure 2.2: The three basic types of process mining: (a) discovery, (b) conformance, and (c) enhancement. Source: [2].

Figure 2.2 demonstrates how process models can be created using the three process mining techniques. These techniques use the event log which is produced by a software system that assists real situations.

Compared to other analysis approaches, process mining has three distinctive features or characteristics [63].

1. Process mining techniques are considered process-centric, not data-centric compared to data mining techniques. For instance, concurrency processes may not be fully described in traditional data mining structures such as decision tree techniques.

2. Process mining is deemed intelligent because it learns from historical data, and the results are applied to running cases. For example, the discovery technique predicts the needed time to complete a procedure.

3. Process mining models are accurate because they are based on event data, not opinions about what should happen. For example, modelling the guidance of a situation is different from modelling the traces of that situation. Obtaining event data implies that the investigated system is exist, in contrast to model checking investigation which could be performed in the design phase of a not yet existing system.

The event log can have many attributes or indications other than tracking or following the process flow in a system. These indications help form specific analyses; for example, the investigator could use timestamps attributes in the event log to perform bottleneck analysis. Additionally, resource attributes are used to explore organisational rules analysis, such as enhancing business transparency.
Since interest has grown in analysing event logs recorded from system processes, an IEEE Task Force has developed a manifesto \cite{63}. This manifesto aims to promote process mining as a new analysis tool for optimising operational processes. The manifesto identifies several guidelines and presents numerous challenges regarding using process mining in practice. This manifesto will serve the scientists, consultants, software developers, and end-users to maximise the usage of process mining techniques.

This research deals with users’ logs as clinician behaviour during massive bleeding scenarios. These logs are basically processes followed according to approved medical protocols. Therefore, process mining and its techniques could benefit behavioural analysis and provide more insights into the investigated scenarios.

### 2.8 Examples of Related Literature in Serious Contexts

The work of this research accomplished in an original and novel approaches. Consequently, this thesis presents many perspectives together for the first time, to the best of our knowledge. These perspectives are gamification elements, TIC context, and formal modelling formalisms. Therefore, Section 2.8.1 focuses on the work performed using the TIC context, while Section 2.8.2 explores how several works of literature incorporate formal modelling formalisms with other serious contexts.

#### 2.8.1 The TIC Context Related Work

In addition to the related literature discussed in Section 2.2.2, the following related publications are focused on the TIC context as it is the focus of this research. It is worth mentioning that these publications are exploring the TIC context from a medical point of view, which is beyond the scope of this research interest. Our work is different as it investigates TIC from a data analyst perspective. The reason to explore and evaluate the following literature is to be more familiar with the state-of-the-art research on TIC regarding its treatments and recommendations. In summary the aim is to learn more about the processes that we are going to investigate and model.

There are two directions in exploring the TIC context. One is focusing on analysing TIC quantitatively and qualitatively. The other is focused on understanding the triggers for the TIC condition. The following describes the two directions elaborately.

An example of the first direction is available in \cite{64} work. Roberts et al. \cite{64} performed an investigation to determine the coagulation factors of TIC, mainly the fibrinolytic activity. Their investigation compares the changes in its activity from the patient’s arrival, at three hours and every three hours until 120 hours of arrival. Also, their comparison was performed using the estimated average quantitative values of the coagulation factors of TIC patients and patients without TIC. Another example exists in \cite{65} work, where they
qualitatively compare the difference between TIC and other medical conditions termed disseminated intravascular coagulation (DIC) \[66\]. They identified which coagulation parameters changed or were not included between these blood conditions. In addition, the Gando et al. \[67\] study performed a statistical analysis of patients’ demographic data between patients diagnosed with TIC and DIC patients. This direction is relevant to this thesis’s work as it shows the methods used to analyse TIC contexts. However, our approach uses stochastic modelling to analyse these contexts.

Another research direction is exploring the TIC triggers. Several studies discussed Protein C activation and depletion \[21\], and others focused on impaired coagulation factors, such as factor depletion \[68\], thrombin generation \[69\], and fibrinogen deficiency, although they performed their study on the swine model \[70\]. Further study is focused on how TIC is related to immune system abnormality \[71\]. Consequently, understanding what factors trigger or prevent the clotting process is essential and relevant to this examination.

Contrary to the above literature, this thesis is concerned with how formal modelling formalisms explore the clinician’s behaviour in response to a patient medical condition in the TIC context. Nevertheless, this novel approach is coherent with some medical publications by suggesting using computational models to expect and provide optimal treatment for individual patients \[65\] \[72\].

2.8.2 The Formal Modelling Related Work

Much literature has been published using formal methods or different modelling techniques within medical or sensitive contexts. The reason for selecting this literature is to become more familiar with how formal modelling is used in serious contexts. The following is a discussion of the selected literature objectives, their methodology, and their findings.

Stéphanou and Volpert 2016 \[73\] conduct a classification review on continuous and discrete modelling in biomedical contexts. Their work begins by surveying the hybrid modelling approaches using the PubMed database. They used several keywords to count the produced references. They also study the reference threshold along with the used keywords. They found that recently there has been a rise and increased expansion in the number of references, indicating the increased collaboration between biology, medicine, computing, and mathematics. They identify three different types of hybrid modelling approaches: 1) Independent or decoupled models, which describe the same case using two different ways of modelling or describing two aspects of the same case differently. 2) Adjacent or coupled models in which the output of one model formalism is used as input of the other model formalism. 3) Intricate or entangled models represent a modelling formalism used to describe the case; however, one event of the model is described in a different modelling formalism.

The conclusion of Stéphanou and Volpert \[73\] work is the decoupled models are pri-
Chapter 2. Background and Related Work

Primarily used to study the performance of different models of the same situation, and the coupled models approach is the most adapted approach due to its ability to model complex systems using multi-scale processes. In addition, the intricate models’ approach is the most accurate as these models are mathematical more than computational. However, they also reveal some limitations regarding these modelling approaches. First, the decoupled models are assumed to be a hybrid approach or method rather than hybrid modelling. The second limitation regarding the coupled models approach is its inability to analyse inconsistent cases during these medical contexts. The last limitation concerns the intricate models that appear in the limited number of applications supporting this modelling.

This thesis presents two approaches using both modelling techniques mentioned in Stéphanou and Volpert [73]. However, we focuses on the clinician behaviour during the TIC context.

Kamsu-Foguem et al. 2014 [74] argue that the use of the conceptual graph formalism helps support medical decisions. They conduct their work by representing the Clinical practice guidelines and protocols (CGPs) based on the graph theory operations to give the user more understanding and influence over the associated medical reasoning. Therefore, they provide an example of this approach using adult patients with a hyperosmolar hyperglycemic state in the intensive care unit. They claim that their work helped to represent medical knowledge in a more clarifying way. Nonetheless, this thesis focuses on stochastic modelling formalisms, trace-driven simulation techniques and numerical modelings to provide better medical decisions that involve estimating the needed medical resources.

Stalidzans et al. 2020 [75] believe that the medical field could benefit from mathematical model features such as simulation and optimisation. Therefore, they propose a method that validates or improves mathematical models of medical nature by simulating an experiment and then using lab experiments or clinical studies to replicate the simulation. Additionally, they present various types of mechanical modelling methods, including Network modelling, Bayesian modelling, Logic modelling, Agent-based modelling, and Stochastic modelling. They also provide different medical examples of where these methods could be used and the number of tools that support each methods. Finally, they reveal that the appropriate selection of the modelling method is based on the available data and the type of phenomena of interest. Their concluding remarks did not consider what type of modelling methods are suitable to understand clinician behaviour in the TIC context.

Massink et al. 2012 [76] present an example of how a stochastic process algebra formalism is used in a critical context. They use a challenging system called emergency egress, where individuals follow specific routes to exit a building. Their scalable analysis approach deals with the specific agent interaction in discrete form and the general system behaviour in continuous form. They certify that such an approach provides more realistic scenarios.
for evacuation plans. These scenarios consider the different situations that could happen during an evacuation; for instance, evacuee injuries or evacuee change of route to look for another evacuee. Furthermore, due to the hybrid system behaviour observed in their work, this research also demonstrates the same phenomena. Also, their work is related because they produce PEPA models in their investigation.

Bortolussi and Policriti 2009 [77] propose a method to convert ordinary differential equations (ODE) and stochastic concurrent constraint programming (sCCP) of biological systems models. Furthermore, they show that such transformation should keep the same rates between the two formalisms with respect to equal models' behaviour. However, they reveal that their method could not be performed directly in some cases, which require a middle class of dynamic systems called hybrid automata [78] to ensure model equivalence. In relation to this thesis, the model equivalence approach is explored in choosing which modelling formalisms are more suitable than others, discussed in Chapter 4.

2.8.3 Other Concepts Related Work

An example of how process mining is used in medical contexts is present in the work of Mans et al. 2015 [79]. They use different data sets from the Maastricht University Medical Center (MUMC) and the Academic Medical Center (AMC) in Amsterdam. They demonstrate that process mining techniques and their tools are useful in improving medical quality and reducing medical inefficiencies. Moreover, they propose the types of process are more suitable to investigate. These processes could be the medical services such as CT-scan, the non-medical services such as informing patient’s relatives, the processes of patient transportation, and the processes of outpatient clinic patients. Consequently, many use cases illustrated how applicable process mining is, including the identification of bottlenecks, more depth processes investigation, and comparison of healthcare processes. Their findings and recommendations are related to behaviour analysis of this research. We use many analysis techniques that are mentioned in process mining literature.

Simulation models in medical contexts gain significant attention. This attention relates to different points of view, including educational settings or emergency services. An example of this view is the work of Krishnan et al. 2017 [80] that weighs up the opportunities and obstacles of using simulation models in medical education. They insist on adapting education simulation; there is a need for a solid proof that it is functional. Furthermore, they suggest supplementary studies focusing on improving patient outcomes using simulation. In relation to this thesis is the use of a specific type of simulation termed trace-driven simulation to evaluate the clinician’s behaviour. In addition, this simulation was used to test different modifications on the clinician’s behaviour to improve patient outcomes.

Another example is the work of Aboueljini et al. 2013 [81] that debates the use of simulation models to optimise the performance of emergency medical services. They
evaluate different simulation models from the different geographic regions of interest and analyse the decisions associated with these models. Lastly, they encourage enabling optimal or near-optimal solutions from these simulation models. Moreover, they recommend more collaborative efforts between other non-medical emergency services such as firefighters.

2.9 Conclusion

In summary, this chapter covers some of the related materials in this research. It commenced by presenting two medical scenarios examples. Afterwards, we introduced our data collection approach and discussed possible approaches to evaluate system qualities alongside some case studies in which these approaches have been used. After that, we briefly cover the concepts considered in this research project. Also, we present the different concepts not involved in this thesis development while pointing out that these concepts are recommended for future research directions. Finally, we showed how our research approaches inspired and differed from the related literature.

The next chapter will discuss the method used to derive behaviour data. Also, we will explore how this method stimulates the clinician experience using provided real-life scenarios.
Chapter 3

The Research Context: The Serious Web-based Sketch Simulation

3.1 Introduction

Gamification has been used widely in the healthcare domain. An extensive exploration is provided in [82] on using game science innovations in a medical context. Many Gaming Innovation Science (GIS) techniques serve the same purpose in medical education: training or improving clinician actions. For example, GIS may be referred to as simulation, gamified training platform, electronic game or mobile application. We use gamification in this project to accomplish several purposes 1) it will reduce the data collection problem in a serious context, 2) it will stimulate the clinician experience, in the sense of encouraging the clinician to perform an action based on certain triggers, and 3) it will provide us with varied data from multiple users using logs of the chosen interactions.

This chapter covers aspects of the gamification tool used in this research. The context used in this tool is TIC, which may occur in the context of massive bleeding trauma [1], as mentioned in Section 2 of Chapter 2. Many methods are available to obtain behavioural data in these critical contexts. For example, the data analyst observes the doctor’s behaviour in an operating room or interviews the doctors regarding their actions in such situations. However, this behaviour and its data are not always accessible to the data analyst because of the patient’s critical health condition or the limited number of individuals who can attend these scenarios. In addition, the doctors are unavailable to collect the required information for behaviour analysis, mainly because these doctors usually have limited time to do anything besides providing health care. Therefore, we propose an approach to collect such critical data called Gamification. It designs a simulation of the
investigated context accompanied by game elements to trigger the clinician’s experience to collect their interactions during the chosen context. According to [19], most bleeding cases happen uncommonly and are associated with high mortality, so this approach is essential to improve the clinician’s behaviour during this context without being in the actual environment.

Many versions resulted of using a gamification approach. The original version was developed by Hamit Soyel\(^1\) from Queen Mary University of London (QMUL) as part of a European project\(^2\). The original version of the sketch simulation was equipped with many interventions, and each intervention had a different effect on the simulated patient’s medical condition. Moreover, an anaesthetist, named Dan Nevin\(^3\), provides these effects and physiological model parameters used in this sketch simulation. Furthermore, they specify how these interventions would affect the medical condition of the played scenario. For instance, infusing one pack of a blood product called PRBC would lower heart rate by 1%, raise blood pressure by 1.5%, increase potential of hydrogen (PH) by 0.25%, increase beryllium (Be) by 2.5%, and increase Lactate by 2%. Based on actual cases, they also determine the sketch simulation parameters, such as the number of scenes, the scene time, and speeding up the sketch simulation time by ten times the real medical scenarios.

The purpose of the original version was to compare how supportive the decision-making process is to include a specific blood test called VHA\(^5\) in the sketch simulation to improve the use of blood products. Specifically, they compare the benefits of having a blood test algorithm exist in the sketch simulation rather than check the algorithm using a traditional method: using hard copy or wall sign. And yet, despite that purpose, our approach is to improve this existing sketch simulation with a newer version and achieve many other objectives. These objectives are:

1. Improve the understanding of the coagulopathy trauma context to non-medical background experts.
2. Make the sketch simulation platform-independent, not only operating on IOS devices.
3. Analyse the sketch simulation user behaviour using the resulting logs to determine the best log to discover the optimal log.
4. Provide a training tool for educational purposes.

As previously mentioned in the literature review chapter, there are different types of massive trauma bleeding. Thus, to treat such conditions, numerous interventions must be made during a limited time based on the clinicians’ knowledge and the health institution’s

\(^1\)http://eecs.qmul.ac.uk/profiles/soyelhamit.html
\(^2\)https://tacticgroup.dk
protocols. Our approach aims to facilitate the reality of the massive bleeding context to make the sketch simulation user behave similarly to what they would be in the natural environment. So, this gamification approach provides essential information related to these medical cases and triggers the clinicians’ expertise by building a real-world that enables them to perform various interventions and observe the impact of these interventions.

This chapter is structured as follows: First, it starts by describing the sketch simulation’s components. Second, an explanation is presented of the sketch simulation design and creation. Third, a walk-through of the sketch simulation will be presented. Lastly, we discuss an outline of the sketch simulation experiment settings and illustrate some of the experiments observations as well as demonstrate log data structured and the way they were acquired.

### 3.2 The Sketch Simulation Framework

This section explains the scope and structure of the sketch simulation. It starts by presenting the sketch simulation parts, followed by the sketch simulation interface elements. Then it concludes with some of the sketch simulation characteristics and discusses the sketch simulation differences between its scenes during the same scenarios.

This sketch simulation has two main parts: sketch simulation interface and sketch simulation logic. Briefly, the sketch simulation interface is used to deliver as much information as required to build the needed reality of the massive bleeding environment. Moreover, the sketch simulation interface allows the user to imagine the adapted scenario using simple triggers, such as vital signs readings and popup feedback messages. Likewise, it enables the sketch simulation user to interact and be involved deeply with the sketch simulation’s scenarios. The sketch simulation logic also includes the medical context or settings based on the sketch simulation scenarios. Also, because these settings are changeable, the sketch simulation logic is developed to adjust to changes, such as different protocols or distinct names. These changes are accomplished manually using simple modifications to the sketch simulation logic.

The sketch simulation interface has different elements presented in Figure 3.1. We categorised these elements into two main types: i) elements that make the sketch simulation more realistic, and ii) elements that keep the participants engaged with the simulation. However, in the first version of this sketch simulation, there is only one element that improves participant engagement. This element is the scene timer that exists to specify how much time is left before the scene ends.

The other realistic elements are as follows. Firstly, the Incident details element contains some information and comments about the scene and the user’s role in this situation. Secondly, the Interventions element is the available actions to perform on the pa-
Chapter 3. The Research Context: The Serious Web-based Sketch Simulation

tient. The sketch simulation is equipped with interventions to be performed based on the chosen scenario. In the case of the conducted experiment, these interventions are configurable, whereas here, we defined them under seven headings: Initial management, Patient packaging, Airway management, Breathing management, Circulation management, Fluid management, Monitoring and Drug therapy. Third, the element of the vital signs involves measurements of the human body’s essential functions such as Heart Rate (HR), Blood Pressure (BP), Respiratory rate (RR) and Saturation of peripheral Oxygen (SpO2) including the Glasgow Coma Scale (GCS). The fourth element is the set of Blood results, which consist of several test results available upon requests, such as Haemoglobin (Hb), Platelet count, and Lactate. Finally, the element of the Potential problems contains a list of the possible medical problems the patient having currently in each scene. This list is based on the participant selection of the most likely problems that the scenario patient is having. Figure 3.1 shows the relationship between these elements and other parts of the sketch simulation; for instance, each scene has a set of available interventions, and each intervention is logged using its timestamp alongside its score, discussed later.

It is essential to include these diverse elements as they are significant to incorporating details of the trauma case and its environment. Moreover, it is worth mentioning that these previous headings are not fixed and can be modified manually to fit different cases and scenarios by adding or removing the needed headings.

In the same manner, one of the essential features of this serious sketch simulation is representing the local fridge and its current contents visually in the sketch simulation scene. The local fridge displays the available blood products, which are PRBC, FFP, Cryo and Platelets. Furthermore, the sketch simulation developed with a specific form of blood analysis named ROTEM unite. Figure 3.2 demonstrates the parameters that the clinician uses to determine how is the clotting is forming and how strong it is. Moreover, the sketch simulation also includes a set of rules that the anaesthetist should follow due to the ROTEM test results. These rules are suggested by the collaboration mentioned above, shown in Table 3.1.

<table>
<thead>
<tr>
<th>Type</th>
<th>Cause</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIBRINOGEN</td>
<td>FIBTEM CA5 &lt;10mm</td>
<td>4 g</td>
</tr>
<tr>
<td>PLATELETES</td>
<td>(EXTEM CA5 – FIBTEM CA5) &lt;30mm</td>
<td>1 pool</td>
</tr>
<tr>
<td>PLASMA</td>
<td>EXTEM CA5 &gt;40mm AND EXTEM CT &gt;80s</td>
<td>4 units</td>
</tr>
<tr>
<td>TRANEXAMIC ACID</td>
<td>EXTEM LI30 &lt;85%</td>
<td>1 g</td>
</tr>
</tbody>
</table>

The sketch simulation is configurable, and it can accommodate many medical scenes. However, for this investigation and this specific version of the sketch simulation, each
Chapter 3. The Research Context: The Serious Web-based Sketch Simulation

Figure 3.1: The sketch simulation elements

scenario has three different scenes that emulate distinct physical locations. These scenes are Prehospital, Resus, and Theatre. Although there are three scenes for each scenario, there are some differences among these scenes. One difference is that each scene has different interventions available to perform. For instance, the local fridge notion in the Prehospital scene (which could be an ambulance) is unavailable, so there are limited blood products available compared to Resus and Theatre scenes.

Another example is that ordering blood tests and scanning tests are not available in the Prehospital scene due to inappropriate equipment on board the ambulance, unlike the Resus scene, which has additional resources. Another difference is that the potential health problems in the Prehospital scene vary from the Resus and Theatre scenes based on the case symptoms because it is impossible to reach diagnoses with limited facilities available in the ambulance. A further difference is noted regarding the scene duration. Each scene has a different duration. Just as important, it is worth mentioning that two of the three scenes are connected within local fridge contents. In other words, the ordered
blood products in the Resus scene are moving to the Theatre scene.

This serious web-based sketch simulation provides many features. One of the sketch simulation features is the user behaviour score. Each action performed by the user will be scored based on predefined grading. A qualified anaesthetist provided the grading for the particular version used experimentally. This grading is used to determine how performed actions are suitable in such a scenario. Also, the user score has been used to assess the quality of the user behaviour sequence. In addition, the feedback aspect of the sketch simulation is present in two ways: pop-up messages and coloured highlights. These two ways are used to increase the sketch simulation’s user interactivity with the sketch simulation reality. For example, the pop-up messages appear when ordering scan tests or when blood test results are ready. Also, the coloured highlights appear at the scene ending to notify which interventions the user chose correctly and which interventions the user had missed. Another feature of the sketch simulation is the use of a log to record user behaviour. This technique allows for a deep examination of user choices to justify their choice correctly. In addition, this technique is suitable for collecting data because of the critical context the sketch simulation is based on and to overcome the difficulties in such an environment. Just as important, this sketch simulation aims to stimulate and acquire the knowledge that these experienced anaesthetists have in such critical situations.
3.3 The Sketch Simulation Development Process

This section discusses the development process of this sketch simulation, then describes the sketch simulation’s two versions and points out the differences between them with more focus on the version developed as part of this research.

Eliciting the sketch simulation user’s knowledge was the purpose of developing this sketch simulation. This purpose contrasts with typical games that consider the game’s reality essential, although enough reality was required to trigger appropriate responses. Therefore, context reality was not a critical factor in the design process of this sketch simulation. Nonetheless, the literature is full of many suggestions and requirements needed to make an effective serious game [84] [85] [83]. Considering the aforementioned literature, we found four requirements are fundamental to designing a serious game:

1. **Context** which covers how the game is used effectively and how the game’s environment presented.

2. **User actions** demonstrate how their activities influence the game outcomes.

3. **Representation** that provides the level of familiarity and engagement that the game has to offer.

4. **Assessment/feedback** which determines the difference between game use from leisure activities to educational ones.

Accordingly, this sketch simulation design process suits these requirements. Specifically, the sketch simulation context here is TIC alongside its protocols, and the user actions are the available interactions in each scenario. Moreover, the sketch simulation representation is available in many examples, such as vital signs readings and the local fridge elements. Furthermore, the assessment of the sketch simulation is expressed using the grading system, while its feedback is defined using the tracking and popup messages elements. Correspondingly, Figure 3.3 shows the different factors used to determine the sketch simulation design. For example, the context forms the user engagement and the representation of the sketch simulation. Similarly, user feedback impacts the sketch simulation representation and the sketch simulation goal.

Our approach followed the above fundamental requirements in the developing process of this gamification. Two versions were created using two different programming domains. The original version of the sketch simulation, which was part of the European collaboration as mentioned at the start of this chapter, was developed using Xcode. Xcode is an integrated development environment (IDE) used to build software suitable for Apple’s device operating systems. Figure 3.4 displays one of the original version interfaces, explained as follows:
1. The left side of this figure shows the available interventions.

2. The top middle of the figure is for describing the patient situation highlighting the scene name and its timer, while the bottom middle of the figure is for the patient vital signs and the ROTEM test analysis.

3. The top right of the figure is for the potential problems, and the bottom right is for the blood test results.

4. The far top right corner shows an arrow to move to the next scene and the (X) sign used to abort the scene.

This sketch simulation version was intended to be an application on an iPad to benefit from its physical portability advantage. Subsequently, the log data examined in this research were produced using the original version of this sketch simulation. However, this approach exposes three limitations resolved using a newer version of the sketch simulation. These limitations are i) financial, since iPad devices are expensive; ii) analytical, because the produced logs were not extensive to satisfy different analysis approaches; and which is most important, iii) platform dependence, as the original sketch simulation version works only on IOS devices, ensuring that the sketch simulation is more portable.
Chapter 3. The Research Context: The Serious Web-based Sketch Simulation

As part of this investigation, we developed a newer version of the sketch simulation. Several objectives targeted the development of the newer version of the sketch simulation, including overcoming the limitations mentioned earlier and making the sketch simulation cross-platform available for broader use. Therefore, we designed the newer version of the sketch simulation to work on a web browser as web pages presented in Figure 3.5. As a result, the newer version of the sketch simulation uses three different web-development languages: HyperText Markup Language (HTML), JavaScript (JS) and Cascading Style Sheets (CSS). To be specific, HTML is used to create the primary web page contents, and in the same way, JS is applied to make the web page contents interactive, and CSS is utilised to style the web page contents. In addition, this sketch simulation’s version has enhanced the portability feature compared to the original version due to the use of a web-based system that is relatively independent of the platform.

Just as important, the new version of the sketch simulation has been developed with four features:

1. A tracking element shows the sketch simulation’s user what interventions were cho-
Chapter 3. The Research Context: The Serious Web-based Sketch Simulation

Figure 3.5: One of the sketch simulation scenarios interfaces of the new version of the sketch simulation

2. The new version makes it possible to collect extensive context data concerning user behaviour and its effect compared to the original version.

3. The newer version uses a table-driven scene type. The table-driven method or design uses data structures instead of if-then statements to drive program logic. This method was used to make the sketch simulation scenario more flexible.

4. The newer version updates and improves the pop-up feedback messages to be more comprehensive than the original version. For example, more interactions with the medical team were added to resemble what is usually happen during such scenario.

3.4 The Sketch Simulation Walk-through

This serious sketch simulation software consists of three scenarios developed by a qualified anaesthetist based on actual health cases. The first one of these scenarios is a training scenario used to familiarise the user with the sketch simulation interactions and the sketch
simulation environment. The other two scenarios are to record the user interventions and behaviour for analysis purposes. Figure 3.6 clarifies the sketch simulation pathway the user takes within the sketch simulation.

![Figure 3.6: The sketch simulation pathway](image)

The sketch simulation starts by offering the user the choice of one of the scenarios. The screen will change to the first scene on selection, which is Prehospital. The participant should then read the incident details, do the suitable interventions, and select the potential problems. As soon as the scene time, which is a predefined adjustable duration of the scene, has ended or the participant finishes performing the needed interventions and marking the potential problems, the user should click on the arrow button in the top right of the sketch simulation interface. Afterwards, a message will pop up showing the scene score then the sketch simulation interface will provide feedback to the user by highlighting the most appropriate interventions and potential problems that the user should choose and indicates which wrong interventions the user performed in the scene. Then the sketch simulation interface will change to the Resus scene.

The user should play the Resus scene in the same manner as the Prehospital scene.
However, there are some differences, such as different available interventions and a large set of potential problems. One of the central interventions that have a significant impact on how to play the sketch simulation is blood administration, shown in Figure 3.7. Figure 3.7 demonstrates the process of ordering and infusing blood products in the sketch simulation. The process starts with checking the medical condition to evaluate whether blood products are needed or not, then checking the local fridge to see the available blood products. If there are needed blood products, then blood product infusing should be started or ordering more blood products should be initiated. When it is initiated, the blood bank should prepare the requested blood products, which involve a delay based on the requested blood type, and then they will be moved to the local fridge. This process would be repeated every time a blood product needed until the end of the scene.

It is worth mentioning that some interventions have a different impact than others. For example, based on the scenario, some interventions have a catastrophic impact, leading to the end of the scene and the scene score will reduced by 1000 to indicate catastrophic intervention were chosen.

Figure 3.7: The blood usage process in the sketch simulation
3.5 The Sketch Simulation Experiments

This section presents the experiment settings used to produce the user’s log. Afterwards, a description of the produced logs and their contents is presented.

Before we initiated this research, 24 anaesthetists and doctors used the first version of the sketch simulation, as presented in Table 3.2. The participants were divided into two groups, A and B. The A group represents the participants who have a simulation of the app to support the ROTEM data, whereas group B represents the participants who did not have the ROTEM feature included in their sketch simulation. Moreover, the experiments were performed in two different locations. The first place was in Royal London Hospital “RLH”, which had 16 participants. The second place was the Royal Victoria infirmary - Newcastle “RVI”, with 8 participants. At the start, the experiment demonstrator illustrated the sketch simulation pathway to the participants, as well as they have been given a chance to try the sketch simulation using the provided training scenario.

Table 3.2: The logs groups with naming examples, (x) for the number of the sketch simulation user.

<table>
<thead>
<tr>
<th>Experiments</th>
<th>RLH</th>
<th>RVI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>Ax1a</td>
<td>Bx1b</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>Ax2a</td>
<td>Bx2b</td>
</tr>
</tbody>
</table>

After completing the sketch simulation experiment, the participants were asked (in a tech report) about their experience using this sketch simulation. Indeed, the general response was positive, and the participants found the simulation reality to be close to a massive bleeding scenario in the real world. However, in addition to that, they were asked a series of questions. These questions aim to collect the participants’ responses regarding: (1) The scenarios’ realism. (2) Any missing interventions or problems. (3) The engagement level to the sketch simulation interfaces. (4) The instruction’s clarity. (5) The scene’s duration. (6) The physical settings of the experiments.

The participants’ responses indicated several issues with the simulation implementation and the scenarios’ context. The following are the responses to the above questions: (1) The participants considered the scenarios generally realistic. (2) Naming issues were reported, which refer to the hospital naming conventions. Also, the participants noted some missing interventions, such as warming fluids. These issues made it complex to decide which suitable interventions to perform. (3) To easily collect the experiments and use data, a MacBook pro simulating an iPad was used. This transition caused many difficulties, for example, the difference between a touchscreen and a mouse, especially in sliding between the local fridge and analysis displays. Also, some concerns were expressed regarding the inability to reverse an intervention. A further difficulty arose due to the vast number of
interventions, which led the participants to check all the interventions sequentially. This
behaviour could delay performing a suitable intervention such as ordering needed blood
products. All of these issues led to a lower engagement level in the simulation. (4) The
participants signify that there were records of what had been done on the patient in real
situations. However, they indicate that the simulation was missing such a feature. (5) The
sketch simulation time, which was faster than the actual situation by ten times, led to a
shorter time to do the required mental calculations. (6) All participants indicated that the
experiment rooms were acceptable for the experiments. There was one interruption from
the cleaners during one experiment. However, the participant involved commented that
there are many interruptions in real situations. Most of these expressed concerns, issues
and difficulties were improved or added in the newer version of the sketch simulation.

Because of the sketch simulation participation, a log of each participant’s use was
produced. These logs were anonymous and the naming structured is presented in Table
3.2. The sketch simulation design records the user behaviour and allows for automatic
download of this performance log into the user device in the experiment. The resulting
log is simply a text file that has selected user behaviour information during the sketch
simulation scenarios, which is available after completing all the scenario scenes.

The structure of the produced log consists of different parts of the user behaviour. These
parts are 1) each scene score and what time that scene ends; 2) the infused blood
products in each scene with their timestamps; 3) some of the chosen interventions, along
with what time these interventions occur; and 4) the selected potential problems together
with the timestamp of each one of these problems. Figure 3.8 presents an example of the
resulting log of the sketch simulation participation showing the structure of the log file.

Examining the clinician logs and their contents provides many investigation opportu-
nities. First, these logs allow us to classify the clinician’s behaviour using the scene score.
Also, they help us to avoid blood product wasting by studying the available logs to pre-
dict the needed blood products in these scenarios. Furthermore, we could distinguish the
best and worst behaviour by investigating the performed interventions and finding ways
to optimise these behaviours by referring to the used protocols within these contexts. As
mentioned in the introduction chapter, this research project aimed to achieve these inves-
tigations by making them part of our research objectives. Therefore, Chapter 7 of this
thesis contains an extensive evaluation of the produced logs.

3.6 Conclusion

To conclude, this chapter presents the context of this research by using gamification ap-
proach to collecting data in an inaccessible context. Also, it discusses the sketch simulation
framework and its related components and explains the design process used to develop this
Chapter 3. The Research Context: The Serious Web-based Sketch Simulation

Figure 3.8: An example of the logs available from the original version of the sketch simulation.

sketch simulation. Furthermore, it presented the development of the used serious sketch simulation and its versions. Also, it sheds some light on how the data logs are derived using two experiment settings and how we planned to use these data throughout this research.

The next chapter demonstrates a review of three choosing modelling formalisms using a case study. We performed this review to pick out the suitable formalism to model the research context discussed in this chapter, which is massive bleeding cases.
Chapter 4

Reviewing Different Existing Modelling Formalisms

4.1 Introduction

There are many reasons for considering PEPA, CARMA, SPN in this investigation. The context of this study has discussed medical scenarios that can be expressed using these notations. Second, the stochastic behaviour made by the investigated users and the design of sketch simulation that allows for arbitrary choice of actions is convenient to that notations. Third, process algebra notations such as PEPA and CARMA are more accessible and possess a wide range of available tools similar to the wide support of SPN. Consequently, we started our investigation by using PEPA as an established formalism, proving its usefulness in many cases. We subsequently explored the CARMA formalism because it is based on the knowledge of PEPA and offers more expressive power compared to the PEPA formalism. We then considered the SPN formalism as a different approach to PEPA and CARMA and used the features of Petri Nets, such as its ease of use by creating its models graphically and the available number of tools that support SPN. Furthermore, we compare these three formalisms as the literature shows limited comparison regarding such notations together. Figure shows the steps of this evaluation visually.

This evaluation focuses on the model development process and formalism semantics. This approach is justified as it is more suitable for exploring the context or space of a problem. Conversely, we will not focus on other approaches, such as model-checking analysis or discrete event simulation. In the case of a different research approaches, the model-checking approach is appropriate if the formalism models are established, and we want to study their correctness and if we want to answer a precise question regarding a specific aspect of the models.

This chapter is structured as follows. Section 2 introduces the used case study and
Chapter 4. Reviewing Different Existing Modelling Formalisms

Figure 4.1: An overview of the evaluation approach.

4.2 Design

This section aims to show how models using the three notations can be developed to describe the critical features of an A&E scenario, as discussed previously in Chapter 2.

4.2.1 The patient scenario in A&E

Several attempts to describe the patients’ journey in A&E have been published in the literature [86–89]. The authors have used different techniques in their modelling of this behaviour, such as queuing theory and process mining. In more detail, [86] used healthcare as a case study of their modelling of the A&E. They produced and evaluated several conceptual diagrams based on several criteria such as expressiveness, simplicity and scalability. Another contribution was found in [87], when they evaluated the government's ambition to service all A&E patients within four hours using queuing theory model. Furthermore, a study [88] performed in the USA used process mining. They concluded by considering how valuable and flexible process mining is in such sensitive cases. Moreover, [89] proposed a fast-track strategy in A&E and evaluated it using a discrete event simulation model.

The patient flow in the A&E scenario is chosen because it is an important medical context related to the massive bleeding cases investigated in this research, as mentioned in Chapter 2. Precise results from such a comparison will determine which formalism is suitable for modelling massive bleeding cases. Considering all of the above, Figure 4.2
Chapter 4. Reviewing Different Existing Modelling Formalisms

shows an idealised journey of patients through an A&E environment.

![Diagram of patient flow journey in an A&E](image)

**Figure 4.2: The patient flow journey in an A&E.**

When a patient arrives at A&E, the patient passes through several stages. Depending on the patient’s condition or illness, some of these steps are optional. The patient starts with registration, where he/she provides personal information (or it is provided for them), including medical history, if available. Then the patient moves to the triage process, where a nurse determines the illness severity and may take vital signs readings. After that, the patient goes to the doctor for examination and treatment. However, the patient may need lab tests or x-ray scans that can be ordered only by a doctor. Lastly, the doctor decides whether the patient needs admission for further medical care or receives treatment and then is discharged.

4.2.2 Determining model parameters

The investigated formalisms use rates, i.e. parameters of an exponential distribution to describe the average duration of each stage. In this research, we derived some of these rates from the United Kingdom National Health Services (NHS) statistics that are available online on their website \[1\]. Other rates were extracted by studying the undermentioned relevant scientific papers [90], [39], [91], and [92]. The following section describes how we calculate the scenario rates and use them to produce stochastic models.

The registration rate is assumed by comparing a model of a rheumatology department in [39]. They set the rate from a real case study to 44 patients per hour. The triage rate was set by following a study of emergency triage performance timings in [90] where they studied 1114 triage processes. Consequently, the median duration of the triage process was 20 patients per hour. The test process rate was taken from [39]. They have three

\[1\]https://www.england.nhs.uk/statistics/
test processes: the general test, blood test, and an x-ray scan. However, in this research, only one test is considered due to the nature of the accident and emergency department that can potentially consist of all the activities mentioned in [39]. Therefore, the test rate will be set at ten patients per hour. The doctor rate was assumed according to [91] who performed a study on how long the patient in the emergency department has contact with the doctor. Therefore, the doctor rate is four patients per hour. The discharge rate will be set to 14 patients per hour, similar to the discharge rate of [39] as the activities of the discharge process are similar in rheumatology and emergency departments. The admission rate was set to three patients per hour, according to [92] when they managed to reduce the admission process from a median of 43 minutes to a median of 26 minutes. Table 4.1 shows the system rates as follows:

<table>
<thead>
<tr>
<th>Components</th>
<th>Rate of service (patient / hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Registration</td>
<td>44</td>
</tr>
<tr>
<td>Triage</td>
<td>20</td>
</tr>
<tr>
<td>Test</td>
<td>10</td>
</tr>
<tr>
<td>Doctor</td>
<td>4</td>
</tr>
<tr>
<td>Discharge</td>
<td>14</td>
</tr>
<tr>
<td>Admit</td>
<td>3</td>
</tr>
</tbody>
</table>

The NHS provides monthly statistics of patients visiting Accident and Emergency (A&E). In addition, the NHS website provides helpful information about the waiting times of patients and the duration of treatment, transfer or discharge. According to the latest NHS statistics, in March 2018, there were around 2 million patient visits to accident and emergency departments. Thus, on average, there are approximately 450 visits per day to every accident and emergency department in the UK.

The number of each of the system components is essential in this investigation. There are many scenarios which could be used to analyse the performance of these models. In particular, the model performance may change depending on the number of patients, triage nurses or even doctors. Here, the evaluation is based on the system performance when the number of patients is fixed, but the formalism is different.

### 4.3 Implementation

This section focuses on how to implement the above scenario into the investigated tools. This empirical review used the PEPA Eclipse plug-in tool to create the PEPA model. Also, we used the CARMA Eclipse plug-in for developing the CARMA model. Moreover, despite SPN having many available tools, we used the ORIS tool to generate the SPN model because it is free of charge and offers advanced performance analysis alongside a
graphical editor. As mentioned before in Chapter 2, we chose these formalisms because of their features and abilities to analyse models precisely. In addition, these tools offer many metrics that are useful in analysing and understanding any created models.

4.3.1 PEPA model of A&E scenario

\[
\begin{align*}
\text{New\_Patient} & \triangleq (\text{arriveNew}, r_{\text{arriveNew}}) . \text{New\_Register}; \\
\text{New\_Register} & \triangleq (\text{register}, r_{\text{register}}) . \text{New\_Triage}; \\
\text{New\_Triage} & \triangleq (\text{triage}, r_{\text{triage}}) . \text{See\_Doc}; \\
\text{See\_Doc} & \triangleq (\text{newDoc}, r_{\text{newDoc}}) . \text{New\_discharge} \\
& + (\text{newDoc}, r_{\text{newDoc}}) . \text{New\_test} \\
& + (\text{newDoc}, r_{\text{newDoc}}) . \text{New\_Admit}; \\
\text{New\_test} & \triangleq (\text{test}, r_{\text{test}}) . \text{See\_Doc}; \\
\text{New\_Admit} & \triangleq (\text{admit}, r_{\text{admit}}) . \text{Stop}; \\
\text{New\_discharge} & \triangleq (\text{discharge}, r_{\text{discharge}}) . \text{Stop}; \\
\text{Stop} & \triangleq (\text{stop}, r_{\text{discharge}}) . \text{Stop}; \\
\text{Register} & \triangleq (\text{register}, r_{\text{register}}) . \text{Register}; \\
\text{Triage} & \triangleq (\text{triage}, r_{\text{triage}}) . \text{Triage}; \\
\text{Test} & \triangleq (\text{test}, r_{\text{test}}) . \text{Test}; \\
\text{Doctor\_New} & \triangleq (\text{newDoc}, r_{\text{newDoc}}) . \text{Doctor\_New}; \\
\text{Discharge} & \triangleq (\text{discharge}, r_{\text{discharge}}) . \text{Discharge}; \\
\text{Admit} & \triangleq (\text{admit}, r_{\text{admit}}) . \text{Admit}; \\
\text{New\_Patient} & \triangleright_\kappa (\text{Register}||\text{Triage}||\text{Test}||\text{Doctor\_New}||\text{Discharge}||\text{Admit})
\end{align*}
\]

where \( \kappa = \{\text{register, triage, test, newDoc, discharge, admit}\} \)

The initial patient flow model shown in Figure 4.2 can be represented as the code above using PEPA syntax. The patient journey activities in an A&E are defined as a series of co-operations between several components. For example, the following PEPA expression means:

\[
\text{New\_Patient} \triangleq (\text{arriveNew}, r_{\text{arriveNew}}) . \text{New\_Register};
\]

The new patient begins with the action \text{arriveNew} at a predefined rate \( r_{\text{arriveNew}} \) to change its state to \text{New\_Register}. Then the patient flow sequence is transient through the whole system until the \text{Stop} state is reached.

Figure 4.3 illustrates the usefulness of the function called “abstraction view” which shows how all the system components are connected. From this figure, we can observe that the model is connected as it is supposed to be by comparing it to the diagram in Figure 4.2.
4.3.2 CARMA model of the A&E scenario

Using the model abstractions in Figure 4.3, we developed a CARMA model that aims to produce the same behaviour, as shown in the coming code below. As in the PEPA example, the CARMA model of the A&E scenario has several components: Patient, Register, Triage, Doctor, Test, Admit and Discharge. Due to the nature of this study, we did not need to include the location of these components. Because we are focusing on components’ behaviour, the location of these components is implicit. For example, the behaviour block in Patient component expresses how this component interacts with other components in the system. When a shared action is performed, the component state changes to a matching state in the system.

In addition, to provide further explanation for the Patient component, the component behaviour is expressed as:

\[
\text{arPatients} = \text{arrival}[\text{false}]<>\{}\cdot \text{rPatients};
\]

means a broadcast with a guard that is false and that this is a way to model internal actions in CARMA, i.e. an action that does not synchronise with an action of another component. Also, the expression:

\[
\text{rPatients} = \text{reg}[\text{true}]<>\{}\cdot \text{tPatients};
\]

denotes a broadcast with a guard that is true and that this is a way to model external actions in CARMA, i.e. an action that does synchronise with an action of another component, and in this case, it synchronises with Register component, and so on.
Moreover, the Register component in this scenario only performs one action. Similarly, other components in this scenario, such as Triage, Doctor, Test, Admit and Discharge also perform one action only. As such, this model specification clearly does not fully use the expressive power of CARMA. Some of the above-discussed parts of the CARMA model are presented in the following:

```plaintext
component Patients( ) {
    store {}
    behaviour {
        arPatients = arrival*[false]<>{}.rPatients;
        rPatients = reg[true]<>{}.tPatients;
        tPatients = tmove[true]<>{}.dPatients;
        dPatients = dmove[true]<>{}.disPatients + dmove[true]<>{}.tsPatients
            + dmove[true]<>{}.aPatients;
        tsPatients = tsmove[true]<>{}.dPatients;
        aPatients = ad[true]<>{}.Stop;
        disPatients = dis[true]<>{}.Stop;
        Stop = s[true]<>{}.Stop;
    }
    init { arPatients }
}

component Register( ) {
    store {}
    behaviour {
        regist = reg[true](){}.regist;
    }
    init { regist }
}

system AccidentAndEmergency {
    collective {
        new Patients();
        new Register();
        new Triage();
        new Doctor();
        new Test();
        new Admit();
        new Discharge();
    }
}
In the definition of the Patient component using CARMA specification, there is a block named \textit{store}. This block is used to add attributes to the component. Furthermore, there is a difference between how the actions happen between the components by specifying whether it is an input action by using ( ) or an output one by using \textless \textgreater{}. Also, different policies could be considered by varying the conditions associated with an action. These expressive features are not available in other process algebra notations like PEPA.

\subsection*{4.3.3 SPN model of the A&E scenario}

In this study, we use the ORIS tool \cite{55} to specify and analyse the SPN model, given in Figure 4.4. Different features allow us to choose ORIS. For example, ORIS is free to use without any required licence. It offers an easy-to-use graphical interface to create SPN models, and supports several types of analysis, including transient analysis \cite{93}, which is vital in this investigation.

The structure of the SPN model is the same as the model outline given in Figure 4.2. Patients are represented as tokens, and the firing rules for transitions ensure that at most one patient undertakes a specific action at any time. Therefore, modifying the firing rule for the \textit{reg} action would potentially allow us to consider different arrival patterns.
4.3.4 Implementation differences in the models

Conducting this empirical review disclosed many valuable differences. One area where we found significant differences in the model construction process. Regarding the model-creating perspective, although the three formalisms produced similar models, we noted some differences between these formalisms regarding the used tools for creating our case study model. The key differences between each formalism are as follows: the first thing to notice is the PEPA syntax, which is restricted compared to the CARMA syntax and the SPN syntax. As we explored PEPA formalism previously in Chapter 2, we found PEPA offers a limited number of interactions between its components. This limitation is not found in CARMA or SPN formalisms, as presented in Chapter 2, where their components’ interactions can be specified according to the case study.

Another difference is related to the SPN model’s construction, which is easy, as it uses a drag-and-drop feature for creating its models, unlike PEPA and CARMA model construction, which use writing commands to build their models. Also, representing SPN components with a circle and their movement with an arrow is simpler than representing the components of PEPA and CARMA. This simplicity is observed when using PEPA or CARMA where there is a need for typing the name of their components and specified their behaviour in writing, as mentioned in Chapter 2.

Finally, another thing to notice is how the CARMA model developed by describing every component’s behaviour in detail. Each component consists of store and behaviour attributes to specify the behaviour precisely. This expressiveness feature was not available in PEPA or SPN, as mentioned in Chapter 2. According to that, this feature is more practical for the purpose of this thesis where we want to investigate the clinician’s behaviour in TIC situations in detail, as it will be explored in Chapter 5.
4.4 Results

The investigated formalisms offer numerous analysis techniques that researchers can use to understand models better. This study focuses on the transient population level, as all three tools support this analysis. This measure captures how the flow of patients through the system components varies over time and allows us to consider the scalability of the tools and compare the specific values obtained.

The following subsections display the results of the three conducted experiments. They produced several figures consisting of several curves showing the number of patients in any model process at any hour. All the resulting figures have the same scales of units. The "x-axis" represents the number of hours during the day of an A&E. Also, the "y-axis" means the number of patients in each experiment visiting an A&E. However, the ORIS tool results have a different representation of the "y-axis". The "y-axis" in the ORIS tool shows the places’ probability value based on experiment time, and in the case that further details regarding the population are required, hovering over the plotted curves will provide such information.

All things considered, the following section is a discussion of a single-population experiment produced from the three formalisms followed by an investigation of a multiple-population experiment.

4.4.1 Discussion

Figure 4.5 shows the results when we test the formalisms with a single population. The performance of these models is equivalent by showing that all the models reach their final component around the second hour. Despite that, CARMA results present more visible plotting of other components such as Doctor and Triage than other formalisms. Given these points, this similarity between the formalism results gives us confidence in our modelling of this investigation.

The results of the multiple population experiment are presented in Figure 4.6. This experiment tests these formalisms with 50 patients loaded into the produced models. This experiment shows significant differences between these formalisms. Regarding performance, PEPA finished handling the patient population around the 19th hour, unlike CARMA, which handled all the population around the second hour.

4.4.2 Model result differences

The models’ results uncover three main differences between the used formalisms and their tools. The first one is related to the number of analysis types that every tool supports, even though discussing the analysis algorithms and techniques that these formalisms are supporting is out of the scope of this research, as we focused on creating models and
exploring the formalisms’ semantics. However, we found that PEPA and SPN tools support many analysis techniques and algorithms compared to the CARMA tool. The second finding is how the components of PEPA and CARMA tools communicate with each other. We found that the PEPA tool components behave and interact sequentially while the CARMA tool components behave and interact in parallel. The final finding is relevant when the ORIS tool failed to handle such a large population, and it only managed to perform its analysis with five patients, unlike the previous formalisms. This finding may refer to the machine’s limited capabilities in this study or the tool itself.

Figure 4.5: The experiment results of single population plotted from the three notations.
Chapter 4. Reviewing Different Existing Modelling Formalisms

(a) PEPA

(b) CARMA

(c) SPN

Figure 4.6: The experiment results of multiple population plotted from the three notations

4.5 Conclusion

Referring back to the research questions of this thesis in section 1.1, this chapter answers the second question. It presents an empirical review of three analytical approaches: PEPA, CARMA and SPN, and an idealised model of an A&E system is specified and analysed in each formalism. Although the same underlying system with the same parameters is modelled in each formalism, the analysis gives rise to very different results due to the different underlying analysis capabilities of the modelling tools, particularly in multiple population cases.

From our point of view, it is not very easy to determine which formalism is better. As shown in Chapter 2 of this thesis, PEPA is loaded with several analysis capabilities that serve the user’s purpose if they look to analyse their model in more depth and different aspects, such as Markovian or performance analysis. Alternatively, CARMA offers more
expressive syntax, allowing the user’s models to be more comprehensive, whereas SPN provides graphical features of its model, which are helpful if the users do not have enough knowledge of text-based formalisms. We chose the CARMA formalism for this study due to its ability to model any system expressively, as the massive bleeding cases consist of vast and complex interventions that eventually affect health outcomes.

The following chapters will discuss creating models of the massive bleeding cases based on the user logs behaviour using CARMA and discrete simulation strategies.
Chapter 5

An Approach to Modelling a Massive Haemorrhage Case Using CARMA

5.1 Introduction

This chapter presents a stochastic approach to modelling clinician behaviour during massive bleeding cases. These behaviours were derived as logs using the sketch simulation introduced in Chapter 3. As mentioned in the previous chapter, we chose the CARMA modelling formalism when we evaluated different modelling notations.

This chapter is structured as follows: The following section briefly introduces the stochastic approach used to model the investigated context. After that, Section 5.2 begins with a concise description of the complex interventions in relation to massively bleeding patients. A clinician usually performs these interventions in an operating room. We then introduce the CARMA model of such a scenario in Section 5.3. Section 5.4 illustrate the characteristics of the CARMA model. The model results are provided in Section 5.5, followed by a discussion of these results. Finally, Section 5.6 concludes with a summary of the prominent insights of this chapter.

5.1.1 CARMA

In addition to CARMA examples mentioned in Section 2.3 and Subsection 4.3.2, we found another case suitable to be included in CARMA cases. The aim of this chapter is to use CARMA to model a class of medical interventions performed on severely injured patients. Therefore, this chapter is focused on many objectives to achieve; firstly, it tests the CARMA formalism as a suitable technique in such critical domains as health application; secondly, it uses CARMA features by modelling such complex interventions;
finally, it shows the outcomes or benefits resulting from this approach.

### 5.2 The Massive Haemorrhage scenario

In this scenario, we concentrated this investigation on four blood products: PRBC, FFP, Cryo, and Platelets, as mentioned in Chapter 3. Furthermore, the related protocols of this investigation are adapted from Royal London Hospital (RLH) shown in Figure 5.1 and Royal Victoria Infirmary (RVI) presented in Figure 5.2.

Figure 5.1 and Figure 5.2 show the several steps that need to be taken when a major haemorrhage occurs. Also, they show who is responsible and what is their responsibility. In addition, they indicate which lab analysis and reading they should observe. However, they present some differences between them, especially in blood pack contents. For instance, Figure 5.1 points out two blood packs to order: Pack A which consist of 4 units of PRBC and 4 units of FFP, and Pack B which consist of 6 units of PRBC, 6 units of FFP, 2 Cryo, and 1 pool of platelets. Figure 5.2 conversely, indicates three blood packs to order: Pack 1 includes 4 units of PRBC and 4 units of FFP. Pack 2 which consist of 4 units of PRBC, 4 units of FFP, and 2 pools of platelets. Pack 3 consist of 4 units of PRBC, 4 units of FFP, 2 Cryo, and 1 pool of platelets.

The proposed scenario is based on real-life medical cases. These cases have been transformed into a serious sketch simulation. This transformation was initially performed by a European collaborative called Targeted Action for Curing Trauma Induced Coagulopathy (TACTIC). After that, we developed an improved version of this sketch simulation, as discussed in Chapter 3. The aim of these sketch simulation versions is to examine the anaesthetists’ interventions in such cases. Another motivation to create this sketch simulation was to create a sketch simulation of what is happening in an Operating Room, eliminating the difficulties in attending and experimenting with a real patient case in an Operating Room, as mentioned in Chapter 3.

Here, the concern is how formal methods may be used in the medical domain in this critical context. Using the above sketch simulation versions, user logs of the medical interventions were extracted from two experiments conducted with clinical staff at RLH and RVI, as explained in Chapter 3.

We used these logs to develop our model. Therefore, the model accuracy of the produced CARMA model is high because it is based on performed interventions not predicted interventions. In addition, this accuracy is based on what happened in contrast to what is supposed to happen in the protocols. Figure 5.3 shows an example of the produced log.

---

3. [https://www.c4ts.qmul.ac.uk/intrn-projects/tactic](https://www.c4ts.qmul.ac.uk/intrn-projects/tactic)
Figure 5.1: The used massive bleeding protocol in RLH
### NUTH Major Haemorrhage Protocol (MHP) RVI

#### Early Recognition of Major Haemorrhage
- Suspected ongoing haemorrhage
- Systolic BP <90mmHg
- Poor response to initial fluids
- Penetrating Trauma / Positive FAST Scan / Prehospital Alert

#### Call for Senior Help
- Establish Team Leader and Roles
- Escalate via parent team
- Consider need for Anaesthetic or Critical Care input
- Call 29999

#### Assess ABCDE
- Attach monitoring
- High Flow O2
- Large bore IV or IO access, use rapid infuser e.g. Belmont or Level 1 (if available)

#### Take Samples
- Group and Save, FBC, Coag (PT, APTT, Claus Fibriogen), U&E
- Near patient testing - ABC, HaemoCue, ROTEM (if available)

#### Initiate Major Haemorrhage Protocol
- Phone Blood Bank on 29289
- State ‘Activate Major Haemorrhage Protocol’
- Give Patient ID: MRN, Forename, Surname, Date of Birth, Male/Female, Location
- Give a ‘named contact person’ name and number for further communication during the Major Haemorrhage
- Send Porter for Major Haemorrhage Pack 1 immediately
- Use Major Haemorrhage Prescription documents delivered in cool box

#### Early Haemorrhage Control
- **Compressible**
  - Direct pressure/haemostatic dressing
  - Saline fractures including pelvis
  - Apply tourniquet proximal to wound
- **Non Compressible**
  - Consider Interventional Radiology
  - Consider Damage Control Surgery
- **Obstetrics**
  - 4 T’s – Tone, Tissue, Trauma, Thrombin
- **GI Bleed**
  - Consider Drugs – Terlipressin and Antibiotics forvariety (as per Cirrhosis Care Bundle)
  - Early review by Gastro Reg (in hours) or Medical Reg (out of hours)
  - Consider IJ or Surgery
- **Reverse Anticoagulation**
  - Discuss with Haematology Registrar on Call (via switchboard)

#### Cell Salvage
- Consider use in all cases
- Avoid in gross contamination and malignancy
- Consider need for leucocyte filter e.g. Obstetrics
- Don’t rely on cell salvaged blood for resuscitation (slow rate of collection) – re-transfuse when able

#### Resuscitate and Prevent Coagulopathy
- **Give Tranexamic Acid 1g bolus IV**
- **Commence transfusion in ratio of 3RBC:1 FFP**
- **Pack 2 – 4 RBCs, 4 FFP, 2 Platelets**
- **Pack 3 onwards – 8 RBCs, 4 FFP, 3 PTL, 2 Cryo**
- Keep products in cool box after checking, prior to use
- **Give Tranexamic Acid 15mg/kg bolus IV**
- **Commence transfusion in ratio of 5ml/kg RBC:5ml/kg Octoplas**
- After every 15ml/kg RBC and 15ml/kg Octoplas - give 5ml/kg PR and 5ml/kg Cryo
- NB: First MHP pack may contain FFP prior to Octoplas being available

#### Repeat samples (After each MHP pack)
- **Group and Save 2nd sample (unless already done)**, FBC, Coag (PT, APTT, Claus Fibriogen), U&E
- **Near patient testing – ABC, HaemoCue, ROTEM (if available)**

#### Prevent
- **Hyperthermia**
  - Early active patient warming
  - Warmed blood components
- **Acidosis**
  - Measure ABG and lactate
- **Hyperkalaemia**
  - Aim K+ <4.0
  - Give 10 units Actrapid in 50ml 50% Dextrose IV over 30mins, check BM as per NUTH protocol
- **Hypokalaemia**
  - Aim (Ca2+) >1.0
  - Give 10mls 10% CaCl2 IV over 10mins
- **Hypothermia**
  - Early active patient warming
  - Warmed blood components
- **Acidosis**
  - Measure ABG and lactate
- **Hyperkalaemia**
  - Aim K+ <4.0
  - Give 10 units Actrapid in 50ml 50% Dextrose IV over 30mins, check BM as per NUTH protocol
- **Hypokalaemia**
  - Aim (Ca2+) >1.0
  - Give 10mls 10% CaCl2 IV over 10mins
- **Give 0.5mL/kg Actrapid in 5mL/kg 10% Dextrose IV over 1 hour, check BM after 15mins, then every 30 mins**
- **Give 0.2mL/kg 10% CaCl2 IV over 10 mins**

#### Treatment Targets
- **Temp >38°C**
- **pH >7.2**
- **Base Excess < -6**
- **Lactate <2**
- **Hb >100 during haemorrhage, Hb >80 after haemorrhage control**
- **Plts >100**
- **Fib >1.5 (Fib <2.0 for obstetrics)**
- **Ca >3.0**
- **K+ <5.5**

#### Stand-down Major Haemorrhage Protocol when no longer required.
Inform Blood Bank and return any unused blood components to the laboratory immediately.

Figure 5.2: The used massive bleeding protocol in RVI
after using the above sketch simulation versions. This Figure demonstrates the interventions used during each scene of the sketch simulation. More specifically, the top section of Figure 5.3(a) presents the performed interventions and when they were performed in the PreHospital scene. Also, the interventions and their timestamp of resus scene were presented in the middle section of Figure 5.3(a). Lastly, the bottom section is for theatre scene details. Moreover, Figure 5.3(b) illustrates the ordered and used blood products grouped depending on each scene.

The sketch simulation, introduced in Chapter 3, provides extensive activities for an anaesthetist to perform. This thoroughness is essential to understand why an anaesthetist chooses to perform one interaction rather than another and if the time affects their decision. In this investigation, we focus on blood ordering and infusing and how the patient’s vital signs are used in practice to guide this process. Also, the delay or duration of these activities is taken into account. We could summarise the operations of the scenario as follows:

1. The doctor, usually an anaesthetist, uses blood products from the local fridge.
2. If the needed blood products are not available in the local fridge, order more blood products or blood packs from the blood bank. There are two available blood packs: Pack A contains four PRBCs and four FFPs, and Pack B contains four PRBCs, four FFPs, two Cryos, and one Platelet.
3. Based on the type of request and blood products, there is a delay. This delay involves the amount of time taken to arrive and thaw some of the blood product types.
4. Infuse blood products into the patient.
5. Order a specific blood test.
6. Request a blood gas test.
7. Order VHA which is a blood coagulation analysis test called (ROTEM) [95].
8. A collection of different interventions not related to blood management. We only consider these interventions because their execution consumes time and affects vital signs readings.
9. Check the displays for the patient’s vital signs, local fridge contents, and test results.

In addition to the above operations, a critical periodic change is the time factor affecting several values such as vital signs, blood test results and ROTEM values as long as the scene has not ended or its time is over.
Figure 5.3: The performed interventions during the sketch simulation scenes


5.3 The CARMA Model of the Massive Haemorrhage Scenario

The process of developing the CARMA model of this specific situation was done through many steps, detailed in this section. First, we present the characteristics we anticipate from this model. Second, we discuss the method we follow to produce the CARMA model. Lastly, we present the issues related to the CARMA results.

5.3.1 The CARMA model characteristics

The development process of the massive bleeding CARMA model anticipated many characteristics:

1. The environment and location concepts should be insignificant as the clinician executes all the available intervention activities of the medical scene in the same place.

2. The model should be designed to explore specific aspects of the clinician’s behaviour, particularly in this research, which focuses on blood ordering and infusing.

3. Because of the CARMA expressiveness, it should be able to include every performed intervention from the log and limit the level of abstraction that is usually associated with modelling formalism.

4. It should be capable of including other insubstantial activities such as checking the local fridge or reading the blood test results.

5. The CARMA simulator is likely to be able to calculate the needed blood products in the chosen scene based on the medical protocol suggestions and ROTEM algorithms.

5.3.2 The CARMA model’s development method

The construction of the model was based on the approach used in the literature [30, 35, 36]. However, in our model, the location of the components is ignored due to the nature of the investigated domain. With this in mind, the distance between the components is irrelevant here because all the scenario components are typically available in the same operating room. Moreover, we choose to neglect the component locations to generalise the outcome of this research to fit every hospital layout or structure. Despite that, an important attribute expressed here by the CARMA model is the concept of blood reservoirs in the local fridge. This attribute makes CARMA formalism unique and practical in such an environment comparing to as an example PEPA formalism.

There are several components in the model used to describe the scenarios under consideration. These components are:
Chapter 5. An Approach to Modelling a Massive Haemorrhage Case Using CARMA

1. LogXXX component shows the log of the chosen medical interventions resulting from the sketch simulation’s experiment.

2. LocalFridge component represents the contents of the available blood products to use immediately.

3. IrrActions component describes a medical intervention that takes time but whose specific details are not of interest in the model.

4. The ROTEM component illustrates the use of the ROTEM algorithm.

5. LAB component to perform the ordered blood tests.

6. The Display component, which displays blood test results and ROTEM results.

7. The CLOCK and TimeFactor components to perform periodic changes on several values during the simulation time.

The development process of the CARMA model involves many steps. First, we create the component, define its local store, and determine its initial behaviour. After that, we establish the model global store and add the patient’s vital signs, blood test results, and ROTEM values from a predefined patient’s case. Then several functions were created to calculate the ROTEM values after each specific action the sketch simulation’s user performed. After that, we specify the evolution rule after each action executed by the clinician. Following this, we add the system collectively, in other words, we compose the system from its components described above. Finally, we set the appropriate observations of any value in the systems.

There are many challenges in developing such a model. Finding the normal range of vital signs readings in abnormal medical cases was one of them. We overcome this challenge by comparing all the available logs and by referring to the literature to identify what are the expected readings. Another challenge was indicating when the bleeding becomes controlled. This indication was not provided from the sketch simulation nor the available logs. So, after meeting with medical expert, they advised to observe the Haemoglobin (Hb) readings to reach its normal range. One more challenge is concern how to calculate the performed interventions effects to the vital signs readings. This challenge solved by examining the development documentations of the sketch simulation.

After that, we defined a suitable log to include in our model to clarify how the model works. Then we created the sequence of interventions that happened in the log. However, as discussed earlier at the start of this chapter, we only focused on blood ordering and infusing. Therefore, many interventions are irrelevant as study objectives, but they have been included in the model as they take time to performed. Moreover, we consider the concurrency of the model actions. Many patterns display this concurrency as follows: Firstly,
as the sequence of multiple actions execution, ordering a blood product continues to execute another intervention, such as a blood test, without waiting for the blood product’s arrival. Another example is when other components finish performing a requested action, such as a blood test or ROTEM, the display component represents the notifications received when a request is complete regardless of the current intervention execution. Lastly, this scenario contain many periodic interventions, meaning interventions that associated with duration to be executed. the CARMA model performs the periodic change over time using the clock and time factor components. To do this accurately, we divide the periodic actions into two actions; the first is for the time duration, and the other is to execute the time effect on the desired values. Appendix A contains the full CARMA model.

5.3.3 The CARMA model results issues

CARMA uses a standard kinetic Monte-Carlo algorithm to analyse its models, which helps calculate the execution time when the next activity is selected [46]. In addition, CARMA uses the Statistics package of Apache Commons Math4 to perform a statistical analysis of the collected data [46]. In this scenario, we examine the movement of the blood products when ordering from the blood bank and when arriving in the local fridge. The next section presents and discusses the conducted experiments in details.

5.4 Model results & discussion

We monitored how the blood products were infused into the patients and removed from the local fridge. Furthermore, we observed the vital signs changes during an experiment as blood products were infused or time effects were applied. There are three subsections in this section. It starts with presenting the model parameters. Then, we describe the conducts experiments and show their results. Lastly, we discuss the results of these experiments and highlight the findings of such approaches.

5.4.1 The model parameters

The model parameters are an essential aspect of correctly studying the model’s behaviour. As mentioned earlier in Chapter 3, the cases provided by a professional anaesthetist in this scenario are part of a dedicated group project. Therefore, we obtained all the rates from the sketch simulation versions, and it is worth pointing out that the sketch simulation time is ten times faster than the real-time. The time unit in this scenario is seconds; thus, we set the rate value for most model activities to 1 second; however, other activities are associated with a delay. Table 5.1 shows all the duration of actions in the model in detail.

4http://commons.apache.org
Table 5.1: Parameter for the model.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ordering Pack A</td>
<td>5 seconds for PRBCs then 60 seconds for FFPs</td>
</tr>
<tr>
<td>Ordering Pack B</td>
<td>5 seconds for PRBCs then 60 seconds for the rest</td>
</tr>
<tr>
<td>Ordering PRBC</td>
<td>5 seconds for each one PRBC</td>
</tr>
<tr>
<td>Ordering FFP</td>
<td>60 seconds for each one FFP</td>
</tr>
<tr>
<td>Ordering Platelet</td>
<td>60 seconds for each one Platelet</td>
</tr>
<tr>
<td>Ordering Cryo</td>
<td>60 seconds for each one Cryo</td>
</tr>
<tr>
<td>Ordering Blood test</td>
<td>50 seconds for each test</td>
</tr>
<tr>
<td>Ordering Blood gas test</td>
<td>30 seconds for each test</td>
</tr>
<tr>
<td>Ordering ROTEM</td>
<td>57 seconds for each usage</td>
</tr>
<tr>
<td>Time effects</td>
<td>Every 30 seconds</td>
</tr>
<tr>
<td>Other Activities</td>
<td>1 second</td>
</tr>
</tbody>
</table>

5.4.2 The experiments results

As mentioned earlier in this section, we conducted several experiments from the CARMA model. The first one shows how the contents of the local fridge changed after executing some activities. The second experiment illustrates how the vital signs changed according to the execution of some activities during the simulation. CARMA simulation wizard offers a set of conditions to control the experiment, such as simulation time, replications number, and samplings number. To clarify the resulting figures, the X-axis is for the simulation time, and the Y-axis is for the value of the observed variables in the model. Therefore, we set the simulation time to 180 seconds, similar to most of the behavioural log’s duration in the investigated scene.

Ordering and Infusing Blood Products Experiment

The first observation is concerned with blood product ordering and infusing. According to the chosen log used in the model, there are some blood product ordering activities, such as ordering pack A, which, as mentioned earlier, contains four PRBCs and four FFPs. Next, Figure 5.4 shows how the simulation experiment added the requested blood products over time. The graph shows that the duration for adding PRBCs is faster than FFPs, which reflects the durations in Table 5.1. After that, we observe how the blood products are infused into the patients and removed from the local fridge contents, which is illustrated in Figure 5.5. Lastly, Figure 5.6 demonstrates how blood products become available and then removed depending on the sequence of activities brought from the log.
Figure 5.4: The fridge contents are changing over time representing ordering blood products activities. The X-Axis is time and the Y-Axis is fridge contents in packets or units. (PR,F) represents the number of PRBC packets in the fridge and (F,F) represents the number of Fresh Frozen Plasma packets in the fridge during the experiment.

Figure 5.5: The blood products are increasing over time representing infusing blood products activities. The X-Axis is time and the Y-Axis is fridge contents in packets or units. (PRBC) represents the number of PRBC packets infused into the patient and (FFP) represents the number of Fresh Frozen Plasma packets infused into the patient during the experiment.
Chapter 5. An Approach to Modelling a Massive Haemorrhage Case Using CARMA

Figure 5.6: How the whole blood products represented over time depending on the executed activities. The X-Axis is time and the Y-Axis is fridge contents in packets or units. (PR,F) represents the number of PRBC packets in the fridge and (F,F) represents the number of Fresh Frozen Plasma packets in the fridge. Also, (PRBC) represents the number of PRBC packets infused into the patient and (FFP) represents the number of Fresh Frozen Plasma packets infused into the patient during the experiment.

Vital Signs Experiment

This simulation experiment concerned how blood product infusing affects the patient’s vital signs. As mentioned earlier in the CARMA model Section 5.3, CARMA provides the ability to determine which variables are evolving and how that evolution happens. Figure 5.7 provides details of the evolution when modelling the investigated log. The resulting graph shows that this log maintained steady interventions to fix the time effects only. The used interventions unexpectedly seems not aiming to improving the patient’s health. This is a reasonable actions, keep in mind that there is one more scene to heal the patient and this is an emergency case, so the normal range would not be applicable here. In addition, the graph illustrates how blood pressure readings have been significantly affected by the time effects, unlike heart rate readings which have been affected slightly.
Figure 5.7: The patient’s vital signs over time depending on the executed activities. The X-Axis is time and the Y-Axis is the vital signs readings.

5.4.3 Discussion

Based on the results above, we learned several lessons from these experiments. Firstly, they show that CARMA is an applicable technique to model complex interventions in the medical context. The produced model and the results derived from it support such claim. Also, the results provide a way to study, examine and experiment in this critical domain. Secondly, the solely available analysis method, namely stochastic simulation, in CARMA exposes some limitations in examining and investigating its model. Here, we were able to observe how certain variable perform during the model components interactions in a stochastic way. Further analysis would derive more insightful knowledge about the behaviour of these components in such domain. Thirdly, the results show a notation of hybrid systems, namely continuous event system and discrete event system.

The continuous event system is described in fluid approximation [96, 97] which is present regarding how the variables changed during the simulation. This notation seems suitable in this scenario because it involves dealing with fluids such as blood products nature. However, adding blood products to the local fridge is performed in units, which are discrete events therefore, the fluid approximation is unsuitable for this type of intervention, unlike the infusion of blood products, which is a convenient representation of fluid approximation. Last but not least, conducting the second experiment reveals that the log is missing some information necessary to check the result and improve its validity,
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which is done in the next Chapter. An example of missing data from the behavioural log is recording the patient’s vital signs regularly after each intervention.

Apart from the above lessons, the transformation from a chosen log to the CARMA model revealed unexpected situations. These situations occurred in investigating the recorded activities in the logs and the results of the experiments. For example, the chosen log activities of the medical scene are executed within 180 seconds, whereas in the case of the experiment time, the experiment concludes without completing all the activities. Another example of an unexpected situation we noticed when the sketch simulation played, it provides extra information that triggers the user’s choice of intervention properly. This behaviour is not entirely recorded in the log, so adding a display component in the model is justified to capture that behaviour.

5.5 Conclusion

This chapter illustrated how CAS and mainly CARMA formalism could be used to model a system with significant and different interventions interact to achieve specific goals. Furthermore, it provides the answers to the first research question of this thesis, introduced in section 1.1.

The discussed case study and its scenarios contain vast amount of interventions that could be interacted with each other to serve one goal, which is improving patient health. This is the main reason to chose such formalism to capture the interactions behaviour then analyse them in details. Furthermore, the complex interventions in the investigated medical conditions during a critical context are a) ordering and then infusing blood products and b) performing blood tests. Chapter 7 shows the way of using this model to analyse the clinician behaviour, specifically, in estimating the needed blood products. Moreover, and due to the model’s design generality, the resulting model can efficiently be applied to most of the medical interventions according to the used protocol by replacing or adding suitable functions.

The discovered lessons in the discussion section show that this approach was inconclusive in effectively analysing the clinician’s behaviour. As introduced early in the results discussion section, the noticeable hybrid systems observe in this case study played a considerable role in eliminating definitive analysis results. More specifically, the fluid approximation in infusing blood products from the local fridge into the patient affects the analysis results. Therefore, updating the CARMA formalism to cope with this shortcoming is required. However, due to the unavailability of the CARMA source code, we undertake different approaches introduced in the next chapter.

The next chapter lays the development process of a discrete simulation tool using Java and explores Microsoft Excel’s ability to model the massive bleeding scenarios as CARMA
modelling formalism fails to provide helpful insights regarding the behaviour log analysis. These tools will provide the ability to overcome the CARMA analysis tools limitations.
Chapter 6
Simulation and Evaluation of Massive Haemorrhage Cases

6.1 Introduction

This chapter describes the activities introduced to extend the analysis of the CARMA models mentioned in Chapter 5. At the end of the last chapter, we noted that the CARMA model needed further enhancement. However, the CARMA source code was unavailable to be extended. Moreover, the formalisms PEPA and SPN were eliminated earlier due to their limited ability to deal with massive interventions, which is one of the strengths of CARMA. Thus, we proposed two approaches to model the clinician’s behaviour recorded in the logs that resulted from the sketch simulation experiments, introduced in Chapter 3. The first approach is developing a Trace-Driven simulation tool using the Java programming language. The second approach utilises the Excel capabilities and features to model that behaviour numerically.

The structure of this chapter is the following: First, the Java simulation tool is introduced, which covers the objectives of such an approach and the justification to develop this tool, followed by the workflow of the tool, then an example of one of the tool’s outputs. After that, we present the Excel numerical modelling approach alongside its strengths and weaknesses. Next, we present the implementation of the numerical model and present the results of such software. Furthermore, we discuss the potential value of the numerical model in the individual analysis of a chosen log, as well as the collective analysis of a group of chosen logs.
6.2 The Java based Trace-Driven Simulation Tool

As mentioned in the previous chapter, the CARMA model of the massive bleeding cases shows some behaviours which defer from the real world, most importantly, the fluid approximation displayed how the blood products moved or infused from the hospital blood bank to the scene’s local fridge. Here, we present an approach to overcome such limitations by creating a tool that uses the experiment logs or traces and allows for discrete actions as well as continuous ones. Next, we present detailed steps in designing this tool as part of this research project. First, we propose the objectives and usefulness of this approach. After that, we demonstrate the structure of this approach and its related components with their logic. We then explain the tool’s implementation based on the desired objectives and essential components using different Java features, followed by how the produced tool operates perfectly. Lastly, we provided one example of the tool results files.

Several studies [98] and [99] have highlighted and evaluated many tools and applications for simulating a behaviour trace or log. The study conducted by [98] evaluated eight different tools. They focused on which programming language used, features, performance, and supported formalisms. Their objective is to support the modeller decision to chose suitable tool. Moreover, research produced by [99] highlights the importance of process mining and simulation when they utilised together. The author also discusses the relation between process mining and simulation techniques and how they complete each other. Our approach is designed to serve a number of objectives:

- Study the effects of the timing interventions effectively. We reproduced the clinician behaviour recorded in the log of the sketch simulation. This type of reverse engineering is challenging to perform in the sketch simulation due to the sensitive timing that affects the patient’s vital signs and the requested blood test results.

- Fill in the missing data from the sketch simulation logs needed for complete data analysis.

- Study the medical outcomes of a log or behaviour and examine several ways to improve them.

- Check the scenario blood products and find ways to reduce blood product waste.

- Investigate how the decision-making processes are affected by the process’s duration and the clinician’s actions. More specifically, the focus is to evaluate the time sensitivity in these complex scenarios.

- Provide feasible results to compare with other analysis techniques such as Excel numerical modelling.

- Explore the effect of the stochastic behaviour on the created tool results.
6.2.1 The Tool Generic View

Developing a Java programming language tool can be achieved by many strategies. However, we proposed a strategy that is most appropriate to the investigated context, as Figure 6.1 illustrates. Intentionally, we designed the tool to operate in a similar way as the sketch simulation. However, there are some differences implemented to achieve the list of objectives mentioned above. One of the critical differences is to treat the repetitive time effects explicitly, while in the sketch simulation, it is treated implicitly. The following sections present an overview of the tool mechanism and discuss the main components in detail.

![Figure 6.1: The Generic architecture of the proposed tool](image)

The Tool objects

In referring to the two red boxes in left side of Figure 6.1, the tool requires two main objects: behaviour log and profile, which is a predefined scene settings. The behaviour log contains the many interventions performed by a clinician. The chosen scene, referred to as profile, is PreHospital, Resus or Theatre scene-setting, as explained in Chapter 3. We load these two objects into the tool, consisting of many components. These components
range from ordering blood products to ordering blood tests and executing the time effects routinely. The following section highlights these components in detail.

**The Tool components**

The combined components of this tool represent the primary interventions that concern the behaviour analysis in this study, and the actions by the clinician executed using the sketch simulation of the massive bleeding scenarios. One of these components is ordering blood products. As mentioned in Chapter 3, the sketch simulation allows the different types of blood ordering, such as Pack A, Pack B, and individual blood products. An example of the Pack A ordering mechanism in the tool is shown in the Algorithm 1. Other types of blood ordering would follow the same structure of Algorithm 1, however, take into consideration the differences between the different types of blood ordering such as timing and blood types.

**Algorithm 1** The algorithm for ordering PACK A

```plaintext
procedure PACK A

report Initial Timestamp

wait 5 seconds for 4 PRBCs
PRBC ← PRBC + 4

report 4 PRBCs added

report Timestamp

wait 50 seconds for 4 FFPs
FFP ← FFP + 4

report 4 FFPs added

report Finishing Timestamp

end procedure
```

Algorithm 1 summarises the activities of ordering blood products. Firstly, the initial timestamp is recorded in the tool screen and the output files, and then it is waits for 5 seconds. Secondly, the number of PRBC units is increased by four, and a record of that increase is reported with its timestamp in the tool screen and the output files too. Following that, there is a waiting time of 50 seconds for four FFP units to be added. Finally, when the FFP units are updated, a record of that update is created in the tool screen and the output files associated with the finishing timestamp.

Another component of this tool is the ability to simulate ordering different blood tests, as mentioned in Chapter 3, when discussing the different interventions available to the clinician. To be more specific, the clinician could order standard Blood tests, Blood Gas tests, and VHA tests. Hence, because we have different types of blood tests, we present different algorithms as an example of the functionality of this component. The first example is presented in Algorithm 2 which illustrates the steps of ordering standard
Algorithm 2 The algorithm for ordering standard Blood test

procedure STANDARD BLOOD TEST
  report Initial Timestamp
  wait 50 seconds for the tests results
  report Tests results are available
  report Finishing Timestamp
end procedure

blood tests. Moreover, the blood gas test activities are similar to Algorithm 2 so there is no need to be repeated. Another example is the steps of ordering the VHA blood test, which is presented in Algorithm 3.

Algorithm 3 The algorithm for ordering VHA blood test

procedure VHA TEST
  report Initial Timestamp
  wait 5 seconds for calculating FIBRINOGEN need
  report FIBRINOGEN need is available
  report Timestamp
  wait 10 seconds for calculating PLATELETES need
  report PLATELETES need is available
  report Timestamp
  wait 15 seconds for calculating PLASMA need
  report PLASMA need is available
  report Timestamp
  wait 20 seconds for calculating TRANEXAMIC ACID need
  report TRANEXAMIC ACID need is available
  report Timestamp
  report Finishing Timestamp
end procedure

The last component of the tool is the Time effects component which represents the periodic changes during the scenario scene, as explained in Chapter 3. These changes affect many values, such as vital signs readings and blood test results. The procedure of this component is explained in Algorithm 4.

As the Algorithm 4 shows, the time effects procedure updates the vital signs readings and the blood test results every 30 seconds, equivalent to five minutes in the real world, as discussed in Chapter 3 when we presented the sketch simulation timing. In addition, it is essential to mention that this procedure is executed concurrently as soon as the tool run. Furthermore, this concurrent execution does not lock the used variables from being updated as need from other algorithms.

There are other components to make the tool perform correctly and comprehensively. One of the other components is infusing blood products into the patients, which is also
Algorithm 4 The algorithm for Time effects

```
procedure TIME EFFECTS
  while CurrentDuration ≤ EndDuration do
    report Initial Timestamp
    wait 30 seconds
    update Vital Signs readings
    update Blood Tests result
  end while
  report Finishing Timestamp
end procedure
```

responsible for computing the consequences of such interventions on vital signs and blood tests. Another component is the irrelevant actions component, which is accountable for the interventions that are not directly realted to the research objectives. However, these actions are essential, as they were recorded in the sketch simulation logs and they consumed time which affects the investigated readings. Also, because they are performed arbitrarily, we used them to make the tool perform stochastically by adding a random delay in each action equivalent to the resulting logs from the sketch simulation.

The tool outputs

The results files of this tool are customisable based on the investigation objectives; however, for this project objectives, our focus is on three aspects: vital signs records, ordering blood products records, and giving or infusing blood products records. We applied the same patient model that have been used in the sketch simulation, describes in Chapter 3. This model is used to update the readings of the investigated objectives in this tool.

Previously, in Chapter 3, we showed an example of the resulting logs from the sketch simulation, and we observed that these logs are missing some critical information associated with the clinician’s behaviour. Consequentially, we used this procedure to record the missing data. Additionally, due to its execution every 30 seconds sketch simulation time, we repeatedly logged the changes to keep track of the effects during the scenario scene.

6.2.2 The Implementation Process

Implementing such a tool requires advanced knowledge about the capabilities and features provided by the Java programming language. This tool results from many Java ordinary practices such as classes and methods. However, three distinctive characteristics are used in this tool. First, using `Java Threads` to allow the Java program to perform concurrent tasks. Second, `Java Files` to keep records of the Java program’s desired tasks. Third, `Java Random` to enable the program to perform stochastic behaviour equivalently to the clinician behaviour recorded in the logs. A brief background of these techniques is available
The usefulness of Java threads

The created tool, developed as part of this research, uses Java Threads to perform the concurrent behaviour observed in the clinician logs. Generally, many complex interventions that occurred during the investigated scenarios come with a duration or a delay until these interventions are completed; for instance, ordering blood products requires a specific amount of time until they are ready to use. Another example is noticed when ordering blood tests which includes waiting for the results to arrive. During these waiting times, the clinician can perform other interventions when the context scenarios are described, as mentioned in Chapter 3. We used Java threads to execute the interventions associated with a delay in being completed. Also, we used many Java Thread methods to control the sequence execution of the Java program and guide the access of tool variables. Furthermore, Java Threads offers many advantages which is discussed in the appendix of this thesis.

The usefulness of Java files

The presented tool uses the Java files to study the clinician behaviour in more depth. Therefore, this Java attribute allows us to collect more critical data and information, in contrast to what we had in the sketch simulation logs, which are missing much meaningful information regarding the clinician’s behaviour. Furthermore, the usefulness of the Java files attribute is to analyse the individual clinician behaviour; for instance, we used it to create a file which enables us to observe the patient’s vital signs during the scene scenario and create a file to the number of the local fridge blood products throughout all the executed interventions in the scene.

6.2.3 The Tool Workflow

The workflow of the presented tool contains the following steps:

1. Choose a specific clinician behaviour from the available logs.

2. Modify many variables related to the scene scenario.

3. Adjust the scene duration based on the details of chosen log.

4. Determine how many interventions concern the research objectives, such as blood product ordering and blood tests request.

5. Specify the number of irrelevant interventions performed in the log.
6.2.4 The Tool Validity approach

To raise our confidence in our trace-driven simulation tool, we performed a comparison between the tool output file and the behaviour log from the sketch simulation. Figures 6.2 and 6.3 demonstrate this comparison.

Figure 6.2: The infusing blood products process derived from one of the logs

Figure 6.3: The infusing blood products process derived from the trace-driven tool

The Figures 6.2 and 6.3 demonstrated a comparison of the blood products infusing process. It shows the different types of blood products and the infused number of each one at any given time in the scene duration. Despite the fact that there are timing differences between the charts, which is referred to as the designed stochastic notation into the tool,
we notice many similarities trends between these charts, which provide some confidence that the tool performs as it intended to do and in a similar way of the sketch simulation.

6.2.5 The Tool Results

The tool execution has resulted in many files. These files are in Comma Separated Values “CSV” format. We chose this format because it allows the data to be used and manipulated by many spreadsheets and data management systems. Table 6.1 shows an example of the resulting file using the Java simulation tool.

Table 6.1: An example of the tool result file. The “Delta” represents the routine time effects

<table>
<thead>
<tr>
<th>Time</th>
<th>HR</th>
<th>BPH</th>
<th>BPL</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>00:00:30</td>
<td>136.35</td>
<td>107.25</td>
<td>66.30</td>
</tr>
<tr>
<td>40</td>
<td>00:00:40</td>
<td>136.35</td>
<td>107.25</td>
<td>66.30</td>
</tr>
<tr>
<td>42</td>
<td>00:00:42</td>
<td>132.26</td>
<td>113.69</td>
<td>70.28</td>
</tr>
<tr>
<td>60</td>
<td>00:01:00</td>
<td>133.58</td>
<td>110.84</td>
<td>68.52</td>
</tr>
<tr>
<td>60</td>
<td>00:01:00</td>
<td>133.58</td>
<td>110.84</td>
<td>68.52</td>
</tr>
<tr>
<td>90</td>
<td>00:01:30</td>
<td>134.92</td>
<td>108.07</td>
<td>66.81</td>
</tr>
<tr>
<td>120</td>
<td>00:02:00</td>
<td>136.27</td>
<td>105.37</td>
<td>65.14</td>
</tr>
<tr>
<td>150</td>
<td>00:02:30</td>
<td>137.63</td>
<td>102.74</td>
<td>63.51</td>
</tr>
<tr>
<td>162</td>
<td>00:02:42</td>
<td>133.50</td>
<td>108.90</td>
<td>67.32</td>
</tr>
<tr>
<td>162</td>
<td>00:02:42</td>
<td>129.50</td>
<td>115.43</td>
<td>71.36</td>
</tr>
<tr>
<td>162</td>
<td>00:02:42</td>
<td>126.91</td>
<td>120.05</td>
<td>74.21</td>
</tr>
<tr>
<td>162</td>
<td>00:02:42</td>
<td>125.64</td>
<td>122.45</td>
<td>75.70</td>
</tr>
<tr>
<td>162</td>
<td>00:02:42</td>
<td>121.87</td>
<td>129.80</td>
<td>80.24</td>
</tr>
<tr>
<td>162</td>
<td>00:02:42</td>
<td>118.21</td>
<td>137.59</td>
<td>85.05</td>
</tr>
<tr>
<td>162</td>
<td>00:02:42</td>
<td>114.67</td>
<td>145.84</td>
<td>90.16</td>
</tr>
<tr>
<td>180</td>
<td>00:03:00</td>
<td>115.81</td>
<td>142.20</td>
<td>87.90</td>
</tr>
<tr>
<td>192</td>
<td>00:03:12</td>
<td>115.81</td>
<td>142.20</td>
<td>87.90</td>
</tr>
<tr>
<td>192</td>
<td>00:03:12</td>
<td>112.34</td>
<td>150.73</td>
<td>93.18</td>
</tr>
</tbody>
</table>
Table 6.1 displays the output file using the Java simulation tool, consisting of many rows and columns. Each row contains the activity duration from the start of the scene in two formats: the number of seconds and the time format. Also, it has the patient’s vital signs that concern this research: heart rate “HR” and blood pressure “BPH” and “BPL” which refer to systolic and diastolic pressure respectively. In addition, it has the type of intervention that caused this record to be logged. Investigating Table 6.1 shows the recorded activities when each specified action happen. This resulting information were not available completely from the recorded log of the sketch simulation. For example, we can see the effects of infusing 3 units of FFP on the heart rate and blood pressure, and so on.

Referring back to what mentioned earlier in Section 6.2, the Java based trace-driven simulation tool and its resulting files were satisfying all the mentioned objectives. Furthermore, in the next chapter, we used the resulting files in our analysis to produce insights regarding the clinician’s behaviour to prove the usefulness of this tool.

6.3 A Numerical Modelling Approach

A numerical modelling approach was used as an alternative way to examine the clinician behaviours recorded in the resulting logs from using the sketch simulation. Numerical modelling has many advantages, such as its time saving and cost-effective compared to using experiments to evaluate examined objectives, as presented earlier in Chapter 2. Different software supports such an approach, for example, NCSS, MATLAB, and Excel. However, in this research project, we chose Excel software to do the numerical modelling of a clinician’s behaviour in one of the massive bleeding scenarios, due to its strengths coming in the next section. Specifically, as mentioned at the start of this chapter, we used this numerical modelling approach to examine the available logs from a different view in order to derive some insights regarding the observed behaviour. In addition, we used this approach to study the effects of the chosen interventions visually and examine the impacts when we try to improve the behaviour by introducing additional interventions or removing chosen interventions based on the related protocols.

6.3.1 The numerical modelling strengths and weaknesses

Excel is equipped with many features that could be useful in this investigation [100]. First, the Excel interface is considered relatively easy to use and more familiar compared to other software, such as NCSS and MATLAB. Second, it includes calculation power with many functions and formulas helpful in analysing the data and deriving insights. Third, it supports data visualisation techniques by using charts to represent the data expressively and descriptively. Fourth, Excel has its programming language to code almost all the
manual activities to be performed automatically. The next chapter demonstrates how some of the discussed strengths are utilised in this investigation.

However, besides the above pros, Excel exposes some weaknesses. One of these weaknesses comes from a security perspective, mainly when it is used within industrial domains. This weakness, nonetheless, is not a concern in this investigation. Another weakness regarding Excel is considered time-consuming software for learning a specific syntax of a maths formula or performing a routine activity with a massive amount of data.

6.3.2 The numerical modelling implementation and results

Developing the numerical model using Excel involves many activities. Initially, we choose a suitable log from the available logs resulting from the sketch simulation, a complete discussion of the chosen criteria for a suitable log is discussed in the next chapter. Next, we determine which variables to observe in the log based on these research objectives, such as vital signs of the patient. After that, we divide each log based on the scenario scene then we rearrange the logged interventions based on their timestamps in ascending order.

Lastly, we write the effecting formulas related to the performed interventions, such as the effects of infusing specific blood products on the vital signs and blood tests variables.

This approach allows us to examine the recorded log more thoroughly. It enables us to modify the series of interventions and observe the effects of adding or removing intervention. However, this examination in contrast to the Java based trace-driven simulation tool approach where the interventions can only be examine once the program finish of all the interventions in the log. Despite that, one noticeable downside of using the Excel approach is the need to repeat all the above activities to prepare another log to be examined. Figure 6.4 provides an example of Excel’s numerical modelling approach.

Figure 6.4: An example of the Excel Modelling
Figure 6.4 gives an idea of what this approach enables us to examine. The top side of the Figure shows the observed variables related to this investigation: the vital signs readings and the blood test results. Also, the left side displays the performed interventions alongside their effects on the observed variables presented in the rest of the Figure. Furthermore, the presented model using this approach facilitates observing and studying the effects of each intervention on the vital signs readings and the blood results. Moreover, doing so overcomes the missing information from the sketch simulation logs.

Earlier, we presented an approach to develop a numerical model to study the individual clinician behaviour log using Excel software. However, we use Excel additionally to study and analyse a group of clinician behaviour logs using the available information from these logs. As mentioned before in Chapter 3, the logs contain broad information such as the scene score, the given blood products and the potential problems. Therefore, the next chapter proposes how some of this information is applied using Excel to analyse clinician behaviour to reach meaningful insights.

6.4 Conclusion

In conclusion, this chapter presents two approaches to overcome the exposed limitations from the CARMA modelling of the massive bleeding scenario, as demonstrated in the previous chapter. The first approach is a trace-driven simulation developed using Java, while the other approach is numerical analysis developed using Excel. In the first approach, we presented the objectives and motivations to design such tool. Also, we discussed the activities involving developing this tool alongside the used techniques from Java. Furthermore, we provide an example of the resulting files as an evidence to show the usefulness of the tool.

The second approach is presenting spreadsheets as a means to analyse the logs from the sketch simulation. We choose Excel as the spreadsheet software to conduct our investigation. Also, we explore the strengths and weaknesses of Excel to justify our choice. Lastly, we discuss the results of such an approach and show how it effectively examines the sketch simulation logs. Consequently, each approach has benefits in overcoming the CARMA model limitations and extracting extra information needed for a complete clinician behaviour analysis. Moreover, the findings of this chapter address extended answers for the second research question of this thesis, mentioned earlier in Section 1.1.

The next chapter introduces the advantages of using these approaches in details. It is focused on analysing the log data using different techniques. In order to obtain valuable insights, we used various practices of data analysis from the developed models and tools and other analysing techniques.
Chapter 7

Log Analysis and Experimentation

7.1 Introduction

The analysis of logs resulting from health contexts can be used for many purposes, such as increasing the quality of healthcare and reducing healthcare costs, discussed earlier in Chapter 2 Section 2. This research project analyses the resulting logs from the sketch simulation introduced in Chapter 3 to obtain insights from such analysis. We used the several models and tools that were created during the development of this research project, such as:

1. The Oprocess Algebra approach represented in CARMA models, and discussed in Chapter 5;
2. The trace-driven simulation tool designed using Java, introduced in Chapter 6; and
3. The numerical models using Excel, introduced in Chapter 6.

We aim to achieve many objectives during this analysis process. The first objective is to single out the best behaviour from the logs to study them more thoroughly. The best log here is identified based on several criteria that will be discussed later. Another objective is to choose the best logs that were analysed to confirm whether the executed behaviour interventions followed the associated protocols. The last objective is to provide suggestions to (i) manage the related medical resources effectively, (ii) improve the patient’s medical outcomes, and (iii) optimise the treatment process duration. Therefore, we used many log analysis techniques throughout this log analysis process. These techniques are correlation analysis, intervention deviations, lead time reduction, and pattern recognition. There are many reasons for choosing these techniques. First, they allow us to employ the research models and tools that were designed as part of this thesis development. Furthermore, they may empower achieving the earlier objectives in a straightforward manner.
Figure 7.1 illustrates the conducted log analysis process in this chapter. The left side of the figure shows the logs, in grey colour, as the starting point. These logs are then moved into data preparation methods, in orange colour. Next, there are four analysis techniques, in green colour, using the logs after they are prepared. Each technique uses several models or tools, marked in red colour. Then the results of these techniques support achieving the objectives, in a sky blue colour, of this analysis process, presented in the previous page.

This chapter is organised as follows: we introduce the essential data preparation process to make the log analysis possible. After that, it describes each technique mentioned earlier and utilizes the produced models and tools during this thesis development, wherever it is possible. Consequently, we derive several heterogeneous insights from each technique, followed by a discussion of the analysis observations gained from the results of each technique thoroughly.

### 7.2 Data Preparation

The available logs from the sketch simulation were collected in a raw format, as mentioned in Chapter 3. Figure 3.8 shows an example of how the logs were provided. Therefore, there is a need to make the log analysis process capable to work successfully. Moreover,
to allow the log analysis techniques to be used in for efficient way. Two approaches used to prepare our log data. These approaches are log normalisation and artificial ignorance. The following sections demonstrate their usage in more detail:

### 7.2.1 Normalisation of Logs

The term *Normalisation* is typically understood to mean shifting data into an agreeable range in order to reduce data redundancy. However, from a log analytical perspective, it is defined as amending the log texts to make them analysable [101]. A study conducted by Stewart et al. [101] shows a few types of text errors that usually happen in the logs: such as typos, acronyms, and domain-specific terms. Similarly, there have been many medical investigations that have used log normalisation techniques, for example, [102–104].

As part of this research project, the sketch simulation logs were initially provided in raw format that combined all the collected data from the scenario scenes. After that, as a normalisation activity, they have been transformed and classified into multiple Excel sheets for log analysis. Firstly, the interventions are classified depending on their related scene. Secondly, their transformation process was done by copying the exact name of the intervention with its timestamp into the same column. Table 7.1 presents a screenshot of an example of one of the logs after the normalisation process is performed. It shows that the interventions are divided in accordance with the related scene as well as being clearly expressed and have enhanced their readability compared to Figure 3.8.

### 7.2.2 Artificial ignorance

*Artificial ignorance* may be defined as the type of log analysis technique that neglects insignificant activities from being recorded in the system logs [105]. This technique is similar to the case of Prewett and James [106] which they have used among other techniques to filter harmless logs from a security point of view.

The term ‘artificial’ indicates that this technique is usually executed computationally, especially for continuous logging activities and large-scale logs; however, we performed this technique manually due to our small logs’ size. For instance, in Chapter 5, we designed the CARMA model with a component named ‘IrrActions’, which was for the interventions that were not included in this thesis’s objectives. We consider these interventions irrelevant because they do not have a significant impact on our study objectives, as mentioned in Section 5.3. In a similar fashion, we designed the trace-driven simulation tool with a function called ‘irrAction’ for the purposes mentioned earlier, as detailed in Chapter 6. The last example of this process is converting the sketch simulation logs to Excel. This conversion is used to remove the undesirable interventions and focus on the ones that serve these analysis objectives. For this research project, we focus on clinicians’ behaviour in

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specific domains such as blood product management and the execution of blood analysis called ROTEM as it is related for administrating additional blood products based on given algorithms, as presented in Chapter 3. Table 7.2 shows a screenshot of the result of this ignorance process in Excel. It shows the interventions that are related to this research such as blood products. For example, the second line of Table 7.2 illustrates there are two units of PRBC given in PreHospital scene at 8:41:58.

### 7.3 Correlation Analysis

Correlation analysis can be loosely described as the activity which combines information from different resources in order to form a better and broader knowledge [107, 108]. However, correlation analysis in our context may be referred to as log correlation. In our investigation, we used this technique to nominate and then decide which log is the best based on a collection of criteria, as the following sections show.

#### 7.3.1 The best log selection

Deciding which log is best is crucial as it will guide this investigation to deepen understanding of the massive bleeding situation. Using the data provided by the available logs,
some criteria appear to be worth consideration. We propose four criteria: the scene score, blood product wastage, vital signs readings at the end of the scene and the scene duration. We chose these criteria as they are more relevant to some of the research objectives than others. The following is a brief discussion of these criteria combined with the process used to gain the criteria results.

**Blood products wastage criteria**

One of these data is how many blood products the sketch simulation user ordered and how much they used in each scene. Table 7.3 presents the blood product data in the Resus scene from all the logs. To illustrate more, we need a process that uses several data from the available logs, to get beneficial results. This process contains several steps. First, it started by counting the ordered blood products and the used blood products in each behaviour from the available logs. After that, by estimating the difference between these quantities, we have the wastage of any log classified based on each blood product type and the total waste of the whole blood products.

As a result from this process, we produce Table 7.3. It includes the name of each log on the left side. Also, it has the number of units of each ordered blood product and the number of units left unused as wastage. In addition, it shows the total units wasted in

<table>
<thead>
<tr>
<th>Pre-Hospital</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>P 08:41:58</td>
<td>PRBC</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>P 08:42:37</td>
<td>PRBC</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>P 08:42:53</td>
<td>TXA</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>P 08:43:24</td>
<td>TXA</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>RESUS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R 08:44:09</td>
<td>ROTEM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R 08:44:15</td>
<td>Pack A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R 08:45:03</td>
<td>PRBC</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>R 08:45:48</td>
<td>Pack B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R 08:45:55</td>
<td>PRBC</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>R 08:45:57</td>
<td>FFP</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>R 08:46:03</td>
<td>FFP</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>THEATRE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T 08:47:24</td>
<td>ROTEM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T 08:48:22</td>
<td>PRBC</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>T 08:48:26</td>
<td>AlgView</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T 08:48:31</td>
<td>Cryo</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>T 08:48:55</td>
<td>PRBC</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>T 08:49:00</td>
<td>FFP</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>T 08:49:02</td>
<td>Platelets</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>T 08:49:12</td>
<td>ROTEM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T 08:50:07</td>
<td>Pack B</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chapter 7. Log Analysis and Experimentation

Each log. So, to come to the point, Table 7.3 shows four logs have less total wastage of blood units compared to the other logs. These logs are RLH-B31b with total wastage of 7 blood units, RLH-B81b with total wastage of 7 blood units, RVI-aA1a with 16 blood units and RVI-2B1b with total wastage of 15 blood units.

This low wastage measure is likely to be the result of several factors. For instance, it may refer to this clinician’s behaviour following the protocol appropriately. Also, it may indicate that this behaviour is not considering the possibility of ordering and infusing more blood products in the last scene (Theatre). In addition, it may be because this clinician’s behaviour suggests some lack of experience with the used massive bleeding protocol or the clinician was unfamiliar with the sketch simulation usage.
Table 7.3: Blood products wastage of all the logs in Resus scene of scenario 1. (O) stands for Ordered and (W) stands for Waste

<table>
<thead>
<tr>
<th>RESUS Scene</th>
<th>PRBC O</th>
<th>PRBC W</th>
<th>FFP O</th>
<th>FFP W</th>
<th>Cryo O</th>
<th>Cryo W</th>
<th>Platelet O</th>
<th>Platelet W</th>
<th>Total W</th>
</tr>
</thead>
<tbody>
<tr>
<td>RLH-A11a</td>
<td>34</td>
<td>16</td>
<td>34</td>
<td>13</td>
<td>10</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>36</td>
</tr>
<tr>
<td>RLH-A21a</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>16</td>
<td>6</td>
<td>2</td>
<td>5</td>
<td>4</td>
<td>42</td>
</tr>
<tr>
<td>RLH-A31a</td>
<td>16</td>
<td>12</td>
<td>16</td>
<td>13</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>31</td>
</tr>
<tr>
<td>RLH-A41a</td>
<td>32</td>
<td>32</td>
<td>32</td>
<td>32</td>
<td>8</td>
<td>8</td>
<td>4</td>
<td>4</td>
<td>76</td>
</tr>
<tr>
<td>RLH-A51a</td>
<td>34</td>
<td>14</td>
<td>34</td>
<td>15</td>
<td>10</td>
<td>8</td>
<td>5</td>
<td>4</td>
<td>41</td>
</tr>
<tr>
<td>RLH-A61a</td>
<td>28</td>
<td>23</td>
<td>28</td>
<td>23</td>
<td>8</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>55</td>
</tr>
<tr>
<td>RLH-A71a</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>RLH-A81a</td>
<td>30</td>
<td>30</td>
<td>33</td>
<td>33</td>
<td>12</td>
<td>12</td>
<td>9</td>
<td>9</td>
<td>84</td>
</tr>
<tr>
<td>RLH-B11b</td>
<td>22</td>
<td>17</td>
<td>22</td>
<td>16</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>39</td>
</tr>
<tr>
<td>RLH-B21b</td>
<td>22</td>
<td>19</td>
<td>22</td>
<td>20</td>
<td>6</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>46</td>
</tr>
<tr>
<td>RLH-B31b</td>
<td>8</td>
<td>2</td>
<td>8</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>RLH-B41b</td>
<td>16</td>
<td>12</td>
<td>16</td>
<td>16</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>34</td>
</tr>
<tr>
<td>RLH-B51b</td>
<td>16</td>
<td>12</td>
<td>22</td>
<td>18</td>
<td>4</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>32</td>
</tr>
<tr>
<td>RLH-B61b</td>
<td>16</td>
<td>11</td>
<td>16</td>
<td>14</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>31</td>
</tr>
<tr>
<td>RLH-B71b</td>
<td>12</td>
<td>6</td>
<td>12</td>
<td>10</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>21</td>
</tr>
<tr>
<td>RLH-B81b</td>
<td>10</td>
<td>2</td>
<td>10</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>RVI-1A1a</td>
<td>22</td>
<td>7</td>
<td>22</td>
<td>12</td>
<td>6</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>RVI-2A1a</td>
<td>16</td>
<td>14</td>
<td>16</td>
<td>11</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>28</td>
</tr>
<tr>
<td>RVI-3A1a</td>
<td>22</td>
<td>7</td>
<td>22</td>
<td>12</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>26</td>
</tr>
<tr>
<td>RVI-4A1a</td>
<td>16</td>
<td>4</td>
<td>16</td>
<td>4</td>
<td>6</td>
<td>3</td>
<td>6</td>
<td>5</td>
<td>16</td>
</tr>
<tr>
<td>RVI-1B1b</td>
<td>28</td>
<td>22</td>
<td>28</td>
<td>22</td>
<td>8</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td>RVI-2B1b</td>
<td>10</td>
<td>6</td>
<td>10</td>
<td>6</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>15</td>
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<tr>
<td>RVI-3B1b</td>
<td>20</td>
<td>14</td>
<td>20</td>
<td>16</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>36</td>
</tr>
<tr>
<td>RVI-4B1b</td>
<td>16</td>
<td>10</td>
<td>18</td>
<td>12</td>
<td>6</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>26</td>
</tr>
</tbody>
</table>

Scene score criteria

The total score of all the interventions made by the sketch simulation user; can be extracted from the logs data directly. As mentioned in Chapter 4, each intervention has a predefined score provided by an expert based on the sketch simulation scenarios discussed in Section 4.4. Therefore, we used the total score for each scene to assess the sketch simulation user’s behaviour. Thus, this criterion determines which sequence of interventions the clinician performs in an appropriately timed way.

Table 7.4 provides the total score of the Resus scene in Scenario 1 of the sketch sim-
ulation from the available logs. As can be seen from the results, many logs score high such as log RLH-A11a and log RLH-A51a. However, some logs are misleading because a wrong intervention is associated with substantial negative scores from executing catastrophic interventions during the sketch simulation scene. An example of this calamitous intervention is when performing a clamshell thoracotomy intervention during the RESUS scene of Scenario B. Such an intervention will lead to terminating the scene and a high negative score.

Table 7.4: The total Resus scene scores of all the logs of the first scenario.

<table>
<thead>
<tr>
<th>RESUS-Scene</th>
<th>Score</th>
<th>RESUS-Scene</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>RLH - A11a</td>
<td>100</td>
<td>RLH - B11b</td>
<td>57</td>
</tr>
<tr>
<td>RLH - A21a</td>
<td>-937</td>
<td>RLH - B21b</td>
<td>76</td>
</tr>
<tr>
<td>RLH - A31a</td>
<td>38</td>
<td>RLH - B31b</td>
<td>-964</td>
</tr>
<tr>
<td>RLH - A41a</td>
<td>-1010</td>
<td>RLH - B41b</td>
<td>-14</td>
</tr>
<tr>
<td>RLH - A51a</td>
<td>100</td>
<td>RLH - B51b</td>
<td>36</td>
</tr>
<tr>
<td>RLH - A61a</td>
<td>44</td>
<td>RLH - B61b</td>
<td>12</td>
</tr>
<tr>
<td>RLH - A71a</td>
<td>-992</td>
<td>RLH - B71b</td>
<td>55</td>
</tr>
<tr>
<td>RLH - A81a</td>
<td>7</td>
<td>RLH - B81b</td>
<td>20</td>
</tr>
<tr>
<td>RVI - 1A1a</td>
<td>-1911</td>
<td>RVI - 1B1b</td>
<td>35</td>
</tr>
<tr>
<td>RVI - 2A1a</td>
<td>-910</td>
<td>RVI - 2B1b</td>
<td>4</td>
</tr>
<tr>
<td>RVI - 3A1a</td>
<td>79</td>
<td>RVI - 3B1b</td>
<td>10</td>
</tr>
<tr>
<td>RVI - 4A1a</td>
<td>46</td>
<td>RVI - 4B1b</td>
<td>27</td>
</tr>
</tbody>
</table>

Vital signs reading criteria

The patient’s vital signs are used as indicators to determine whether a clinician’s behaviour is performed acceptably. Many vital signs values refer to the medical situation of a patient [6]. However, this game focuses on only two vital signs values: Heart rate (HR) and Blood Pressure (BP). The focus on these two vital signs is important because they are indicative when infusing any blood product type, and they are updated repeatedly during the scene every 30 seconds. Nevertheless, an ideal value of the vital signs always ranges between two values based on the patient’s personal information such as age and gender. In this game, the first provided scenario ideal readings of the vital signs are presented in Table 7.5.

The provided scenario includes initial readings of the related vital signs when each scene starts. For example, in the Resus scene of the first scenario, vital signs readings are HR=135 and BP=110/68. The result of this criterion is based on the scenario details available in Table 7.6. According to the vital signs readings at the end of each scene, no single log achieves ideal readings in all the related vital signs because of the critical situation in this scenario. However, some logs performed well and came close to the ideal
Table 7.5: The ideal reading of vital signs in adults. Developed from [6].

<table>
<thead>
<tr>
<th></th>
<th>Temperature</th>
<th>Heart rate</th>
<th>Pulse</th>
<th>Blood pressure</th>
<th>Respiratory rate</th>
<th>Oxygen saturation</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>37°C</td>
<td>60-99 beats per minute</td>
<td>60-99 beats per minute</td>
<td>120/80mmHg</td>
<td>12-16 breaths per minute</td>
<td>95-100%</td>
<td>7.3-7.5</td>
</tr>
</tbody>
</table>

Reading by the end of the Resus scene, for example, RLH-B81b and RVI-3B1b. It is important to note that the vital signs reading were not available in the logs data. Instead, they are calculated by adopting a reverse engineering technique using the Java-based simulation tool created in this research, discussed in Chapter 6.

Table 7.6: The vital signs reading by the end of the Resus scene of the first scenario.

<table>
<thead>
<tr>
<th>RESUS Scene</th>
<th>End Reading</th>
<th>RESUS Scene</th>
<th>End Reading</th>
</tr>
</thead>
<tbody>
<tr>
<td>RLH - A11a</td>
<td>93.9</td>
<td>211.2</td>
<td>130.6</td>
</tr>
<tr>
<td>RLH - A21a</td>
<td>133.5</td>
<td>107.4</td>
<td>66.4</td>
</tr>
<tr>
<td>RLH - A31a</td>
<td>130.9</td>
<td>112.9</td>
<td>69.8</td>
</tr>
<tr>
<td>RLH - A41a</td>
<td>140</td>
<td>99</td>
<td>61</td>
</tr>
<tr>
<td>RLH - A51a</td>
<td>102.8</td>
<td>172.9</td>
<td>106.9</td>
</tr>
<tr>
<td>RLH - A61a</td>
<td>127</td>
<td>119.2</td>
<td>73.7</td>
</tr>
<tr>
<td>RLH - A71a</td>
<td>137.7</td>
<td>102.9</td>
<td>63.6</td>
</tr>
<tr>
<td>RLH - A81a</td>
<td>139</td>
<td>102</td>
<td>63</td>
</tr>
<tr>
<td>RVI - 1A1a</td>
<td>109</td>
<td>156</td>
<td>96.5</td>
</tr>
<tr>
<td>RVI - 2A1a</td>
<td>137.6</td>
<td>99</td>
<td>61.2</td>
</tr>
<tr>
<td>RVI - 3A1a</td>
<td>118.3</td>
<td>131.7</td>
<td>81.4</td>
</tr>
<tr>
<td>RVI - 4A1a</td>
<td>109.2</td>
<td>160.4</td>
<td>99.2</td>
</tr>
</tbody>
</table>

Scene duration

The scene duration is used to indicate the engagement level and involvement with the sketch simulation reality. Although this information is not included in the log directly, it is derived using the time of the first and last interventions made for each scene. Then we estimate the duration of each scene based on the available information on the interventions. Despite that, we acknowledge that these results would not be accurate and reflect the scene duration of each log precisely. This inaccuracy is due to the fact that there are no data
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for the start and end time of each scene in the available logs. Table 7.7 offers the Resus scene duration of each log.

Table 7.7: The Resus scene duration of the first scenario.

<table>
<thead>
<tr>
<th>RESUS Scene</th>
<th>Start Time</th>
<th>End Time</th>
<th>Duration</th>
<th>RESUS Scene</th>
<th>Start Time</th>
<th>End Time</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>RLH-A21a</td>
<td>11:54:12</td>
<td>11:58:12</td>
<td>00:04:00</td>
<td>RLH-B21b</td>
<td>08:37:25</td>
<td>08:42:20</td>
<td>00:04:55</td>
</tr>
<tr>
<td>RLH-A31a</td>
<td>15:22:17</td>
<td>15:25:22</td>
<td>00:03:05</td>
<td>RLH-B31b</td>
<td>10:03:11</td>
<td>10:08:55</td>
<td>00:05:44</td>
</tr>
<tr>
<td>RLH-A41a</td>
<td>11:31:15</td>
<td>11:33:31</td>
<td>00:02:16</td>
<td>RLH-B41b</td>
<td>15:19:40</td>
<td>15:20:44</td>
<td>00:01:04</td>
</tr>
<tr>
<td>RLH-A61a</td>
<td>08:27:42</td>
<td>08:31:22</td>
<td>00:03:40</td>
<td>RLH-B61b</td>
<td>15:14:40</td>
<td>15:16:33</td>
<td>00:01:53</td>
</tr>
<tr>
<td>RLH-A81a</td>
<td>08:21:45</td>
<td>08:23:22</td>
<td>00:01:37</td>
<td>RLH-B81b</td>
<td>09:58:03</td>
<td>10:05:08</td>
<td>00:07:05</td>
</tr>
<tr>
<td>RVI-1A1a</td>
<td>09:41:52</td>
<td>09:48:12</td>
<td>00:06:20</td>
<td>RVI-1B1b</td>
<td>09:06:07</td>
<td>09:08:56</td>
<td>00:02:49</td>
</tr>
<tr>
<td>RVI-2A1a</td>
<td>09:48:53</td>
<td>09:55:05</td>
<td>00:06:12</td>
<td>RVI-2B1b</td>
<td>09:33:00</td>
<td>09:35:27</td>
<td>00:02:27</td>
</tr>
<tr>
<td>RVI-4A1a</td>
<td>08:37:56</td>
<td>08:41:41</td>
<td>00:03:45</td>
<td>RVI-4B1b</td>
<td>09:50:19</td>
<td>09:54:31</td>
<td>00:04:12</td>
</tr>
</tbody>
</table>

The best log decision

In summary, we present four different criteria to filter the available 24 logs. This process determines which log is best to improve the clinician’s behaviour in the massive bleeding context. According to the indicators mentioned above, six logs shown as better than others. The best logs are RLH-A61a, RLH-B11b, RLH-B21b, RLH-B51b, RLH-B71b and RLH-B81b. Tables 7.3, 7.4, 7.6 and 7.7 show clear evidence that these six logs were superior compared to the other logs with respect to the four identified criteria. Nonetheless, out of all these best logs, the log RLH-B81b outperformed the other logs, particularly in the blood product wastage criterion, which was regarded as one of the research objectives.

7.4 Deviation Analysis

The term ‘Deviation Analysis’ has come to be used to refer to a study of how far the executed interventions differ from the suggested protocols [109]. In this analysis, we studied how the log interventions and their medical outcomes differ from the anaesthetist recommendations to the ideal scenario outcomes.

This type of analysis is conventionally similar to Conformance Checking, or Conformance Testing [110]. In addition, these types of analysis are verified in many cases, especially in the healthcare context, such as [111], and [112].
7.4.1 Patient’s Medical Outcomes Deviations

As mentioned in Section 3.4, the massive bleeding cases were provided by an expert anaesthetist based on actual health cases. Furthermore, the anaesthetist also provided the ideal medical readings of the patient’s vital signs and blood test results at the end of the scene as to what they should be in similar cases. Figure 7.2 shows the fragment of the available logs deviates from the recommended patient medical status. We conduct this technique to provide a piece of evidence that this technique could be applied in this study using the log data. Furthermore, this figure was produced using a numerical model designed by Excel, discussed earlier in Chapter 6.

![Figure 7.2: The scenario ideal outcomes are compared to different logs. The X-Axis is the investigated vital signs and blood tests and the Y-Axis is the values of these notations at the end of each clinician’s behaviour.](image)

A closer inspection of Figure 7.2 shows the ideal numbers of the presented medical case conditions represented in blue colour in this Figure. Moreover, we evaluate the medical values status of the ideal readings against the nominated best behaviour logs. The horizontal axis represents the different medical indications, while the vertical axis is for the value of these indications. Also, each colour’s different points state each medical indicator’s results within the examined logs by the end of the scene. What can be clearly seen in this Figure 7.2 is the general similarities of $Ph$, $Lact$, $Hb$, $INR$, and $Fibrinogen$ readings. These similarities may refer to the slight impact of the used interventions on these readings. Many differences, by contrast, between the ideal readings and the logs readings are illustrated by Figure 7.2. These differences could mainly indicate the different settings between real-life cases and the sketch simulation environment.
7.5 Pattern Recognition

Pattern recognition can be loosely described as identifying trends in a large number of things or events \[113\]. It involves many tasks, such as (i) classifying, appending a trend to a predefined group or class, and (ii) clustering, categorising a trend to a new class or group. Additionally, it is an analysis that covers most types of data, whether they are images, texts, or audio. Specifically, in this thesis, we studied part of the available logs in order to find trends in clinician behaviour. The investigation results are shown in Figure 7.3.

![The Point of Ordering and Infusing Blood Products](image)

Figure 7.3: During the RESUS scene, the behaviour pattern from the logs of B group. The X-Axis is the examined clinicians’ behaviour and the Y-Axis is the duration from the scene start.

Figure 7.3 presents an overview of how the available logs trend is being captured. In order to increase the correctness and consistency of our findings, we focused our examination on the B group of the RLH experiment. To make a fair comparison we used only one group of the logs because different groups used different medical protocols or performed different medical scenarios in the sketch simulation.

The vertical axis of Figure 7.3 is for the scene time, and the horizontal axis is designated for group B of RLH logs. What is interesting about the data trends in this figure is that 75% of the logs displayed the same sequence of activities. These activities are started by ordering blood tests, then ordering blood products, infusing PRBC blood products, and finally infusing other blood products. This pattern is indeed in agreement with the medical protocol’s suggestions to start the treatment process with a blood test and then ordering blood products as required. Conversely, when the behaviour has not been following the
protocol suggestions, it might have been caused by the need to control the bleeding, which is also one of the protocol suggestions. However, in this virtual environment, the evidence to confirm that the massive bleeding is controlled was not available. Another reason for not following the same activity pattern may refer to the presentation and the ordering of the interventions in the sketch simulation design.

The finding of this analysis has shown, conclusively, that they are compatible with other studies’ results that used pattern recognition techniques in the medical context. In particular, fine examples of this type of analysis are available in [114] and [115].

7.6 Lead Time Reduction

The general use of the term ‘Lead Time Reduction’ is sometimes equated with the ability to eliminate the inessential tasks, costs and waiting times to improve the productivity of behaviour [116]. Therefore, in this thesis, this analysis aimed to 1) improve the clinician behaviour by reducing blood wastage as a result of estimating the required blood products, and 2) improve the elected best clinician behaviour by the patient’s medical condition measured by the vital signs readings and the blood test results.

7.6.1 Estimating the required blood products

Several strategies are used to determine how many blood products are needed before the scene begins. This allows for using needed blood units immediately to reduce the delay of waiting for the blood product packs to arrive in the local fridge.

Using the CARMA model

The CARMA model, discussed in Chapter 5, provides a way to simulate the effects of each intervention based on an assumption about rates derived from the game. In this research, the focus is on the blood management interventions performed in the game. Parts of the blood management interventions are the four blood products related to this scenario, which affect the patient’s vital signs and blood test results. The ROTEM algorithm indicates the needed number of blood products from each type. However, PRBC is typically associated with whether the bleed is controlled or not. So, in this digital environment or setting, it is not possible to observe the stoppage of bleeding. For that reason, this approach will focus on the remaining three blood products (FFP, Cryo and Platelet). It is worth mentioning that the most recent sketch simulation version includes updated messages and feedback from the surgeon about the patient’s condition, but this was not in the version used to collect the behavioural data.

We configured the CARMA model, discussed in Chapter 5, to execute all the activities related to blood products in every single time unit. However, CARMA performs only
the activity that satisfies a set of conditions based on the ROTEM algorithm, blood tests and the patient’s vital signs. By doing so, the CARMA model allows measuring the used blood products to achieve predefined medical targets. Figure 7.4 reveals the model results. These results show that for this scene would need at least 8 units of CRYO, 2 units of FFP and 3 units of Platelets. These estimations are calculated based on the scene vital signs readings at the beginning and the scene duration.

![Figure 7.4: CARMA model results of how much blood products are needed. The X-Axis is time and the Y-Axis is the number of used blood products.](image)

**Using the sketch simulation logs with statistics**

The sketch simulation logs and the resulting Excel files provide records of the user interventions. Focusing on blood management activities, we are concerned about ordering blood products from the blood bank and infusing/giving the available blood products from the local fridge. There are different experiment settings noticed from the sketch simulation logs. These experiments are conducted in two hospitals (RLH and RVI) within two groups of anaesthetists (A and B). Table 7.8 shows how many blood products were ordered and used in each log of scenario one within the RESUS scene. In the bottom part of the table, we calculate the Mode, Mean, Standard Deviation (SD), and Confidence Interval (CI) of the ordered and used blood products. Using this technique could show an indication of how much is needed of each type of blood product if similar medical cases arrive at the hospital.
Table 7.8: The number of blood units ordered (O) and used (U) in Scenario 1 from all the available logs as well as the statistical results of Mode, Mean, Standard Deviation (SD), and Confidence Interval (CI).

<table>
<thead>
<tr>
<th>RESUS - Scenario 1</th>
<th>PRBC O</th>
<th>PRBC U</th>
<th>FFP O</th>
<th>FFP U</th>
<th>Cryo O</th>
<th>Cryo U</th>
<th>Platelet O</th>
<th>Platelet U</th>
<th>TXA</th>
</tr>
</thead>
<tbody>
<tr>
<td>RLH-A1a</td>
<td>34</td>
<td>18</td>
<td>34</td>
<td>21</td>
<td>10</td>
<td>7</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>RLH-A2a</td>
<td>20</td>
<td>0</td>
<td>20</td>
<td>4</td>
<td>6</td>
<td>4</td>
<td>5</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>RLH-A3a</td>
<td>16</td>
<td>4</td>
<td>16</td>
<td>3</td>
<td>6</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RLH-A4a</td>
<td>32</td>
<td>0</td>
<td>32</td>
<td>0</td>
<td>8</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RLH-A5a</td>
<td>34</td>
<td>20</td>
<td>34</td>
<td>19</td>
<td>10</td>
<td>2</td>
<td>5</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>RLH-A6a</td>
<td>28</td>
<td>5</td>
<td>28</td>
<td>5</td>
<td>8</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>RLH-A7a</td>
<td>10</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>RLH-A8a</td>
<td>30</td>
<td>0</td>
<td>33</td>
<td>0</td>
<td>12</td>
<td>0</td>
<td>9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RLH-B11b</td>
<td>22</td>
<td>5</td>
<td>22</td>
<td>6</td>
<td>6</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>RLH-B21b</td>
<td>22</td>
<td>3</td>
<td>22</td>
<td>2</td>
<td>6</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>RLH-B31b</td>
<td>8</td>
<td>6</td>
<td>8</td>
<td>6</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RLH-B41b</td>
<td>16</td>
<td>4</td>
<td>16</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RLH-B51b</td>
<td>16</td>
<td>4</td>
<td>22</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RLH-B61b</td>
<td>16</td>
<td>5</td>
<td>16</td>
<td>2</td>
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<td>2</td>
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<tr>
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<td>12</td>
<td>6</td>
<td>12</td>
<td>2</td>
<td>6</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>RLH-B81b</td>
<td>10</td>
<td>8</td>
<td>10</td>
<td>8</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RVI-1A1a</td>
<td>22</td>
<td>15</td>
<td>22</td>
<td>10</td>
<td>6</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>RVI-2A1a</td>
<td>16</td>
<td>2</td>
<td>16</td>
<td>5</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>RVI-3A1a</td>
<td>22</td>
<td>15</td>
<td>22</td>
<td>10</td>
<td>6</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>RVI-4A1a</td>
<td>16</td>
<td>12</td>
<td>16</td>
<td>12</td>
<td>6</td>
<td>3</td>
<td>6</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>RVI-1B1b</td>
<td>28</td>
<td>6</td>
<td>28</td>
<td>6</td>
<td>8</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>RVI-2B1b</td>
<td>10</td>
<td>4</td>
<td>10</td>
<td>4</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RVI-3B1b</td>
<td>20</td>
<td>6</td>
<td>20</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>RVI-4B1b</td>
<td>16</td>
<td>6</td>
<td>18</td>
<td>6</td>
<td>6</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>MODE</td>
<td>16.0000</td>
<td>6.0000</td>
<td>16.0000</td>
<td>4.0000</td>
<td>6.0000</td>
<td>2.0000</td>
<td>2.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>MEAN</td>
<td>19.8333</td>
<td>6.4167</td>
<td>20.2917</td>
<td>5.7917</td>
<td>5.7917</td>
<td>2.1667</td>
<td>3.2500</td>
<td>0.6667</td>
<td>0.6250</td>
</tr>
<tr>
<td>SD</td>
<td>7.6358</td>
<td>5.4994</td>
<td>7.7539</td>
<td>5.3384</td>
<td>2.5492</td>
<td>1.9076</td>
<td>1.8085</td>
<td>0.6872</td>
<td>0.6960</td>
</tr>
<tr>
<td>CI</td>
<td>3.0549</td>
<td>2.2002</td>
<td>3.1022</td>
<td>2.1358</td>
<td>1.0199</td>
<td>0.7632</td>
<td>0.7236</td>
<td>0.2749</td>
<td>0.2784</td>
</tr>
</tbody>
</table>

Using the Java tool simulation

In this section, we performed our investigation using two elements, the massive bleeding protocols and the most affected blood test item in each transfused blood product. Consequently, the target values are established from this examination in Table 7.9.

Table 7.9: The targets values related to each blood product

<table>
<thead>
<tr>
<th>Blood</th>
<th>Test</th>
<th>Target value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRBC</td>
<td>Hb</td>
<td>8 and more</td>
</tr>
<tr>
<td>FFP</td>
<td>INR</td>
<td>1.2 and less</td>
</tr>
<tr>
<td>Cryo</td>
<td>Fibrinogen</td>
<td>1.5 and more</td>
</tr>
<tr>
<td>Platelet</td>
<td>Platelet’s count</td>
<td>100 and more</td>
</tr>
</tbody>
</table>
For this reason, we made several modifications to the Java-based trace-driven simulation tool, presented in Chapter 6. These adjustments include a loop that will iterate similarly to the scene duration and the delta effects of the scene. Another change is to include the ROTEM in the loop alongside the blood test functions. The output of the simulation is the following:

Given PRBC = 6  
Given FFP = 15  
Given Cryo = 4  
Given Platelet = 6  
Given TXA = 3

Let us elaborate further on these results. They show how much each blood unit is needed based on the values of Table 7.9. For example, to achieve a 100 platelet count, the patient needs 6 units of Platelets. As mentioned above, the needed results were based on examining the medical protocol, presented in Chapter 5, and following the anaesthetist’s recommendations regarding the vital signs readings at the end of each scene.

7.6.2 Improving the best log

After identifying the best log from the available logs, the best log investigation is started. The aim of this technique is to improve the patient’s medical outcomes by following the medical protocol instructions. Therefore, we focused on improving the best log by studying it in three different aspects:

- Detect any opportunity to perform any suitable intervention, based on the related medical protocols.
- Identify any prospect to order blood packs or infuse blood products at an earlier point in time.
- Recognise any triggers to infuse a specific blood product.

From the sketch simulation design and context, the time effect will occur every 30 seconds of the sketch simulation time. It will increase the patient’s heart rate and lower blood pressure while modifying the blood test results. Furthermore, each blood product has a specific impact on the patient’s vital signs and blood test results. This log improvement approach uses the Excel model, presented in Chapter 6, to demonstrate the effect of each intervention, such as time and blood infusing. Adapting this approach is helpful to overcome some of the missing data in the available logs, for example, vital signs readings and blood test results. In addition, this approach allows us to observe the results of each change in the series of log interventions.
Approach finding & discussion

Studying the best log, discussed earlier in Section 7.3, reveals several findings, as shown in Table 7.10. This Table was created using the approach presented earlier in Chapter 6. The first finding from Table 7.10 is observed when investigating the sequence of the log interventions that indicate there were deviations from the massive haemorrhage protocol of RLH. For instance, there is a difference in ordering blood tests frequently as the blood test results were missing. Another difference is infusing different blood products such as Platelets, and Cryo was not performed. Also, the last difference is a lower number of ROTEM tests performed than the protocol instructed. However, these insufficient ROTEM interventions are justified because this log was from the B group, which did not have the ROTEM tool integrated into the sketch simulation, and they had to do the ROTEM calculation as they do in reality. The second finding of studying the chosen log is noted by focusing on the log timestamps, which show long waiting periods or gaps between the user’s interventions.

As mentioned before, the following improvement approaches are guided by several aspects. And most importantly, we considered the blood test results to trigger the needed blood products. Therefore, we suggest several approaches to improve the best log from the above examination findings and discussions. Adding appropriate interventions to the log is one of the log improvement approaches as well as removing the time gaps from the log. In the same way, another approach to improving the log is combining these two approaches. The discussion of these approaches is following:
Table 7.10: The best user behaviour investigation. (I) = Infused, (O) = Ordered, (P) = Platelets Count, and (F) = Fibrinogen.

<table>
<thead>
<tr>
<th>Interventions</th>
<th>I</th>
<th>O</th>
<th>Time</th>
<th>Ph 6.6</th>
<th>BE -26</th>
<th>Lact 20</th>
<th>Hb 11.1</th>
<th>P 68</th>
<th>INR 22</th>
<th>aPTT 64</th>
<th>F 0.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual in-line stabilisation</td>
<td></td>
<td></td>
<td>09:58:03</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remove Scoop stretcher</td>
<td></td>
<td></td>
<td>09:58:06</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Face mask oxygen</td>
<td></td>
<td></td>
<td>09:58:12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rapid sequence intubation</td>
<td></td>
<td></td>
<td>09:58:25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open thoracostomy</td>
<td></td>
<td></td>
<td>09:58:40</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Intercostal drain</td>
<td></td>
<td></td>
<td>09:58:44</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Venous access - central</td>
<td></td>
<td></td>
<td>09:58:52</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Perform arterial blood gas</td>
<td></td>
<td></td>
<td>09:59:02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time Effect - DELTA</td>
<td></td>
<td></td>
<td>09:59:03</td>
<td>6.587</td>
<td>-25.741</td>
<td>20.808</td>
<td>10.018</td>
<td>66.000</td>
<td>2.428</td>
<td>66.000</td>
<td>0.400</td>
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<tr>
<td>Rapid infusion device</td>
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<td></td>
<td>09:59:03</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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Add suitable interventions to the log

The investigation in Table 7.10 shows that there is a need to infuse Platelets as the Platelets count at the end of the Resus scene was 54 per litre while it should be at least 100 per litre, illustrated at the bottom of Table 7.10 in the column named P. Also, it shows a need to infuse more Cryo as Fibrinogen was at the end of the Resus scene 0.607 g/l while it should be at least 1.5 g/l, illustrated at the bottom of Table 7.10 in the column named F.

In contrast, Table 7.10 shows infusing more PRBC is not needed as Hb was 11.5 grams per deciliter which is good as the critical line is 8 grams per deciliter. Similarly, infusing more FFP was not needed as the INR ratio was 2.02 at the end of the Resus scene, which is better than the critical reading of 1.2.

Therefore, there is a need to add suitable interventions. These interventions are presented in Table 7.11. This table shows ordering more blood tests interventions are performed, following the medical protocol suggestions. Likewise, to achieve blood test targets that are recommended by the medical protocol, more blood products are infused. These improvements were positioned carefully for several reasons. First, there was a gap to perform these interventions such as blood tests. In addition, they would require delay due to the needed blood products were not ordered and therefore they would not be available to be executed. Specifically, to make the suggested interventions obvious in Table 7.11, we have added them without timestamps associated with them.

Removing the time gaps from the log

Log B81b reveals repeated periods of non-action behaviour. Therefore, analysing this log without these gaps is valuable due to many changes. These changes are related mainly to the vital signs readings and blood test results which are associated with the scene duration. In addition, long scene duration is linked with more time effect events compared to short scene duration.

This technique starts by removing the gaps or the non-action periods, which will result in shorter scene duration and consequently will result in fewer time effect events. After that, the patient readings were estimated with a short time duration using Excel. Table 7.12 shows the result of this technique.

Combine the above two techniques

Combining the previous two techniques would create a new log using the optimal knowledge obtained from the used protocol, the studied context, and the details of the provided scenario. Therefore, the modified interventions of the improved log would not be similar to the behaviour of the original log. To be more specific, we mean by improving the log is making as mush as few changes to increase the patient medical outcomes; however, this
Table 7.11: The best log improved using add interventions technique. (I) = Infused, (O) = Ordered, (P) = Platelets Count, and (F) = Fibrinogen.

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technique would not comply with such intention.

Finally, yet importantly, improving the best log is a case of a trade-off between changing the user behaviour log entirely to reach the best available outcomes or keeping a minimum of changes to the original behaviour and decreasing the advantages from such improvements.

Table 7.12: The best log improved using the remove gaps technique. (I) = Infused, (O) = Ordered, (P) = Platelets Count, and (F) = Fibrinogen.

<table>
<thead>
<tr>
<th>BS1b - Resus</th>
<th>Blood Tests</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Interventions</td>
<td>I</td>
<td>O</td>
<td>Time</td>
<td>Ph</td>
<td>BE</td>
<td>Lact</td>
<td>Hb</td>
<td>P</td>
<td>INR</td>
</tr>
<tr>
<td>Manual in-line stabilisation</td>
<td>09:58:03</td>
<td></td>
<td></td>
<td>6.6</td>
<td>-26</td>
<td>20</td>
<td>11.1</td>
<td>68</td>
<td>2.2</td>
</tr>
<tr>
<td>Remove Scoop stretcher</td>
<td>09:58:06</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Face mask oxygen</td>
<td></td>
<td></td>
<td>09:58:12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rapid sequence intubation</td>
<td>09:58:25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DELTA</td>
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<td>6.593</td>
<td>-25.870</td>
<td>20.400</td>
<td>10.545</td>
<td>67</td>
<td>2.255</td>
<td>64.5</td>
<td>0.400</td>
</tr>
<tr>
<td>Open thoracostomy</td>
<td>09:58:40</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interostal drain</td>
<td>09:58:44</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Venous access - central</td>
<td>09:58:52</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perform arterial blood gas</td>
<td>09:59:02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DELTA</td>
<td>09:59:03</td>
<td>6.587</td>
<td>-25.741</td>
<td>20.808</td>
<td>10.018</td>
<td>66</td>
<td>2.311</td>
<td>65.0</td>
<td>0.400</td>
</tr>
<tr>
<td>Rapid infusion device</td>
<td>09:59:03</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pack A</td>
<td>1</td>
<td>09:59:14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pack B</td>
<td></td>
<td>09:59:23</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>6.630</td>
<td>-27.533</td>
<td>19.632</td>
<td>12.367</td>
<td>65</td>
<td>2.369</td>
<td>65.5</td>
<td>0.400</td>
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<td>DELTA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROTEM</td>
<td>10:00:03</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evaluation of GCS</td>
<td></td>
<td>10:00:10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pupil check</td>
<td></td>
<td>10:00:12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Temperature probe</td>
<td></td>
<td>10:00:14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Removal of clothing</td>
<td></td>
<td>10:00:15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Logroll</td>
<td></td>
<td>10:00:27</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DELTA</td>
<td>10:00:33</td>
<td>6.623</td>
<td>-27.305</td>
<td>20.025</td>
<td>11.749</td>
<td>64</td>
<td>2.428</td>
<td>66.0</td>
<td>0.400</td>
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<tr>
<td>FFP</td>
<td>3</td>
<td>10:00:46</td>
<td>6.673</td>
<td>-29.450</td>
<td>18.523</td>
<td>2.064</td>
<td>58.5</td>
<td>0.460</td>
<td></td>
</tr>
<tr>
<td>Chest Xray</td>
<td></td>
<td>10:01:03</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pelvis Xray</td>
<td></td>
<td>10:01:06</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FridgeView</td>
<td></td>
<td>10:01:13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DELTA</td>
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<td>-29.303</td>
<td>18.894</td>
<td>11.161</td>
<td>63</td>
<td>2.116</td>
<td>59.0</td>
<td>0.460</td>
</tr>
<tr>
<td>FridgeView</td>
<td></td>
<td>10:02:40</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FAST scan</td>
<td></td>
<td>10:02:45</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>6.659</td>
<td>-29.156</td>
<td>19.271</td>
<td>10.603</td>
<td>62</td>
<td>2.169</td>
<td>59.5</td>
<td>0.460</td>
</tr>
<tr>
<td>PRBC</td>
<td>3</td>
<td>10:03:35</td>
<td>6.709</td>
<td>-31.343</td>
<td>17.826</td>
<td>13.603</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>FFP</td>
<td>3</td>
<td>10:03:38</td>
<td>6.760</td>
<td>-33.693</td>
<td>16.489</td>
<td>1.843</td>
<td>52.0</td>
<td>0.529</td>
<td></td>
</tr>
<tr>
<td>DELTA</td>
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<td>16.819</td>
<td>12.923</td>
<td>61</td>
<td>1.889</td>
<td>52.5</td>
<td>0.529</td>
</tr>
<tr>
<td>PRBC</td>
<td>2</td>
<td>10:04:50</td>
<td>6.787</td>
<td>-35.201</td>
<td>15.978</td>
<td>14.923</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FFP</td>
<td>2</td>
<td>10:04:52</td>
<td>6.820</td>
<td>-36.961</td>
<td>15.179</td>
<td>1.700</td>
<td>47.5</td>
<td>0.608</td>
<td></td>
</tr>
<tr>
<td>DELTA</td>
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<td>6.814</td>
<td>-36.777</td>
<td>15.483</td>
<td>14.177</td>
<td>60</td>
<td>1.743</td>
<td>48.0</td>
<td>0.608</td>
</tr>
<tr>
<td>Calcium chloride</td>
<td></td>
<td>10:05:08</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Chapter 7. Log Analysis and Experimentation

7.7 Discussions and Observations

As was pointed out in the introduction section of this chapter, we want to achieve many log analysis objectives. These objectives are to nominate the best logs behaviour, confirm whether the executed behaviour interventions followed the associated protocols, and provide different medical suggestions and resource-saving ones. The aim of this section is to recall what was done in this chapter, and then present several discussions and observations of the used log analysis techniques results.

First and foremost, we apply the correlation analysis technique because of the need to select the best behaviour among the available logs. This selection process was based on several criteria: the scene score, blood product wastage, vital signs readings at the end of the scene, and the scene duration. This technique enables us to achieve the first objective of this log analysis. It showed some evidence of which is the best log based on carefully selected criteria.

Additionally, we take advantage of two analysis techniques, namely deviation analysis and pattern recognition, to accomplish the second objective of this log analysis. Firstly, we used the deviation analysis to measure how far the ideal patient’s medical condition compared to the patient’s medical condition resulted from the studied logs. This technique allows us to see if there is space for improvement that can be made to the clinician’s behaviour. In detail, all the studied logs within this technique show higher medical values than the ideal values, especially in vital signs reading. However, the other blood test results values are generally similar except for BE, Platelets, and aPTT values. Secondly, we used pattern recognition to identify the behaviour sequence that these studied logs show. The studies’ logs show a typical pattern that matches their medical protocol guidance. However, some logs were not following that pattern, which is justified in Section 7.5. We successfully confirmed that the studied behaviour and their interventions were following the related protocols. In addition, we provide how these techniques could be useful to achieve the examined objective. Moreover, our approach provides how suitable, to some extent, these techniques are in a medical context.

Another point of discussion is the employment of the lead time reduction technique. This technique is used to provide different suggestions for the efficient use of blood products and medical improvement of the patient’s condition. We used the designed models and tools during this research project, such as the CARMA model, the trace-driven tool and the numerical models. The CARMA model approach did not provide solid and reliable findings, which may be referred to for many reasons, as discussed in Chapter 5. As a result, we used the trace-driven tool and the numerical modelling approaches to enhance the findings of the studied behaviour. In addition, to explore the opportunity toward improving patient health, we investigate the best log behaviour using Excel. This
approach permits us to observe each modification’s effects on the logged behaviour. These modifications were either adding suitable interventions or eliminating time gaps. We also studied the effects of combining the two modifications. Using such approaches granted our findings, and the presented suggestions were justifiable.

Lastly, one of the observations was that the investigated logs show a level of transparency in the logged interventions. The term ‘Process Transparency’ is generally understood to mean recording, managing, and sharing the conducted processes. Also, it raises the validity of the decision-making process by showing that these decisions were based on pieces of evidence [117][118]. However, in the medical context, healthcare providers should be open and able to improve their services and share the information and knowledge of their treatment practices. Moreover, this openness suggests sharing the medical faults to learn from these mistakes and minimise the occurrence of these faults [119]. In this research, the massive amount of details in the recorded data from the sketch simulation logs showed that such transparency is present and that our approach to analysing these logs is valid because it was based on what happened, not on what was supposed to happen. In addition, this transparency suggests that our findings and insights are accountable based on the available logs from the sketch simulation.

To conclude the analysis findings, here we used different log analysis techniques to achieve different objectives:

- **If the analysis goal is classifying the clinician’s behaviour, then we recommend using the correlation analysis technique.** This technique provides the ability to benefit from several data sources to achieve a common goal, as noted in Section 7.3.

- **If the goal is estimating the required medical resources or studying the effects of proposed suggestions, then we suggest using the lead time reduction technique.** This technique is suitable to improve behaviour productivity and studying it to obtain the best possible results, see Section 7.6.

- **If the analysis goal is evaluating the clinician’s behaviour, then we propose to use deviation analysis and pattern recognition techniques.** These techniques allow a comparative feature between the studied behaviour and standard outcomes, as discussed in Sections 7.4 and 7.5.

There are indeed improved results in case we have more data represented in more behaviour logs. For example, we could improve our findings by identifying more patterns. Moreover, we may have a better estimation of the required medical resources. This type of limitation is discussed in detail in the next chapter.
7.8 Conclusion

This chapter described the analysis techniques used in this investigation and the associated models and tools to perform these analysis types. Firstly, we presented the process of preparing the log data to be analysed. Subsequently, we used the correlation analysis technique to determine the best clinician performance log based on several criteria derived from the available log data. After that, we compared the deviation of the provided ideal patient’s medical outcomes with the best behaviour logs medical outcomes. Furthermore, we identified some patterns shown in a group of logs using a pattern recognition technique. In addition, we used the lead time reduction technique to reduce blood product wastage and improve the quality of the nominated best log. Finally, we discussed the techniques above’ results and noted the observations regarding the logging mechanism. Furthermore, and most importantly, we identified the most appropriate technique to use depending on the objective that is need to be achieved. In addition, the discussion of this chapter presents the answers to research questions number three and four, discussed in Section 1.1.
Chapter 8

Conclusion and Future work

8.1 Introduction

The purpose of the current study was to explore suitable methods to understand the aspects influencing the processes or procedures performed in a medical context. We used the clinician behaviour logs to investigate the ability to model the performed interventions in this complex context. Referring to Section 1.1 and 1.2 of this thesis, we specified several questions to be answered throughout this thesis:

1. What is the feasibility of modelling these complex interventions in such an environment?

2. What modelling tools/techniques are most suitable to be adapted?

3. To what extent do the available analysis tools/techniques provide efficient results and deeper understanding of such contexts?

4. Using an example, what improvements, if any, could be recognised and implemented to improve cost-effectiveness?

Chapters 4, 5 and 6 provide answers to the first and second questions. We demonstrated that it is feasible to model the complex processes using two medical scenarios. Furthermore, we explore several modelling formalisms to evaluate and select a suitable one. Chapter 7 addresses the third and fourth questions, by analysing the available logs using the chosen techniques and provides findings alongside improvements to the clinician behaviour logs.

A further research objectives was to develop a framework for data capture in a serious context. Chapter 3 provides our version of a sketch simulation approach that has been used to trigger and record the clinician’s expertise using logs.
8.2 Thesis Contributions

There are four main contributions from this study. Firstly, in Chapter 3, we produced an improved web-based sketch simulation that captures the interventions executed during massive bleed cases. This simulation was based on an IOS version that was developed as part of a European collaboration called TACTIC\textsuperscript{1}. Our achievement in this part was to tackle many aspects raised in this collaboration’s simulation, mainly designing this simulation to run on a web browser which makes it cross-platform. This approach allowed this simulation to be presented to a broader audience who may have limited resources. Furthermore, we introduced many improvements to the sketch simulation, such as making it table-driven, increasing scenarios’ flexibility, and updating the simulation feedback, which improves user engagement.

Secondly, in Chapter 4, we evaluated three modelling formalisms, PEPA, CARMA, and SPN. This is the first evaluation that covers these three formalisms together to the best of our knowledge. In this study, our objective is to find which formalism is suitable for medical context modelling. Therefore, we investigated the patient journey in the A&E department as an example of a medical context situation. This example allows us to evaluate each formalism in different aspects, such as the formalism level of abstraction, ease of use, expressiveness to capture different factors, and formalism analysis capability. Consequently, we select the CARMA formalism to implement our modelling of massive bleed scenarios mainly for its expressiveness and ability to model the complex interventions that occurred in such scenarios.

Thirdly, Chapter 5 proposes the CARMA model of massive bleeding scenarios. CARMA was originally designed to model Collective Adaptive System (CAS) models. However, the created models here use the CARMA formalism in an unconventional way to model medical contexts. This approach allows for a representation of the investigated phenomena. This representation has been performed using, for example, the CARMA components designed by defining their behaviour explicitly.

Fourthly, Chapter 6 presents two approaches to add to the CARMA model findings. These approaches are 1) Trace-driven simulation tool using Java and 2) Numerical modelling using Excel. These approaches are used to replicate one of the logs of interventions. This replication enabled us to monitor the effects of each intervention on the patient’s vital signs readings and blood test results. Furthermore, using these approaches permit us to acquire more behaviour data and compensate for the missing ones in the logs.

Lastly, in Chapter 7, we demonstrated how several analysis techniques were used to analyse the logs from the sketch simulation. These techniques were used to serve different goals. For example:

\textsuperscript{1}https://tacticgroup.dk
1. To explore how these behaviours differ from the protocols guidelines and suggested interventions.

2. To obtain observed patterns within these logs.

3. Finding the optimal behaviour, based on specific criteria.

4. To provide many suggestions that improve the behaviour based on the used protocol.

We also provide what type of analysis technique should be used to obtain certain objectives, detailed in Section 7.7.

8.3 Thesis Limitations

This thesis has some limitations, like any research project. The small logs size features itself as one of the limitations despite the many advantages of small sample size studies [120]. This limitation did not make it possible to generalise the findings or using different analysis techniques, such as machine learning algorithms. The scope of this study was limited to the modelling formalisms PEPA, CARMA, and SPN and their available tools. Additionally, this thesis did not cover the model checking approach needed to proof properties that were not addressed by the stochastic techniques that were used.

Moreover, it is unfortunate that the study did not include a formal validation as it may be considered one of the serious issues [121][122]. Therefore, the validity of the designed sketch simulation, behaviour models, and trace-driven simulation tool was not fully achieved except through limited questionnaires asking the sketch simulation participants to comment on the realism supported by the sketch simulation, among other things, detailed in Section 3.5. Furthermore, the results and the findings of this thesis were based on simulated medical cases presented as a serious game. These cases were introduced to show a sense of abstraction to collect the clinician’s medical experience during these critical medical cases. Therefore, there remains some level of uncertainty regarding the derived insights of this research.

8.4 Future Recommendations

The starting point of the methodology was unconventional. This unconventionality comes from using gaming concepts to trigger the clinicians’ experience within a medical context. These experiences resulted in user interventions that we collected as behaviour logs using the same gaming notation. Shortly afterwards, we modelled the clinician behaviour through multiple modelling formalisms followed by various log analysis techniques to gain
distinguished insights and findings. However, these research findings provide the following insights for future research. These future recommendations were mainly related to designing different research paradigms such as:

- Generalise the finding by considering a wider population. For example, we recommend performing more experiments and collecting more behaviour logs to allow different log analysis techniques.

- Examine the clinician’s behaviour within different medical cases. We focused on massive bleed cases in this research context, so we suggest exploring other critical medical contexts.

- Compare the behaviour of novices and expert clinicians participants. Specifically, we propose measuring the effect of medical experience on behaviour as it is worth observing and analysing the clinician’s familiarity with the medical protocols or guidance in improving the patient’s medical outcomes. Furthermore, we suggest studying the effect of using technology in medical contexts. The technology’s ease of use is one of the aspects in which young medical specialists tend to outperform older ones when using technology considered.

- Adopt different modelling formalisms. This research used PEPA, CARMA, and SPN. Therefore, we encourage future researchers to include other formalisms to develop different models to be studied. One of the recommended modelling notations is Process Mining. Discovering what Process Mining and its tool and techniques have to offer may be valuable in medical contexts.

- One of these research limitations was that a formal validation approach was not performed sufficiently. Therefore, considering several validation procedures is justified as it may expand our knowledge and understanding of this type of medical context.
Bibliography


Bibliography


Appendix A

A.1 The Role of Evaluation

The systematic process to determine which subject is significant is called evaluation \[38\]. For the researchers, evaluation could justify their decisions regarding their inspection plan. One of the evaluation approaches is reviewing and comparing many objects or themes to gain insightful knowledge. In this regards, reviewing different modelling formalisms is valuable in many aspects. For example, it shows the advantages and disadvantages of each formalism. Also, the review reveals the suitability of each formalism to the investigated context. Moreover, it would demonstrate the formalisms’ ease of use for creating models of the explored systems.

A.2 The CARMA model from Chapter 5

// A11a scenario - Resus

const orderBR_rate = 0.02;
const orderBGas_rate = 0.0333333333;

const AddPRBC_rate = 0.2;
const AddFFP_rate = 0.0166667;
const AddPlatelet_rate = 0.0166667;
const AddCryo_rate = 0.0166667;
const addPBrest_rate = 0.0166667;

const firstTic_rate = 0.03333333333;

const doRotem_rate = 0.01750700280112;
component LocalFridge() {
  store {
    attrib PRBC = 0;
    attrib FFP = 0;
    attrib Platelet = 0;
    attrib Cryo = 0;
  }

  behaviour {
    OPA = [true]orderPA(){}.APAPr;
    APAPr = addPAPr*[false]<>{my.PRBC := my.PRBC + 4;}.APAFFP;
    APAFFP = addPAFFP*[false]<>{my.FFP := my.FFP + 4;}.OPA;

    O2PA = [true]order2PA(){}.A2PAPr1;
    A2PAPr1 = addPAPr*[false]<>{my.PRBC := my.PRBC + 4;}.A2PAFFP1;
    A2PAFFP1 = addPAFFP*[false]<>{my.FFP := my.FFP + 4;}.A2PAFPr2;
    A2PAFPr2 = addPAFPr*[false]<>{my.PRBC := my.PRBC + 4;}.A2PAAFFP2;
    A2PAAFFP2 = addPAAFFP*[false]<>{my.FFP := my.FFP + 4;}.O2PA;

    O3PA = [true]order3PA(){}.A3PAPr1;
    A3PAPr1 = addPAPr*[false]<>{my.PRBC := my.PRBC + 4;}.A3PAFFP1;
    A3PAFFP1 = addPAFFP*[false]<>{my.FFP := my.FFP + 4;}.A3PAFPr2;
    A3PAFPr2 = addPAFPr*[false]<>{my.PRBC := my.PRBC + 4;}.A3PAAFFP2;
    A3PAAFFP2 = addPAAFFP*[false]<>{my.FFP := my.FFP + 4;}.A3PAAFFP3;
    A3PAAFFP3 = addPAAFFP*[false]<>{my.FFP := my.FFP + 4;}.O3PA;

    OPB = [true]orderPB(){}.APBPr;
    APBPr = addPBPr*[false]<>{my.PRBC := my.PRBC + 4;}.APBrest;
    APBrest = addPBrest*[false]<>{my.FFP := my.FFP + 4;

    O2PB = [true]order2PB(){}.A2PBPr1;
    A2PBPr1 = addPBPr*[false]<>{my.PRBC := my.PRBC + 4;}.A2PBrest1;
    A2PBrest1 = addPBrest*[false]<>{my.FFP := my.FFP + 4;
    A2PBPr2 = addPBPr*[false]<>{my.PRBC := my.PRBC + 4;}.A2PBrest2;
    A2PBrest2 = addPBrest*[false]<>{my.FFP := my.FFP + 4;}
  }
Appendix A.

\[
\text{my.Cryo} := \text{my.Cryo} + 2; \text{my.Platelet} := \text{my.Platelet} + 1; \text{.O2PB;}
\]

\[
\text{O3PB} = [\text{true}]\text{order3PB()}.\text{A3PBPr1};
\text{A3PBPr1} = \text{addPBPr*}[\text{false}]\langle\{\text{my.PRBC} := \text{my.PRBC} + 4;\}\text{.A3PBrest1};
\text{A3PBrest1} = \text{addPBrest*}[\text{false}]\langle\{\text{my.FFP} := \text{my.FFP} + 4;
\text{my.Cryo} := \text{my.Cryo} + 2; \text{my.Platelet} := \text{my.Platelet} + 1;\}\text{.A3PBPr2};
\text{A3PBPr2} = \text{addPBPr*}[\text{false}]\langle\{\text{my.PRBC} := \text{my.PRBC} + 4;\}\text{.A3PBrest2};
\text{A3PBrest2} = \text{addPBrest*}[\text{false}]\langle\{\text{my.FFP} := \text{my.FFP} + 4;
\text{my.Cryo} := \text{my.Cryo} + 2; \text{my.Platelet} := \text{my.Platelet} + 1;\}\text{.A3PBPr3};
\text{A3PBPr3} = \text{addPBPr*}[\text{false}]\langle\{\text{my.PRBC} := \text{my.PRBC} + 4;\}\text{.A3PBrest3};
\text{A3PBrest3} = \text{addPBrest*}[\text{false}]\langle\{\text{my.FFP} := \text{my.FFP} + 4;
\text{my.Cryo} := \text{my.Cryo} + 2; \text{my.Platelet} := \text{my.Platelet} + 1;\}\text{.O3PB;}
\]

\[
\text{OPr} = [\text{true}]\text{orderPRBC()}.\text{APr};
\text{APr} = \text{addPRBC*}[\text{false}]\langle\{\text{my.PRBC} := \text{my.PRBC} + 1;\}\text{.OPr;}
\text{OPr2} = [\text{true}]\text{order2PRBC()}.\text{APr2};
\text{APr2} = \text{addPRBC*}[\text{false}]\langle\{\text{my.PRBC} := \text{my.PRBC} + 2;\}\text{.OPr2;}
\text{OPr3} = [\text{true}]\text{order3PRBC()}.\text{APr3};
\text{APr3} = \text{addPRBC*}[\text{false}]\langle\{\text{my.PRBC} := \text{my.PRBC} + 3;\}\text{.OPr3;}
\]

\[
\text{OF} = [\text{true}]\text{orderFFP()}.\text{AF};
\text{AF} = \text{addFFP*}[\text{false}]\langle\{\text{my.FFP} := \text{my.FFP} + 1;\}\text{.OF;}
\text{OF2} = [\text{true}]\text{order2FFP()}.\text{AF2};
\text{AF2} = \text{addFFP*}[\text{false}]\langle\{\text{my.FFP} := \text{my.FFP} + 2;\}\text{.AF2;}
\text{OF3} = [\text{true}]\text{order3FFP()}.\text{AF3};
\text{AF3} = \text{addFFP*}[\text{false}]\langle\{\text{my.FFP} := \text{my.FFP} + 3;\}\text{.AF3;}
\]

\[
\text{OP1} = [\text{true}]\text{orderPl()}.\text{AP1;}
\text{AP1} = \text{addPlatelet*}[\text{false}]\langle\{\text{my.Platelet} := \text{my.Platelet} + 1;\}\text{.OP1;}
\text{OP12} = [\text{true}]\text{order2Pl()}.\text{AP12;}
\text{AP12} = \text{addPlatelet*}[\text{false}]\langle\{\text{my.Platelet} := \text{my.Platelet} + 2;\}\text{.OP12;}
\text{OP13} = [\text{true}]\text{order3Pl()}.\text{AP13;}
\text{AP13} = \text{addPlatelet*}[\text{false}]\langle\{\text{my.Platelet} := \text{my.Platelet} + 3;\}\text{.OP13;}
\]

\[
\text{OC} = [\text{true}]\text{orderCryo()}.\text{AC;}
\text{AC} = \text{addCryo*}[\text{false}]\langle\{\text{my.Cryo} := \text{my.Cryo} + 1;\}\text{.OC;}
\text{OC2} = [\text{true}]\text{order2Cryo()}.\text{AC2;}
\text{AC2} = \text{addCryo*}[\text{false}]\langle\{\text{my.Cryo} := \text{my.Cryo} + 2;\}\text{.OC2;}
\]
Appendix A.

OC3 = [true]order3Cryo(){}.AC3;

/*Pr = [my.PRBC > 0]usePRBC(){ my.PRBC := my.PRBC - 1; }.Pr;
F = [my.FFP > 0]useFFP(){ my.FFP := my.FFP - 1; }.F;
P1 = [my.Platelet > 0]usePlatelet(){ my.Platelet := my.Platelet - 1; }.P1;
Tx = [true]useTxA(){}.Tx;

F_R = [my.FFP > 0]useFFP_R(){ my.FFP := my.FFP - 1; }.F_R;
P1_R = [my.Platelet > 0]usePlatelet_R(){ my.Platelet := my.Platelet - 1; }.P1_R;

Pr = [my.PRBC >= 1]usePRBC(){my.PRBC := my.PRBC - 1;}.Pr;
Pr2 = [my.PRBC >= 2]use2PRBC(){my.PRBC := my.PRBC - 2;}.Pr2;
Pr3 = [my.PRBC >= 3]use3PRBC(){my.PRBC := my.PRBC - 3;}.Pr3;

F = [my.FFP >= 1]useFFP(){my.FFP := my.FFP - 1;}.F;
F2 = [my.FFP >= 2]use2FFP(){my.FFP := my.FFP - 2;}.F2;
F3 = [my.FFP >= 3]use3FFP(){my.FFP := my.FFP - 3;}.F3;

P1 = [my.Platelet >= 1]usePlatelet(){my.Platelet := my.Platelet - 1;}.P1;


Tx = [true]useTxA(){}.Tx;

R2 = [my.Platelet >= 1]usePlatelet_R(){}.R2;
R3 = [my.FFP >= 2]use2FFP(){my.FFP := my.FFP - 2;}.R3c;
R3c = [my.FFP >= 2]use2FFP(){my.FFP := my.FFP - 2;}.R3;
R4 = [true]useTxA_R(){}.R4;
}
Appendix A.

init {
  OPA|O2PA|O3PA|OPB|O2PB|O2PB|Pr|Pr2|Pr3|F|F2|F3|P1|P12|P13|C|C2|C3|Tx|R1|R2|R3|R4
}
}

component Doc() {

  store {
  }

  behaviour {
    OPA = [true]orderPA<>{}.OPA;
    O2PA = [true]order2PA<>{}.O2PA;
    O3PA = [true]order3PA<>{}.O3PA;
    OPB = [true]orderPB<>{}.OPB;
    O2PB = [true]order2PB<>{}.O2PB;
    O3PB = [true]order3PB<>{}.O3PB;
    OPr = [true]orderPRBC<>{}.OPr;
    OPr2 = [true]order2PRBC<>{}.OPr2;
    OPr3 = [true]order3PRBC<>{}.OPr3;
    OF = [true]orderFFP<>{}.OF;
    OF2 = [true]order2FFP<>{}.OF2;
    OF3 = [true]order3FFP<>{}.OF3;
    OPl = [true]orderPl<>{}.OPl;
    OPl2 = [true]order2Pl<>{}.OPl2;
    OPl3 = [true]order3Pl<>{}.OPl3;
    OC = [true]orderCryo<>{}.OC;
    OC2 = [true]order2Cryo<>{}.OC2;
    OC3 = [true]order3Cryo<>{}.OC3;
    Pr = [true]usePRBC<>{}.Pr;
    Pr2 = [true]use2PRBC<>{}.Pr2;
  }
}
Appendix A.

Pr3 = [true]use3PRBC<>{}.Pr3;

F = [true]useFFP<>{}.F;
    F2 = [true]use2FFP<>{}.F2;
    F3 = [true]use3FFP<>{}.F3;

P1 = [true]usePlatelet<>{}.P1;
    P12 = [true]use2Platelet<>{}.P12;
    P13 = [true]use3Platelet<>{}.P13;

C = [true]useCryo<>{}.C;
    C2 = [true]use2Cryo<>{}.C2;
    C3 = [true]use3Cryo<>{}.C3;
    Tx = [true]useTxA<>{}.Tx;

R1 = [true]use2Cryo_R<>{}.R1c;
R1c = [true]use2Cryo_R<>{}.R1;
R2 = [true]usePlatelet_R<>{}.R2;
R3 = [true]use2FFP_R<>{}.R3c;
R3c = [true]use2FFP_R<>{}.R3;
R4 = [true]useTxA_R<>{}.R4;
}

init {
    OPA|O2PA|O3PA|O2PB|O2PB|Pr|Pr2|Pr3|F|F2|F3|P1|P12|P13|C|C2|C3|Tx|R1|R2|R3|R4
}
}

component logA11a( ) {

store {
    }

behaviour {
    A1 = irrelevantAction[true]<>{}.A2;
    A2 = irrelevantAction[true]<>{}.A3;
    A3 = irrelevantAction[true]<>{}.A4;
    A4 = irrelevantAction[true]<>{}.A5;
A5 = irrelevantAction[true]<>{}.A6;
A6 = irrelevantAction[true]<>{}.A7;
A7 = startBloodTest[true]<>{}.A8;
A8 = startBGas[true]<>{}.A9;
A9 = startRotem[true]<>{}.A10;
A10 = irrelevantAction[true]<>{}.A11;
A11 = orderPA[true]<>{}.A12;
A12 = order2PB[true]<>{}.A13;
A13 = irrelevantAction[true]<>{}.A14;
A14 = irrelevantAction[true]<>{}.A15;
A15 = irrelevantAction[true]<>{}.A16;
A16 = irrelevantAction[true]<>{}.A17;
A17 = irrelevantAction[true]<>{}.A18;
A18 = checkBloodGas[true]<>{}.A19;
A19 = irrelevantAction[true]<>{}.A20;
A20 = use3PRBC[true]<>{}.A21;
A21 = checkBloodTest[true]<>{}.A22;
A22 = checkRotemResult[true]<>{}.A23;
A23 = irrelevantAction[true]<>{}.A24;
A24 = irrelevantAction[true]<>{}.A25;
A25 = irrelevantAction[true]<>{}.A26;
A26 = irrelevantAction[true]<>{}.A27;
A27 = irrelevantAction[true]<>{}.A28;
A28 = irrelevantAction[true]<>{}.A29;
A29 = use3PRBC[true]<>{}.A30;
A30 = use3FFP[true]<>{}.A31;
A31 = use2Cryo[true]<>{}.A32;
A32 = usePlatelet[true]<>{}.A33;
A33 = startBGas[true]<>{}.A34;
A34 = startRotem[true]<>{}.A35;
A35 = use3PRBC[true]<>{}.A36;
A36 = use3PRBC[true]<>{}.A37;
A37 = use3FFP[true]<>{}.A38;
A38 = order3PB[true]<>{}.A39;
A39 = checkBloodGas[true]<>{}.A40;
A40 = use3PRBC[true]<>{}.A41;
A41 = checkRotemResult[true]<>{}.A42;
A42 = checkRotemResult[true]<>{}.A43;
A43 = irrelevantAction[true]<>{}.A44;
A44 = useTxA[true]<>{}.A45;
A45 = irrelevantAction[true]<>{}.A46;
A46 = use2Cryo[true]<>{}.A47;
A47 = use3FFP[true]<>{}.A48;
A48 = irrelevantAction[true]<>{}.A49;
A49 = irrelevantAction[true]<>{}.A50;
A50 = irrelevantAction[true]<>{}.A51;
A51 = irrelevantAction[true]<>{}.A52;
A52 = use3PRBC[true]<>{}.A53;
A53 = use3FFP[true]<>{}.A54;
A54 = startBGas[true]<>{}.A55;
A55 = irrelevantAction[true]<>{}.A56;
A56 = use3FFP[true]<>{}.A57;
A57 = use3Cryo[true]<>{}.A58;
A58 = use3FFP[true]<>{}.A59;
A59 = use3FFP[true]<>{}.A60;
A60 = irrelevantAction[true]<>{}.nil;
}

init { 
A1 
}

component irrActions( ) { 

store { 
}

behaviour { 
A = [true]irrelevantAction(){}A;
}

init { 
A 
}
component Rotem() {

store {
}

behaviour {
SR = [true]startRotem().DR;
DR = [true]doRotem*<>{}.RR;
RR = [true]RotemResults<>{}.SR;
}

init {
SR
}
}

component Display() {

store {
//add controller for the display activities
}

behaviour {
R = [true]RotemResults(){}.CRR;
CRR = [true]checkRotemResult(){}.R;

BR = [true]BloodResults(){}.CBT;
CBT = [true]checkBloodTest(){}.BR;

BG = [true]BGasResults(){}.CBG;
CBG = [true]checkBloodGas(){}.BG;
}

init {
R|BR|BG
}
component lab( ) {

store {
}

behaviour {
SB = [true]startBloodTest(){} . DBT;
DBT = [true]doBloodTest*<>{} . BR;
BR = [true]BloodResults<>{} . SB;

SBG = [true]startBGas(){} . DBG;
DBG = [true]doBGas*<>{} . BG;
BG = [true]BGasResults<>{} . SGB;
}

init {
SB|SBG
}
}

component Clock( ) {

store {
}

behaviour {
FT = [true]firstTic*(){} . ET;
ET = [true]endTic*(){} . FT;
}

init {
FT
}
component TimeFactor( ) {

store {
}

behaviour {
FT = [true]firstTic<>{}.ET;
ET = [true]endTic<>{}.FT;
}

init {
FT
}
}

fun real FIBTEM_CA5( real A, real B, real C ){
real a = floor(0.00685185 * 2880) * A * (-0.01);
real c = A * B * 0.05;
real d = A * C * 0.15;
real f = c+d;
real FEB_CA5 = floor(A+f+a);
return FEB_CA5;
}

fun real EXTEM_CA5(real A, real B, real C, real D){
real a = floor(0.00685185 * 2880) * A * (-0.01);  
real b = A * B * 0.075;
real c = A * C * 0.05;
real d = A * D * 0.075;
real f = b+c+d;
real EX_CA5 = floor(min(54,max(24,A+f+a)));
return EX_CA5;
}

fun real EXTEM_CT(real A, real B, real C, real D){

}
real a = floor(0.00685185 * 2880) * A * 0.005;
real b = A * B * (-0.05);
real c = A * C * (-0.05);
real d = A * D * (-0.05);
real f = b+c+d;
real EX_CT = floor(min(200,max(38,A+f+a)));
return EX_CT;
}

fun real EXTEM_LI30(real A, real B){
real a = floor(0.00685185 * 2880) * A * 0.005;
real e = A * B * (-0.95);
real EX_LI30 = floor(A+e+a);
return EX_LI30;
}

system TAC {

collective {
new logA11a( );
new irrActions();
new LocalFridge( );
new lab();
new Display();
new Rotem( );
new TimeFactor();
new Clock();
}

environment {
store {
//Vital signs values
attrib VS_HR = 135.0;
attrib VS_HBP = 110.0;
attrib VS_LBP = 68.0;
attrib VS_RR = 16.0;
attrib VS_SpO2 = 94.0;
}
//Blood Lab values
attrib BR_Hb = 11.1;
    attrib BR_PLATELETS = 68.0;
    attrib BR_INR = 2.2;
    attrib BR_aPTT = 64.0;
    attrib BR_Fibrinogen = 0.4;

//Blood Gases values
    attrib BG_pH = 6.6;
    attrib BG_PaO2 = 48.0;
    attrib BG_PaCO2 = 6.6;
    attrib BG_BE = -26.0;
    attrib BG_Lactate = 20.0;

//ROTEM values

//Extem values
attrib E_CA5 = 38.0;
attrib E_CT = 55.0;
attrib E_LI30 = 95.0;
attrib E_CFT = 150.0;
attrib E_Angle = 64.0;
attrib E_MCF = 64.0;
attrib E_MCF_t = 1947.0;
attrib E_CLT = 3943.0;

//FEBTEM values
attrib F_CA5 = 5.0;
attrib F_CT = 45.0;
attrib F_CFT = 0.0;
attrib F_Angle = 59.0;
attrib F_MCF = 11.0;
attrib F_MCF_t = 867.0;
attrib F_LI30 = 95.0;
attrib F_CLT = 3615.0;

//Given types
attrib given_PRBC=0.0;
attrib given_FFP=0.0;
attrib given_Platelet=0.0;
attrib given_Cryo=0.0;
attrib given_TxA=0.0;

attrib given_Rotem_FFP=0.0;
attrib given_Rotem_Platelet=0.0;
attrib given_Rotem_Cryo=0.0;
attrib given_Rotem_TxA=0.0;

//ROTEM algorithm values
attrib EX_CT = EXTEM_CT(E_CT,given_Platelet+given_Rotem_Platelet,given_FFP+given_Rotem_FFP,given_Cryo+given_Rotem_Cryo);
attrib FEB_CA5 = FIBTEM_CA5(F_CA5,given_FFP+given_Rotem_FFP,given_Cryo+given_Rotem_Cryo);
attrib EX_CA5 = EXTEM_CA5(E_CA5,given_Platelet+given_Rotem_Platelet,given_FFP+given_Rotem_FFP,given_Cryo+given_Rotem_Cryo);
attrib EX_LI30 = EXTEM_LI30(E_LI30,given_TxA+given_Rotem_TxA);

}
weight {
default { return 1; }
}
rate {
//Conditions to apply the blood infusion
    /*usePRBC{ return (global.VS_HBP<AIMVS_HBP ? usePRBC_rate:0.0); }
useFFP{ return (global.BR_INR>AIMINR ? useFFB_rate:0.0); }
usePRBC{ return usePRBC_rate; }
useFFP{ return useFFP_rate; }
usePlatelet{ return (global.BR_PLATELETS>AIMPLATE ? usePlatelet_rate:0.0); }
useCryo{ return (global.BR_Fibrinogen<AIMFIB ? useCryo_rate:0.0); }
useTxA{return (global.given_TxA == 0.0 ? useTxA_rate:0.0); }
usePA{ return usePA_rate; }
usePB{ return usePB_rate; }

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addPRBC{ return AddPRBC_rate; }
addFFP{ return AddFFP_rate; }
addPlatelet{ return AddPlatelet_rate; }
addCryo{ return AddCryo_rate; }

doRotem*{ return doRotem_rate; }
checkAlgorithm{return 1; }
useFFP_R{ return (global.EX_CA5 > 40.0 && global.EX_CT > 80.0 ?
    useFFP_R_rate:0.0); }
usePlatelet_R{ return (global.EX_CA5 - global.FEB_CA5 < 30.0 ?
    usePlatelet_R_rate:0.0); }
useCryo_R{ return (global.FEB_CA5 < 10.0 ? useCryo_R_rate:0.0); }
useTxA_R{ return (global.EX_LI30 < 85.0 ? useTxA_R_rate:0.0); }

firstTic*{ return firstTic_rate; }
endTic*{ return endTic_rate; }

orderBR*{ return orderBR_rate; }
orderBGas*{ return orderBGas_rate; }
checkBR*{ return checkBR_rate; }
checkBGas*{ return checkBGas_rate; }

irrelevantAction{return irA_rate; }*/
doBloodTest*{ return 0.02; }
doBGas*{ return 0.0333333333; }
doRotem*{ return 0.01750700280112; }

addPAPr*{ return 0.2; }
addPAFFP*{ return 0.0166667; }
addPBPr*{ return 0.2; }
addPBrest*{ return 0.0166667; }
addPRBC*{ return 0.2; }
addFFP*{ return 0.0166667; }
addPlatelet*{ return 0.0166667; }
addCryo*{ return 0.0166667; }
//useFFP{ return (global.BR_INR > 1.5 ? 1:0.0); }
//usePlatelet{ return (global.BR_PLATELETS > 100.0 ? 1:0.0); }
//useCryo{ return (global.BR_Fibrinogen < 1.5 ? 1:0.0); }

//use2FFP_R{ return (global.EX_CA5 > 40.0 & global.EX_CT > 80.0 ? 1:0.0); }
//usePlatelet_R{ return (global.EX_CA5 - global.FEB_CA5 < 30.0 ? 1:0.0); }
//use2Cryo_R{ return (global.FEB_CA5 < 10.0 ? 1:0.0); }

firstTic*{ return firstTic_rate; }

default { return 1; }
}

update {
//When an activity performed, a relative updates happens
usePRBC{ VS_HR := global.VS_HR - ( global.VS_HR * 0.01);
       VS_HBP := global.VS_HBP + (global.VS_HBP * 0.015);
       VS_LBP = global.VS_LBP + (global.VS_LBP * 0.015);
       BR_Hb := global.BR_Hb + 1*1;
       BG_pH := global.BG_pH + ( global.BG_pH * 0.0025) ;
       BG_BE := global.BG_BE + (global.BG_BE * 0.025);
       BG_Lactate = global.BG_Lactate - (global.BG_Lactate * 0.02);
}

global.given_PRBC := global.given_PRBC+1;
}

use2PRBC{ VS_HR := global.VS_HR - ( global.VS_HR * 0.01*2) ;
       VS_HBP := global.VS_HBP + (global.VS_HBP * 0.015*2);
       VS_LBP = global.VS_LBP + (global.VS_LBP * 0.015*2); BR_Hb := global.BR_Hb + 1*2;
       BG_pH := global.BG_pH + ( global.BG_pH * 0.0025*2) ;
       BG_BE := global.BG_BE + (global.BG_BE * 0.025*2);
       BG_Lactate = global.BG_Lactate - (global.BG_Lactate * 0.02*2);
}

global.given_PRBC := global.given_PRBC+2;
}

use3PRBC{ VS_HR := global.VS_HR - ( global.VS_HR * 0.01*3) ;
       VS_HBP := global.VS_HBP + (global.VS_HBP * 0.015*3);
       VS_LBP = global.VS_LBP + (global.VS_LBP * 0.015*3); BR_Hb := global.BR_Hb + 1*3;
       BG_pH := global.BG_pH + ( global.BG_pH * 0.0025*3) ;
       BG_BE := global.BG_BE + (global.BG_BE * 0.025*3);
       BG_Lactate = global.BG_Lactate - (global.BG_Lactate * 0.02*3);
}
Appendix A.

```c
global.given_PRBC := global.given_PRBC+3;
}
useFFP{ VS_HR := global.VS_HR - ( global.VS_HR * 0.01) ;
VS_HBP := global.VS_HBP + (global.VS_HBP * 0.02);
VS_LBP = global.VS_LBP + (global.VS_LBP * 0.02);
BR_INR := global.BR_INR - (global.BR_INR * 0.05);
BR_aPTT := global.BR_aPTT - (global.BR_aPTT * 0.025);
BR_Fibrinogen = global.BR_Fibrinogen + (global.BR_Fibrinogen * 0.05);
BG_pH := global.BG_pH + ( global.BG_pH * 0.0025) ;
BG_BE := global.BG_BE + (global.BG_BE * 0.025);
BG_Lactate = global.BG_Lactate - (global.BG_Lactate * 0.02);
E_CT:= global.E_CT - (global.E_CT * 0.05);
E_CA5:= global.E_CA5 + (global.E_CA5 * 0.05);
F_CT:= global.F_CT - (global.F_CT * 0.05);
F_CA5:= global.F_CA5 + (global.F_CA5 * 0.05);
given_FFP := global.given_FFP+1;
EX_CT := EXTEM_CT(global.E_CT,global.given_Rotem_Platelet+
global.given_Platelet,global.given_FFP+global.given_Rotem_FFP,global.given_Cryo+global.given_Rotem_Cryo);
FEB_CA5 := FIBTEM_CA5(global.F_CA5,global.given_FFP+global.given_Rotem_FFP,global.given_Cryo+global.given_Rotem_Cryo);
EX_CA5 := EXTEM_CA5(global.E_CA5,global.given_Platelet+
global.given_Rotem_Platelet,global.given_FFP+global.given_Rotem_FFP,global.given_Cryo+global.given_Rotem_Cryo);}
use2FFP{ VS_HR := global.VS_HR - ( global.VS_HR * 0.01*2) ;
VS_HBP := global.VS_HBP + (global.VS_HBP * 0.02*2);
VS_LBP = global.VS_LBP + (global.VS_LBP * 0.02*2);
BR_INR := global.BR_INR - (global.BR_INR * 0.05*2);
BR_aPTT := global.BR_aPTT - (global.BR_aPTT * 0.025*2);
BR_Fibrinogen = global.BR_Fibrinogen + (global.BR_Fibrinogen * 0.05*2);
BG_pH := global.BG_pH + ( global.BG_pH * 0.0025*2) ;
BG_BE := global.BG_BE + (global.BG_BE * 0.025*2);
BG_Lactate = global.BG_Lactate - (global.BG_Lactate * 0.02*2);
E_CT:= global.E_CT - (global.E_CT * 0.05*2);
E_CA5:= global.E_CA5 + (global.E_CA5 * 0.05*2);
```

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\[ F_{CT} := \text{global.F}_{CT} - (\text{global.F}_{CT} \times 0.05\times2); \]
\[ F_{CA5} := \text{global.F}_{CA5} + (\text{global.F}_{CA5} \times 0.05\times2); \]
\[ \text{given}_{FFP} := \text{global.given}_{FFP}+2; \]
\[ \text{EX}_{CT} := \text{EXTEM}_{CT}(\text{global.E}_{CT},\text{global.given}_{Rotem_{Platelet}}+\text{global.given}_{Platelet},\text{global.given}_{FFP}+\text{global.given}_{Rotem}_{FFP},\text{global.given}_{Cryo}+\text{global.given}_{Rotem}_{Cryo}); \]
\[ \text{FEB}_{CA5} := \text{FIBTEM}_{CA5}(\text{global.F}_{CA5},\text{global.given}_{FFP}+\text{global.given}_{Rotem}_{FFP},\text{global.given}_{Cryo}+\text{global.given}_{Rotem}_{Cryo}); \]
\[ \text{EX}_{CA5} := \text{EXTEM}_{CA5}(\text{global.E}_{CA5},\text{global.given}_{Platelet}+\text{global.given}_{Rotem}_{Platelet},\text{global.given}_{FFP}+\text{global.given}_{Rotem}_{FFP},\text{global.given}_{Cryo}+\text{global.given}_{Rotem}_{Cryo}); \]
\]
\[
\begin{align*}
\text{use}_{3FFF}\{ & \text{VS}_{HR} := \text{global.VS}_{HR} - (\text{global.VS}_{HR} \times 0.01\times3) ; \\
& \text{VS}_{HBP} := \text{global.VS}_{HBP} + (\text{global.VS}_{HBP} \times 0.02\times3); \\
& \text{VS}_{LBP} = \text{global.VS}_{LBP} + (\text{global.VS}_{LBP} \times 0.02\times3); \\
& \text{BR}_{INR} := \text{global.BR}_{INR} - (\text{global.BR}_{INR} \times 0.05\times3); \\
& \text{BR}_{aPTT} := \text{global.BR}_{aPTT} - (\text{global.BR}_{aPTT} \times 0.025\times3); \\
& \text{BR}_{Fibrinogen} = \text{global.BR}_{Fibrinogen} + (\text{global.BR}_{Fibrinogen} \times 0.05\times3); \\
& \text{BG}_{pH} := \text{global.BG}_{pH} + (\text{global.BG}_{pH} \times 0.0025\times3); \\
& \text{BG}_{BE} := \text{global.BG}_{BE} + (\text{global.BG}_{BE} \times 0.025\times3); \\
& \text{BG}_{Lactate} = \text{global.BG}_{Lactate} - (\text{global.BG}_{Lactate} \times 0.02\times3); \\
& \text{E}_{CT}:= \text{global.E}_{CT} - (\text{global.E}_{CT} \times 0.05\times3); \\
& \text{E}_{CA5}:= \text{global.E}_{CA5} + (\text{global.E}_{CA5} \times 0.05\times3); \\
& \text{F}_{CT}:= \text{global.F}_{CT} - (\text{global.F}_{CT} \times 0.05\times3); \\
& \text{F}_{CA5}:= \text{global.F}_{CA5} + (\text{global.F}_{CA5} \times 0.05\times3); \\
& \text{given}_{FFP} := \text{global.given}_{FFP}+3; \\
& \text{EX}_{CT} := \text{EXTEM}_{CT}(\text{global.E}_{CT},\text{global.given}_{Rotem_{Platelet}}+\text{global.given}_{Platelet},\text{global.given}_{FFP}+\text{global.given}_{Rotem}_{FFP},\text{global.given}_{Cryo}+\text{global.given}_{Rotem}_{Cryo}); \\
& \text{FEB}_{CA5} := \text{FIBTEM}_{CA5}(\text{global.F}_{CA5},\text{global.given}_{FFP}+\text{global.given}_{Rotem}_{FFP},\text{global.given}_{Cryo}+\text{global.given}_{Rotem}_{Cryo}); \\
& \text{EX}_{CA5} := \text{EXTEM}_{CA5}(\text{global.E}_{CA5},\text{global.given}_{Platelet}+\text{global.given}_{Rotem}_{Platelet},\text{global.given}_{FFP}+\text{global.given}_{Rotem}_{FFP},\text{global.given}_{Cryo}+\text{global.given}_{Rotem}_{Cryo}); \\
\}
\end{align*}
\]
Appendix A.

```plaintext
usePlatelet{
VS_HR := global.VS_HR - (global.VS_HR * 0.01);
VS_HBP := global.VS_HBP + (global.VS_HBP * 0.02);
VS_LBP = global.VS_LBP + (global.VS_LBP * 0.02);
BR_PLATELETS := global.BR_PLATELETS - (global.BR_PLATELETS * 0.11);
BG_pH := global.BG_pH + (global.BG_pH * 0.0015);
BG_BE := global.BG_BE + (global.BG_BE * 0.025);
BG_Lactate = global.BG_Lactate - (global.BG_Lactate * 0.02);
E_CT:= global.E_CT - (global.E_CT * 0.05);
E_CA5:= global.E_CA5 + (global.E_CA5 * 0.075);
given_Platelet := global.given_Platelet+1;
EX_CT := EXTEM_CT(global.E_CT,global.given_Platelet +
global.given_Rotem_Platelet,global.given_FFP +
global.given_Rotem_FFP,global.given_Cryo+
global.given_Rotem_Cryo);
EX_CA5 := EXTEM_CA5(global.E_CA5,global.given_Platelet +
global.given_Rotem_Platelet,global.given_FFP +
global.given_Rotem_FFP,global.given_Cryo+
global.given_Rotem_Cryo);
}

use2Platelet{
VS_HR := global.VS_HR - (global.VS_HR * 0.01*2);
VS_HBP := global.VS_HBP + (global.VS_HBP * 0.02*2);
VS_LBP = global.VS_LBP + (global.VS_LBP * 0.02*2);
BR_PLATELETS := global.BR_PLATELETS - (global.BR_PLATELETS * 0.11*2);
BG_pH := global.BG_pH + (global.BG_pH * 0.0015*2);
BG_BE := global.BG_BE + (global.BG_BE * 0.025*2);
BG_Lactate = global.BG_Lactate - (global.BG_Lactate * 0.02*2);
E_CT:= global.E_CT - (global.E_CT * 0.05*2);
E_CA5:= global.E_CA5 + (global.E_CA5 * 0.075*2);
given_Platelet := global.given_Platelet+2;
EX_CT := EXTEM_CT(global.E_CT,global.given_Platelet +
global.given_Rotem_Platelet,global.given_FFP +
global.given_Rotem_FFP,global.given_Cryo+
global.given_Rotem_Cryo);
EX_CA5 := EXTEM_CA5(global.E_CA5,global.given_Platelet +
```
global.given_Rotem_Platelet, global.given_FFP +
global.given_Rotem_FFP, global.given_Cryo +
global.given_Rotem_Cryo);
}

use3Platelet{ VS_HR := global.VS_HR - (global.VS_HR * 0.01 * 3);
VS_HBP := global.VS_HBP + (global.VS_HBP * 0.02 * 3);
VS_LBP := global.VS_LBP + (global.VS_LBP * 0.02 * 3);
BR_PATELETS := global.BR_PATELETS - (global.BR_PATELETS * 0.11 * 3);
BG_pH := global.BG_pH + (global.BG_pH * 0.0015 * 3);
BG_BE := global.BG_BE + (global.BG_BE * 0.025 * 3);
BG_Lactate := global.BG_Lactate - (global.BG_Lactate * 0.02 * 3);
E_CT := global.E_CT - (global.E_CT * 0.05 * 3);
E_CA5 := global.E_CA5 + (global.E_CA5 * 0.075 * 3);
given_Platelet := global.given_Platelet + 3;
EX_CT := EXTEM_CT(global.E_CT, global.given_Platelet +
global.given_Rotem_Platelet, global.given_FFP +
global.given_Rotem_FFP, global.given_Cryo +
global.given_Rotem_Cryo);
}

useCryo{ VS_HR := global.VS_HR - (global.VS_HR * 0.01);
VS_HBP := global.VS_HBP + (global.VS_HBP * 0.02);
VS_LBP := global.VS_LBP + (global.VS_LBP * 0.02);
BR_INR := global.BR_INR - (global.BR_INR * 0.05);
BR_aPTT := global.BR_aPTT - (global.BR_aPTT * 0.025);
BR_Fibrinogen := global.BR_Fibrinogen + (global.BR_Fibrinogen * 0.4);
BG_pH := global.BG_pH + (global.BG_pH * 0.0015);
BG_BE := global.BG_BE + (global.BG_BE * 0.025);
BG_Lactate := global.BG_Lactate - (global.BG_Lactate * 0.02);
E_CT := global.E_CT - (global.E_CT * 0.05);
E_CA5 := global.E_CA5 + (global.E_CA5 * 0.075);
F_CT := global.F_CT - (global.F_CT * 0.05);
F_CA5 := global.F_CA5 + (global.F_CA5 * 0.015);
given_Cryo := global.given_Cryo + 1;
EX_CT := EXTEM_CT(global.E_CT, global.given_Platelet +
}
Appendix A.

global.given_Rotem_Platelet, global.given_FFP+
global.given_Rotem_FFP, global.given_Cryo+
global.given_Rotem_Cryo);
FEB_CA5 := FIBTEM_CA5(global.F_CA5, global.given_FFP+
global.given_Rotem_FFP, global.given_Cryo+
global.given_Rotem_Cryo);
EX_CA5 := EXTEM_CA5(global.E_CA5, global.given_Platelet+
global.given_Rotem_Platelet, global.given_FFP+
global.given_Rotem_FFP, global.given_Cryo+
global.given_Rotem_Cryo);

use2Cryo{ VS_HR := global.VS_HR - (global.VS_HR * 0.01*2) ;
VS_HBP := global.VS_HBP + (global.VS_HBP * 0.02*2);
VS_LBP = global.VS_LBP + (global.VS_LBP * 0.02*2);
BR_INR := global.BR_INR - (global.BR_INR * 0.05*2) ;
BR_aPTT := global.BR_aPTT - (global.BR_aPTT * 0.025*2);
BR_Fibrinogen = global.BR_Fibrinogen + (global.BR_Fibrinogen * 0.4*2);
BG_pH := global.BG_pH + (global.BG_pH * 0.0015*2) ;
BG_BE := global.BG_BE + (global.BG_BE * 0.025*2);
BG_Lactate = global.BG_Lactate - (global.BG_Lactate * 0.02*2);
E_CT:= global.E_CT - (global.E_CT * 0.05*2);
E_CA5:= global.E_CA5 + (global.E_CA5 * 0.075*2);
F_CT:= global.F_CT - (global.F_CT * 0.05*2);
F_CA5:= global.F_CA5 + (global.F_CA5 * 0.015*2);
given_Cryo := global.given_Cryo+2;
EX_CT := EXTEM_CT(global.E_CT, global.given_Platelet+
global.given_Rotem_Platelet, global.given_FFP+
global.given_Rotem_FFP, global.given_Cryo+
global.given_Rotem_Cryo);
FEB_CA5 := FIBTEM_CA5(global.F_CA5, global.given_FFP+
global.given_Rotem_FFP, global.given_Cryo+
global.given_Rotem_Cryo);
EX_CA5 := EXTEM_CA5(global.E_CA5, global.given_Platelet+
global.given_Rotem_Platelet, global.given_FFP+
global.given_Rotem_FFP, global.given_Cryo+
global.given_Rotem_Cryo);

use3Cryo{ VS_HR := global.VS_HR - (global.VS_HR * 0.01*3) ;
Appendix A.

\[
\begin{align*}
VS_{HBP} & := \text{global.VS}_{HBP} + (\text{global.VS}_{HBP} \times 0.02 \times 3); \\
VS_{LBP} & = \text{global.VS}_{LBP} + (\text{global.VS}_{LBP} \times 0.02 \times 3); \\
BR_{INR} & := \text{global.BR}_{INR} - (\text{global.BR}_{INR} \times 0.05 \times 3); \\
BR_{aPTT} & := \text{global.BR}_{aPTT} - (\text{global.BR}_{aPTT} \times 0.025 \times 3); \\
BR_{Fibrinogen} & = \text{global.BR}_{Fibrinogen} + (\text{global.BR}_{Fibrinogen} \times 0.4 \times 3); \\
BG_{pH} & := \text{global.BG}_{pH} + (\text{global.BG}_{pH} \times 0.0015 \times 3); \\
BG_{BE} & := \text{global.BG}_{BE} + (\text{global.BG}_{BE} \times 0.025 \times 3); \\
BG_{Lactate} & = \text{global.BG}_{Lactate} - (\text{global.BG}_{Lactate} \times 0.02 \times 3); \\
E_{CT} & := \text{global.E}_{CT} - (\text{global.E}_{CT} \times 0.05 \times 3); \\
E_{CA5} & := \text{global.E}_{CA5} + (\text{global.E}_{CA5} \times 0.075 \times 3); \\
F_{CT} & := \text{global.F}_{CT} - (\text{global.F}_{CT} \times 0.05 \times 3); \\
F_{CA5} & := \text{global.F}_{CA5} + (\text{global.F}_{CA5} \times 0.015 \times 3); \\
given_{Cryo} & := \text{global.given}_{Cryo}+3; \\
\text{EX}_{CT} & := \text{EXTEM}_{CT}(\text{global.E}_{CT}, \text{global.given}_{Platelet} + \text{global.given}_{Rotem}_{Platelet}, \text{global.given}_{FFP} + \text{global.given}_{Rotem}_{FFP}, \text{global.given}_{Cryo} + \text{global.given}_{Rotem}_{Cryo}); \\
\text{FEB}_{CA5} & := \text{FIBTEM}_{CA5}(\text{global.F}_{CA5}, \text{global.given}_{FFP} + \text{global.given}_{Rotem}_{FFP}, \text{global.given}_{Cryo} + \text{global.given}_{Rotem}_{Cryo}); \\
\text{EX}_{CA5} & := \text{EXTEM}_{CA5}(\text{global.E}_{CA5}, \text{global.given}_{Platelet} + \text{global.given}_{Rotem}_{Platelet}, \text{global.given}_{FFP} + \text{global.given}_{Rotem}_{FFP}, \text{global.given}_{Cryo} + \text{global.given}_{Rotem}_{Cryo}); \\
given_{TxA} & := \text{global.given}_{TxA} + 1; \\
\text{EX}_{LI30} & := \text{EXTEM}_{LI30}(\text{global.E}_{LI30}, \text{global.given}_{TxA} + \text{global.given}_{Rotem}_{TxA}); \\
given_{2FFP} & := \text{global.given}_{2FFP} \times (\text{global.VS}_{HR} \times 0.01 \times 2); \\
VS_{HR} & := \text{global.VS}_{HR} - (\text{global.VS}_{HR} \times 0.01 \times 2); \\
VS_{HBP} & := \text{global.VS}_{HBP} + (\text{global.VS}_{HBP} \times 0.02 \times 2); \\
VS_{LBP} & = \text{global.VS}_{LBP} + (\text{global.VS}_{LBP} \times 0.02 \times 2); \\
BR_{INR} & := \text{global.BR}_{INR} - (\text{global.BR}_{INR} \times 0.05 \times 2); \\
BR_{aPTT} & := \text{global.BR}_{aPTT} - (\text{global.BR}_{aPTT} \times 0.025 \times 2); \\
BR_{Fibrinogen} & = \text{global.BR}_{Fibrinogen} + (\text{global.BR}_{Fibrinogen} \times 0.05 \times 2);
\end{align*}
\]
BG_pH := global.BG_pH + (global.BG_pH * 0.0025*2);
BG_BE := global.BG_BE + (global.BG_BE * 0.025*2);
BG_Lactate = global.BG_Lactate - (global.BG_Lactate * 0.02*2);
E_CT:= global.E_CT - (global.E_CT * 0.05*2);
E_CA5:= global.E_CA5 + (global.E_CA5 * 0.05*2);
F_CT:= global.F_CT - (global.F_CT * 0.05*2);
F_CA5:= global.F_CA5 + (global.F_CA5 * 0.05*2);
given_Rotem_FFP := global.given_Rotem_FFP+2;
EX_CT := EXTEM_CT(global.E_CT,global.given_Rotem_Platelet+global.given_Platelet,global.given_FFP+global.given_Rotem_FFP,global.given_Cryo+global.given_Rotem_Cryo);
FEB_CA5 := FIBTEM_CA5(global.F_CA5,global.given_FFP+global.given_Rotem_FFP,global.given_Cryo+global.given_Rotem_Cryo);
EX_CA5 := EXTEM_CA5(global.E_CA5,global.given_Platelet+global.given_Rotem_Platelet,global.given_FFP+global.given_Rotem_FFP,global.given_Cryo+global.given_Rotem_Cryo);
}

usePlatelet_R{ VS_HR := global.VS_HR - (global.VS_HR * 0.01) ;
VS_HBP := global.VS_HBP + (global.VS_HBP * 0.02);
VS_LBP = global.VS_LBP + (global.VS_LBP * 0.02);
BR_PLATELETS := global.BR_PLATELETS - (global.BR_PLATELETS * 0.11);
BG_pH := global.BG_pH + (global.BG_pH * 0.0015) ;
BG_BE := global.BG_BE + (global.BG_BE * 0.025);
BG_Lactate = global.BG_Lactate - (global.BG_Lactate * 0.02);
E_CT:= global.E_CT - (global.E_CT * 0.05);
E_CA5:= global.E_CA5 + (global.E_CA5 * 0.075);
given_Rotem_Platelet := global.given_Rotem_Platelet+1;
EX_CT := EXTEM_CT(global.E_CT,global.given_Rotem_Platelet+global.given_Platelet,global.given_Rotem_FFP,global.given_Cryo+global.given_Rotem_Cryo);
Appendix A.

use2Cryo_R{ VS_HR := global.VS_HR - ( global.VS_HR * 0.01*2) ;
VS_HBP := global.VS_HBP + (global.VS_HBP * 0.02*2);
VS_LBP = global.VS_LBP + (global.VS_LBP * 0.02*2);
BR_INR := global.BR_INR - (global.BR_INR * 0.05*2) ;
BR_aPTT := global.BR_aPTT - (global.BR_aPTT * 0.025*2);
BR_Fibrinogen = global.BR_Fibrinogen + (global.BR_Fibrinogen * 0.4*2);
BG_pH := global.BG_pH + ( global.BG_pH * 0.0015*2) ;
BG_BE := global.BG_BE + (global.BG_BE * 0.025*2);
BG_Lactate = global.BG_Lactate - (global.BG_Lactate * 0.02*2);
E_CT:= global.E_CT - (global.E_CT * 0.05*2);
E_CA5:= global.E_CA5 + (global.E_CA5 * 0.075*2);
F_CT:= global.F_CT - (global.F_CT * 0.05*2);
F_CA5:= global.F_CA5 + (global.F_CA5 * 0.015*2);
given_Rotem_Cryo := global.given_Rotem_Cryo+2;
EX_CT := EXTEM_CT(global.E_CT,global.given_Platelet+
global.given_Rotem_Platelet,global.given_FFP+
global.given_Rotem_FFP,global.given_Cryo+
global.given_Rotem_Cryo);
FEB_CA5 := FIBTEM_CA5(global.F_CA5,global.given_FFP+
global.given_Rotem_FFP,global.given_Cryo+
global.given_Rotem_Cryo);
EX_CA5 := EXTEM_CA5(global.E_CA5,global.given_Platelet+
global.given_Rotem_Platelet,global.given_FFP+
global.given_Rotem_FFP,global.given_Cryo+
global.given_Rotem_Cryo);
}

useTxA_R{
E_LI30:= global.E_LI30 - (global.E_LI30 * 0.95);
F_LI30:= global.F_LI30 - (global.F_LI30 * 0.95);
given_Rotem_TxA:= global.given_Rotem_TxA+1;
EX_LI30 := EXTEM_LI30(global.E_LI30,global.given_TxA+
global.given_Rotem_TxA);
}

endTic*{ VS_HR := global.VS_HR + ( global.VS_HR * 0.01) ;
VS_HBP := global.VS_HBP - (global.VS_HBP * 0.05);
VS_LBP = global.VS_LBP - (global.VS_LBP * 0.05);
BR_Hb := global.BR_Hb - (global.BR_Hb * 0.05);
BR_PLATELETS := global.BR_PLATELETS - (global.BR_PLATELETS * 0.015);
Appendix A.

\[
\begin{align*}
BR_{\text{INR}} &= \text{global.BR}_{\text{INR}} + (\text{global.BR}_{\text{INR}} \times 0.025); \\
BR_{\text{aPTT}} &= \text{global.BR}_{\text{aPTT}} + (\text{global.BR}_{\text{aPTT}} \times 0.05); \\
BR_{\text{Fibrinogen}} &= \text{global.BR}_{\text{Fibrinogen}} - (\text{global.BR}_{\text{Fibrinogen}} \times 0.001); \\
BG_{\text{pH}} &= \text{global.BG}_{\text{pH}} - (\text{global.BG}_{\text{pH}} \times 0.004); \\
BG_{\text{BE}} &= \text{global.BG}_{\text{BE}} - (\text{global.BG}_{\text{BE}} \times 0.025); \\
BG_{\text{Lactate}} &= \text{global.BG}_{\text{Lactate}} + (\text{global.BG}_{\text{Lactate}} \times 0.01); \\
E_{\text{CT}} &= \text{global.E}_{\text{CT}} + (\text{global.E}_{\text{CT}} \times 0.1); \\
E_{\text{CA5}} &= \text{global.E}_{\text{CA5}} - (\text{global.E}_{\text{CA5}} \times 0.05); \\
E_{\text{LI30}} &= \text{global.E}_{\text{LI30}} + (\text{global.E}_{\text{LI30}} \times 0.01); \\
F_{\text{CT}} &= \text{global.F}_{\text{CT}} + (\text{global.F}_{\text{CT}} \times 0.07); \\
F_{\text{CA5}} &= \text{global.F}_{\text{CA5}} - (\text{global.F}_{\text{CA5}} \times 0.02); \\
F_{\text{LI30}} &= \text{global.F}_{\text{LI30}} + (\text{global.F}_{\text{LI30}} \times 0.05); \\
\end{align*}
\]

//Obtain an observation for certain variables

measure HeartRate = global.VS_HR;
measure HighBloodPressure = global.VS_HBP;
measure LowBloodPressure = global.VS_LBP;
measure RespiratoryRate = global.VS_RR;
measure SpO2 = global.VS_SpO2;

measure PRBC = global.given_PRBC;
measure FFP = global.given_FFP;
measure PLATLET = global.given_Platelet;
measure CRYO = global.given_Cryo;
measure TxA = global.given_TxA;

measure BR_Hb = global.BR_Hb;
measure BR_PLATELETS = global.BR_PLATELETS;
measure BR_INR = global.BR_INR;
measure BR_aPTT = global.BR_aPTT;
measure BR_Fibrinogen = global.BR_Fibrinogen;

measure Rotem_FFP = global.given_Rotem_FFP;
measure Rotem_PLATLET = global.given_Rotem_Platelet;
measure Rotem_CRYO = global.given_Rotem_Cryo;
measure Rotem_TxA = global.given_Rotem_TxA;
measure T_FFP = global.given_Rotem_FFP + global.given_PRBC;
measure T_PLATLET = global.given_Rotem_Platelet + global.given_Platelet;
measure T_CRYO = global.given_Rotem_Cryo + global.given_Cryo;
measure T_TxA = global.given_Rotem_TxA;
measure PR_F = max{ my.PRBC | true };
measure P_F = max{ my.Platelet | true };
measure F_F = max{ my.FFP | true };
measure C_F = max{ my.Cryo | true };
measure DocPRBC = #{ Doc[Pr] | true };
measure DocCryo = #{ Doc[C] | true };
measure DocPL = #{ Doc[Pl] | true };
measure DocFFP = #{ Doc[F] | true };
measure EX_CT = global.EX_CT;
measure FEB_CA5 = global.FEB_CA5;
measure EX_CA5 = global.EX_CA5;
measure EX_LI30 = global.EX_LI30;
Appendix B

B.1 The java Simulation Development

A brief background of the techniques that used to develop the Java simulation tool.

B.1.1 Java Threads

A concurrency system or program could be represented in Java as Threads. The Threads in Java are lightweight processes executed based on a set of scheduled settings. Figure B.1 illustrates the life cycle of Java Thread and its different states. The Thread state is one of these states: New, Runnable, Timed waiting, Waiting, Blocked, and Terminated. The Java Thread changes its state due to executing many methods indicated using arrows in Figure B.1 for example, a thread will change its states from New to Runnable using t.start method then after executing run method, this thread state will be changed to Terminated. Also, there is a blog discussing the multithreading in Java in details.¹

B.1.2 Java Files

Input and output data is the main task for any program developed using Java. The Java.io package roughly hold every class needed to execute input and output tasks as shown in Figure B.2. Specifically, there are set of classes that deal with files such as FileOutputStream and PrintWriter classes. FileOutputStream class is utilised when there is a need to create a file where PrintWriter class is used to write data into the file.

¹https://www.mygreatlearning.com/blog/multithreading-in-java/
Figure B.1: The life cycle of Java Thread and its different states. Adapted from [4]
Figure B.2: The Java I/O package hierarchy