

**Towards a Conceptual Modelling Framework
for Participative Hybrid Simulation in
Healthcare**

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Abstract

Hybrid simulation is increasingly recognised as a powerful tool for addressing complex decision-making challenges in healthcare. This approach enables researchers and decision-makers to investigate the interactions among various components of healthcare systems, assess interventions and policy alternatives, and evaluate their potential effects without interfering with actual operations. By integrating diverse simulation techniques, including Discrete Event Simulation (DES), System Dynamics (SD), and Agent-Based Simulation (ABS), hybrid simulation effectively captures both the operational and behavioural dimensions of healthcare systems. This comprehensive integration enhances understanding of system performance and facilitates evidence-based decision-making to improve efficiency, accessibility, and care quality.

However, despite its benefits, hybrid simulation remains underused in research focused on the implications of demographic changes, particularly population ageing, on healthcare service availability and organisation. Population ageing is one of the most significant global transformations of the late twentieth and twenty-first centuries, driven by long-term declines in fertility and mortality. In low- and middle-income countries (LMICs) such as Brazil, this shift is occurring rapidly and unevenly, placing additional pressure on already constrained social and health systems. Brazil's ageing process unfolds in a context of persistent social inequalities and regional disparities, further increasing demand for health services and challenging their capacity to meet the complex needs of older adults. Consequently, policymakers and healthcare planners increasingly recognise the need for analytical tools that can support service evaluation, guide future capacity planning, and promote sustainable models of care for an ageing population.

Simulation offers an opportunity to explore such challenges by enabling experimentation with computer models that represent real-world healthcare processes and interactions. These models

can be used to test alternative strategies for resource allocation, service organisation, and policy interventions before their actual implementation. However, despite its promise, the hybrid simulation literature has not fully explored how these models can be co-developed with stakeholders, such as clinicians, managers, and policymakers, who hold valuable experiential knowledge of the systems being modelled. The lack of active stakeholder participation, particularly during the conceptual modelling (CM) stage, is a recognised limitation in the field. Conceptual modelling defines what the simulation will represent, the level of detail it will include, and the assumptions that will underpin it. Without stakeholder involvement in this process, models risk being misaligned with real decision-making contexts and may fail to produce practical conclusions.

This thesis addresses this gap by proposing a Participative Hybrid Simulation Conceptual Modelling Framework, which adapts and extends the PartiSim methodology, a multi-methodology framework developed initially for participative discrete-event simulation in healthcare. PartiSim provides a structured approach for engaging stakeholders through facilitated workshops that guide problem definition, conceptual model development, and validation. Building on its principles, this research incorporates the participative features of PartiSim into hybrid simulation, thereby creating an integrated process that supports stakeholder collaboration in designing hybrid models.

The proposed framework was developed and evaluated through a real-world case study conducted in Santo Amaro and Cidade Ademar (SACA), two boroughs of São Paulo, Brazil. The case study focused on understanding the impact of population ageing on the local healthcare network, particularly the interaction between primary and secondary care services for older adults. Stakeholders from diverse backgrounds, including healthcare managers, clinicians, operational staff, and public health representatives, took part in facilitated workshops. These sessions encouraged collaborative problem structuring, identification of

system boundaries, and the co-development of a conceptual hybrid model integrating both process and behavioural perspectives.

By engaging participants throughout the modelling process, the study captured a richer and more nuanced understanding of the challenges faced by the SACA healthcare system. The participative approach allowed stakeholders to express their views, share experiential knowledge, and develop a shared vision of the system under study. This process enhanced communication between technical modellers and practitioners, increased transparency in modelling decisions, and improved confidence in the resulting model. Moreover, it encouraged learning among participants, strengthening their capacity to use simulation for decision support.

The framework developed through this research provides practical guidance for modellers seeking to apply hybrid simulation in participative contexts. It sets out stages, activities, and tools for involving stakeholders in conceptual modelling, and offers insights into adapting facilitated approaches to hybrid simulation. The research reflects on methodological and practical adjustments made during the Brazilian case study, including tailoring tools to hybrid model requirements and modifying facilitation techniques to ensure inclusive participation. The final framework incorporates these lessons, offering a structured, replicable approach to developing participative hybrid simulation studies.

In summary, this thesis contributes to both theoretical and practical advances in hybrid simulation in healthcare. It demonstrates that participative methods, when integrated into hybrid simulation, can strengthen the relevance, credibility, and usability of models. The study provides one of the first comprehensive attempts to embed stakeholder engagement within the conceptual modelling of hybrid simulation, particularly in the context of a developing country. It also highlights how such an approach can support better-informed decisions in complex healthcare systems affected by demographic and organisational change. The proposed

framework offers a foundation for future research and practice, enabling hybrid simulation to become a more inclusive and impactful tool for healthcare planning and policy analysis in settings characterised by limited resources and growing population needs.

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Research Declaration:

This section reports the papers that have been published during the doctoral activity.

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Chapter 1 - Thesis Overview

1.1 Chapter Introduction

This chapter provides an overview of the work undertaken. It introduces the research (Section 1.2) and discusses its aims and objectives (Section 1.3). Required ethical approvals are briefly described (Section 1.4). Finally, Section 1.5 presents an overview of the thesis structure, indicating how each chapter contributes to addressing the research aims.

Building on these foundations, Chapter 5 introduces the participatory hybrid conceptual modelling framework developed for this study, while Chapter 6 demonstrates its application within the Brazilian healthcare case study.

1.2 Research Background

Conceptual modelling is a critical stage in the development of simulation studies. It defines what the model represents, the system's boundaries, the level of detail required, and the assumptions that guide the model's structure. In healthcare, where systems are complex, dynamic, and influenced by both organisational and human factors, the conceptual modelling phase is important for ensuring that simulation studies remain valid, transparent, and useful for decision-making. A well-designed conceptual model enables modellers to transform complex real-world problems into manageable, meaningful representations that can be explored through computational simulation.

Despite its importance, conceptual modelling has often been treated as a technical or preparatory activity, receiving less attention than model building, experimentation, or validation. In particular, hybrid simulation, which combines two or more simulation methods such as Discrete Event Simulation (DES), System Dynamics (SD), and Agent-Based Simulation (ABS), poses additional challenges for conceptual modelling. The integration of

multiple paradigms requires careful consideration of how different modelling methods interact, what each method represents, and how data and behavioural assumptions are shared between components. Without a clear conceptual foundation, hybrid models risk becoming inconsistent, opaque, and difficult to interpret.

In recent years, hybrid simulation has gained recognition as a methodology for addressing complex decision-making problems in healthcare (Brailsford *et al.* 2019). Healthcare systems involve a wide range of interacting processes and agents: patients, clinicians, managers, and policymakers all play roles that influence system performance. Hybrid simulation enables the integration of different perspectives on these processes: operational, behavioural, and strategic, into a single coherent model. For example, DES can represent patient flows and resource utilisation, SD can capture long-term policy dynamics and feedback effects, and ABS can model heterogeneous behaviours among individuals and institutions. By combining these approaches, hybrid simulation offers a comprehensive and flexible means of analysing healthcare problems.

However, as the hybrid simulation literature has expanded, a significant methodological gap has persisted in HS conceptual modelling. While many studies demonstrate the technical integration of multiple simulation methods, few describe how the conceptual model underpinning such integration is developed. Moreover, there is limited guidance on how to involve stakeholders, such as healthcare professionals, managers, and policymakers, during the conceptual modelling phase. The absence of participatory approaches in hybrid simulation has been identified as a missed opportunity in the field. A detailed review of these gaps is presented in Section 2.4.

Studies often report that simulation projects fail to achieve implementation because the resulting models are not sufficiently aligned with stakeholder needs or system realities.

Conceptual modelling provides the opportunity to address this problem by engaging stakeholders in defining the model's purpose, structure, and assumptions from the outset.

Stakeholder engagement is increasingly recognised as a key component of successful healthcare modelling. Healthcare problems are inherently multifaceted, and no single group of experts can fully capture the operational and behavioural complexity of the system. Engaging stakeholders enables the inclusion of diverse perspectives and knowledge, ensuring models better reflect the system. Participatory approaches also build ownership and trust in the modelling process, increasing the likelihood that findings will be understood and applied in practice. In simulation research, participative methods have been widely explored within single-method approaches such as DES through frameworks like PartiSim (Tako and Kotiadis 2018a; Tako and Kotiadis 2015). However, their application to hybrid simulation remains largely underdeveloped.

This thesis addresses this methodological gap by developing a Participative Hybrid Simulation Conceptual Modelling Framework that embeds stakeholder engagement into the conceptual design of hybrid simulation studies. The proposed framework adapts the PartiSim methodology, originally designed for participative discrete-event simulation, to support hybrid simulation modelling. PartiSim is a well-established multi-methodology approach that uses facilitated workshops and structured tools to guide stakeholders through the stages of simulation development. By combining elements of Soft Systems Methodology (SSM) (Checkland and Poulter 2020; Robinson et al. 2010) and Discrete-Event Simulation (DES), PartiSim supports the co-production of models that are both technically rigorous and grounded in stakeholder understanding.

Building on PartiSim's participative principles, this research extends the approach to accommodate the unique requirements of hybrid simulation. These include the need to define relationships among multiple modelling paradigms, establish coherent data structures, and

ensure that stakeholders can meaningfully contribute to discussions of system behaviour spanning different levels of abstraction. The adapted framework introduces new tools and modifies existing ones to facilitate this process. It also provides guidance on managing participation across diverse stakeholder groups and on translating their input into hybrid model specifications. PartiSim is reviewed in Section 2.5, and the adapted Hybrid Participative Framework is developed in Chapter 5.

The framework is developed and validated through a case study conducted in Santo Amaro and Cidade Ademar (SACA), two boroughs in the city of São Paulo, Brazil. This case study focuses on the impact of population ageing on the local healthcare system, particularly the integration of primary and secondary care services for older adults. Population ageing has become one of the defining global social transformations of the twenty-first century. It results from sustained declines in fertility and mortality rates and improvements in life expectancy. While this demographic transition is often associated with progress, it also poses significant challenges for health and social care systems, particularly in low- and middle-income countries (LMICs). A detailed description of the SACA healthcare context is provided in Chapter 3, while the empirical participative study is documented in Chapter 6.

In Brazil, population ageing is occurring at a faster pace than in many high-income countries, with fertility rates already below replacement level. This rapid demographic shift is unfolding in a context marked by economic inequality, regional disparities, and limited public resources (Alves 2024; Minayo 2012). Scholars have described this phenomenon as a situation in which Brazil is growing old before becoming rich (Alves 2024). The Brazilian healthcare system must therefore adapt quickly to meet the rising demand for chronic disease management, long-term care, and social support services for older adults. Policymakers and healthcare managers are under increasing pressure to develop sustainable strategies for service delivery, resource allocation, and capacity planning.

Simulation offers a powerful means of exploring such challenges. It enables experimentation with computer models that represent real-world healthcare processes and interactions, allowing the evaluation of alternative policies and system configurations before implementation. However, the complexity of healthcare systems, combined with the uncertainties inherent in demographic and behavioural change, demands simulation models that can capture multiple layers of system behaviour. Hybrid simulation provides a suitable approach for this purpose; nonetheless, its effective use depends on a robust conceptual model developed through collaboration between modellers and stakeholders.

The SACA case study provides a relevant and challenging environment for testing the proposed participative hybrid conceptual modelling framework. In this study, healthcare managers, clinicians, and policymakers were engaged in facilitated workshops to co-develop a conceptual model of the healthcare system. Through participative activities, stakeholders helped define the problem situation, identify the system boundaries, and specify the processes and interactions to be represented in the hybrid model. This collaborative process integrated operational and behavioural perspectives and ensured the resulting model reflected the realities of the local healthcare context.

By focusing on the development of the conceptual model, this research emphasises that the success of hybrid simulation depends not only on technical integration but also on methodological clarity and stakeholder involvement. The participative framework developed in this study helps bridge the gap between modelling theory and practical application. It provides structured guidance for modellers on how to design hybrid simulations collaboratively and demonstrates how participatory conceptual modelling can enhance model credibility, relevance, and implementation potential.

This thesis, therefore, contributes to both the methodological and applied domains of hybrid simulation research. Methodologically, it advances understanding of how conceptual modelling can be structured and facilitated in hybrid contexts, addressing a significant gap in the literature (Tako *et al.* 2019). Practically, it demonstrates how such an approach can be applied to a real-world healthcare problem in a developing country, showing that participative conceptual modelling can be both feasible and valuable in resource-constrained settings. The resulting framework supports modellers, researchers, and decision-makers in developing hybrid simulations that are more transparent, context-sensitive, and aligned with stakeholder needs.

In summary, this research positions conceptual modelling as the foundation of hybrid simulation in healthcare. It argues that involving stakeholders from the earliest stages of model development is essential for producing simulations that are both scientifically robust and practically useful. By adapting and extending the PartiSim methodology, the study presents a novel participative framework to guide the design of hybrid simulations capable of addressing complex healthcare challenges, such as population ageing. The framework developed in this thesis offers a pathway towards more inclusive, credible, and implementable simulation practices, ultimately contributing to improved decision-making and policy development in healthcare systems facing demographic and organisational change.

1.3 Research Aim and Questions

This research is guided by two primary aims that address key gaps in the literature on hybrid simulation in healthcare. The first aim is to develop a methodology to support stakeholder involvement in the creation of facilitated hybrid simulation models. The second aim examines the feasibility of translating the resulting conceptual framework into a hybrid simulation model, using the Brazilian healthcare system as a case study. The specific research questions and objectives that guide the investigation are outlined as follows:

Aim 1: To develop a methodology that guides modellers in involving stakeholders in the development of facilitated hybrid simulation models. The following three research questions have been formulated to guide the study and ensure the research aims are effectively addressed:

Research Question 1:

In what ways can stakeholder engagement be effectively embedded within the conceptual modelling phase of hybrid simulation in healthcare?

Purpose: To examine participatory techniques and frameworks that enable meaningful stakeholder involvement throughout the conceptual modelling process, from initial problem structuring to conceptual model agreement.

Research Question 2:

What modifications are required to existing facilitated simulation methodologies (such as PartiSim) to accommodate the development of hybrid simulation models?

Purpose: To critically evaluate and adapt established facilitated modelling approaches to address the specific methodological and practical challenges of integrating multiple simulation methods (e.g., DES and ABS).

Research Question 3:

What tools, activities, and process stages are essential in a participative hybrid simulation methodology to ensure both methodological robustness and practical relevance in healthcare contexts?

Purpose: To design and validate a structured framework that guides modellers in the development of participative hybrid simulations, ensuring rigour while enhancing usability in real-world healthcare settings.

Aim 2: To investigate the feasibility of translating the conceptual framework into a hybrid simulation model, using the Brazilian healthcare system as a case study.

Research Question 1: What methodological and practical considerations arise when translating the conceptual framework into a hybrid simulation model, and how does the resulting model enhance understanding of ageing-related pressures on Brazil's healthcare system?

Purpose: To demonstrate how conceptual insights can be operationalised in a computational model to understand and analyse the impact of population ageing on healthcare services for older adults.

1.4 Ethical Approval

Ethical approval for this research was obtained from Universidade Catolica do Rio de Janeiro (PUC-RIO) and Kent Business School (KBS) at the University of Kent. The first approval was necessary to comply with Brazilian legislation for research conducted by foreign universities. The Brazilian legislation requires that healthcare research be conducted in partnership with a Brazilian university, and that the university evaluate the study's ethics before it starts. The approval was granted under protocol 121/2020 on February 7th, 2021. The second approval was required because the research involves stakeholders working in Brazil's healthcare system, including facilitated workshops and one-to-one interviews. This permission was granted by the Central Research Ethics Advisory Group at KBS on October 15th, 2021, ref KBSE No: 1806.

1.5 Outline

The remainder of this thesis is organised as follows.

Chapter 2 presents a comprehensive review of the literature on simulation, with a focus on the application of hybrid simulation in healthcare. It also discusses the use of conceptual frameworks to guide the development of hybrid simulation models. Additionally, the chapter

includes a brief overview of stakeholder engagement in simulation, providing essential context for this domain, as well as a section explaining the original PartiSim methodology.

Chapter 3 examines the healthcare system in Brazil, focusing on its structure and challenges, especially in Santo Amaro and Cidade Ademar, two boroughs in the city of São Paulo where the study was conducted.

Chapter 4 presents the research design, methods, and evaluation approach adopted in this study, including the rationale for selecting Simul8, the background of the case study (e.g., the student's roles, stakeholder information, timeline, and motivations), and the roles of the PartiSim and Simul8 experts involved.

Chapter 5 introduces the hybrid conceptual framework as it was developed and refined throughout its application in the Brazilian study.

Chapter 6 describes the Brazilian application study, detailing each stage of the research process and presenting outcomes from the participatory workshops.

Chapter 7 details the conceptual model, the outcomes of the stages in Chapter 6, and the computer model.

Chapter 8 reflects on conducting the research in Brazil and discusses adjustments made to the conceptual framework based on the modeller's experience in developing a hybrid model. The final version of the conceptual framework is presented.

Chapter 9 explores the implications of applying the framework in Brazil, highlighting strengths, weaknesses, and limitations. It also sets out the contributions of this research to the literature. Finally, it concludes by summarising future research areas in the field of hybrid simulation.

Chapter 2 - Literature Review in Single and Hybrid Simulation in Healthcare.

2.1 Chapter Introduction

This chapter reviews the literature on simulation in healthcare. First, Section 2.2 provides a brief overview of simulation before detailing the three most commonly used methods: Discrete-Event Simulation (DES), System Dynamics (SD), and Agent-Based Simulation (ABS) (Mustafee *et al.* 2015). This section presents definitions, advantages, disadvantages, and challenges associated with applying each method, and introduces Hybrid Simulation. In Section 2.3, forty-two case studies were reviewed for aspects related to combining simulation methods (Brailsford *et al.* 2019), along with eleven purely methodological papers and four studies that proposed frameworks. Finally, the last section presents findings on model conceptualisation across 42 papers (Section 2.4), with a brief discussion of stakeholder engagement. Section 2.5 summarises PartiSim, explaining the methodology and its stages.

2.2 Simulation in Healthcare

Over the past decades, numerous definitions of simulation have been proposed. Shannon (1975) described it as the process of designing a model of a real system to understand its behaviour or evaluate operational strategies. Banks (1999) defined it as the imitation of a real-world system's operation over time. Other authors expanded this idea, including elements such as operation systems, purpose, simplification, and experimentation in their definition, describing simulation as *"experimentation with a simplified imitation (on a computer) of an operations system as it progresses through time, for better understanding or improving that system"* (Robinson 2014, page 5). Simulation is often recommended for real-world problems that are too complex, costly, or impractical for direct experimentation (Carson 2005; Maria 1997).

Simulation is a widely used method in Operational Research (OR) for representing real-life problems, and has been successfully applied across various fields such as manufacturing, defence, transportation, and healthcare (Brailsford *et al.* 2019; Jahangirian *et al.* 2010; Taylor *et al.* 2009). In healthcare, the literature on simulation has grown exponentially, as evidenced by publications in high-quality journals and at conferences such as the Winter Simulation Conference (Roy, Shah and Gajjar 2020; Arisha and Rashwan 2016). Simulation methods, including Discrete-Event Simulation (DES), System Dynamics (SD), and Agent-Based Modelling (ABS), have been extensively used to explore and address healthcare issues (Macal and North 2014; Katsaliaki and Mustafee 2011; Brailsford 2007).

Each simulation method is typically suited to specific aspects of a problem. DES is often used to model operations and processes aimed at improving patient flow in healthcare facilities (Abdelghany and Eltawil 2017; Arisha and Rashwan 2016). SD is applied to assess health policies, evaluate disease dynamics, and understand relationships between hospital departments (Ilyas *et al.* 2017; Katsaliaki and Mustafee 2011; Günal and Pidd 2010). ABS examines interactions between heterogeneous agents and their behaviours within a system (Nianogo and Arah 2015). Dos Santos, Kotiadis and Scaparra (2020) compared these methods, noting that while they often focus on operational aspects of healthcare problems, only SD is used with a strategic management perspective. The following sections provide a detailed discussion of DES, SD, ABS, and hybrid simulation methods.

2.2.1 Discrete Event Simulation (DES)

Discrete-Event Simulation (DES) was officially developed in the 1960s to analyse and improve industrial and business processes (Hollocks 2006). It translates complex system behaviour into well-defined events, modelling systems comprising components that represent real-world elements (Ferro, Cordeiro and Ordoñez 2018; Morgan, Howick and Belton 2011; Pidd 2004a). Fishman (2001) categorised these components into seven concepts: work (entities entering the

system), resources (providers of services), routing (pathways for resources), buffers (waiting areas), scheduling (resource availability), sequencing (resource arrangement), and performance (measurement of resource processes over time) (Li *et al.* 2020).

DES has been widely adopted in healthcare, accounting for 296 out of 456 healthcare articles at the Winter Simulation Conference between 2009 and 2015 (Arisha and Rashwan 2016). It is the most common simulation method in healthcare management, featured in 170 out of 231 healthcare simulation papers reviewed by Vázquez-Serrano, Peimbert-García and Cárdenas-Barrón (2021). DES allows a detailed representation of systems and provides information about system performance and scenario analyses (Gönül-Sezer and Ocak 2015). It is used operationally or tactically to answer specific questions, such as allocating resources or evaluating medical interventions (Brailsford and Hilton 2001). DES has addressed three main areas in healthcare: service and intervention planning, health economics, and optimising welfare through effective utilisation of public health funds (Katsaliaki and Mustafee 2011).

In healthcare research, DES has been widely applied to examine and improve patient flow processes. DES has been employed to analyse patient movement across hospital departments, enabling the identification of bottlenecks and the evaluation of interventions designed to reduce waiting times and enhance service delivery, as demonstrated by Hossain, Debusk and Hasan (2017). It has also been used to assess operational modifications, including changes to admission procedures and scheduling systems, with Troncoso-Palacio *et al.* (2018) showing how such adjustments can influence overall hospital efficiency. In the context of emergency care, DES provides a means to evaluate triage protocols, resource requirements, and response strategies during demand surges, as explored by Carmen, Defraeye and Van Nieuwenhuysse (2015). Collectively, these studies exemplify how DES supports the examination of patient flow dynamics and the testing of potential improvements in complex clinical environments.

From the modeller's perspective, the objectives guiding the use of DES extend beyond patient flow to encompass broader concerns relating to resource management, cost-effectiveness, and system capacity—each of which is also examined in depth later in the chapter. Bedoya-Valencia and Kirac (2016) demonstrate that DES enables the simulation of alternative resource allocation strategies, thereby supporting efficiency and cost reductions. Similarly, Ferraro *et al.* (2015) show how DES can be used to forecast future demand and guide capacity planning. Stahl *et al.* (2004) discuss the method's value in evaluating the cost-effectiveness of different treatment pathways, while Singla (2020) illustrates its use in aligning staff schedules with patient demand patterns. These contributions collectively underscore the strategic aims of modellers when employing DES: to represent system variability and uncertainty, to test the implications of multiple scenarios, and to produce evidence that informs decisions on efficiency, quality, and sustainability across healthcare systems.

2.2.1.1 Advantages and disadvantages of DES modelling

Discrete Event Simulation (DES) has distinct advantages and disadvantages. It is praised for its ability to visually represent real-world processes, thereby enhancing model communication through animation and graphics (Dindarloo 2016; Sumari *et al.* 2013). This graphical aspect enhances user understanding and facilitates communication between modellers and end-users, a strength that other simulation methods, such as ABS, often lack (Eldabi *et al.* 2018). DES's graphical representation enables users to observe how the system operates and identify issues like queues and bottlenecks.

DES is flexible in representing various levels of complexity and detail, making it particularly suitable for healthcare modelling (Jun, Jacobson and Swisher 1999). Unlike other mathematical models, such as Markov chain analysis or linear programming, DES can handle complex patient

pathways and allows for scenario testing and *what-if* analyses before implementation, helping to anticipate risks and mitigate unnecessary costs (Karnon and Haji Ali Afzali 2014).

However, DES has several limitations. It can overlook indirect tasks, fail to consider the side effects of facility redesigns, and struggle to capture interactions between entities (Abdelghany and Eltawil 2017; Sumari *et al.* 2013). Additionally, its stochastic nature requires random samples to define system patterns, which can delay projects if the data is insufficient (Hoad and Kunc 2018). Inconsistent data collection can undermine scenario analysis and necessitate numerous assumptions, thereby reducing model accuracy. The need for random data samples is less critical for System Dynamics (SD), which focuses on overall system performance and benefits from more comprehensive system conceptualisation (Morecroft 2015).

2.2.2 System Dynamics (SD)

System Dynamics (SD) emerged from Professor Jay Forrester's work at MIT's Sloan School of Management in the 1950s, developed to help corporate managers better understand industrial processes (Richardson 2011). Forrester applied engineering feedback control principles to management, enabling the study of complex systems exhibiting dynamic behaviours over time (Richardson 2011; Sterman 2002). The core principle of SD is that structure determines behaviour, meaning a system's overall behaviour is shaped by the interactions and relationships among its components.

SD involves identifying problems, formulating causal hypotheses, mapping causal relationships, and translating qualitative models into quantitative simulations (Pastor Ansah and Azeem Qureshi 2013). Key elements of SD include feedback loops (Causal Loop Diagrams), the accumulation of flows into stocks (Stock and Flow Diagrams), and time delays (Sterman 2002; Forrester 1999).

2.2.2.1 Advantages and Disadvantages of SD Modelling

Like Discrete-Event Simulation (DES), System Dynamics (SD) has advantages and limitations. Abdelghany and Eltawil (2017) highlighted two main advantages and one limitation of SD. First, SD models facilitate the representation of an entire system by capturing dynamic interactions among its elements, rather than breaking it down into constituent parts as DES does (Brailsford and Hilton 2001; Lane, Monefeldt and Rosenhead 2000). This holistic view offers a comprehensive understanding of real-world problems and their strategic aspects (Abdelghany and Eltawil 2017). Beyond this holistic approach, it provides a dynamic view of the cause-and-effect relationships among system elements (Robinson and Tako 2012).

Second, SD adopts a top-down, strategic perspective, encouraging modellers to see the broader picture ("the forest rather than the trees") before detailing specific equations and mathematical aspects (Kim and Jun 1995). This approach helps overcome one-sided thinking and is essential for understanding complex phenomena (Ding *et al.* 2018; Swanson 2002). SD does not require extensive numerical datasets; it relies on descriptive and numerical data from mental models, written documentation, and existing datasets (Luna-Reyes and Andersen 2003; Brailsford and Hilton 2001). Hence, it reduces the dependence on large quantities of numerical data, as Forrester (1994) suggested.

However, the primary disadvantage of SD is its macro-level focus, which does not allow for detailed individual variability within the model (Abdelghany and Eltawil 2017). This limitation means SD cannot model the interactions and operations among entities as flexibly or realistically as other methods, such as Agent-Based Simulation (ABS) (Sumari *et al.* 2013). SD models cannot consider different levels of aggregation or heterogeneous mixing and rely heavily on measurable mathematical relationships between variables, making them less suitable

for complex systems with uncertain or unstructured configurations (Ding *et al.* 2018; Figueredo and Aickelin 2013; Parragh and Einzinger 2012).

System Dynamics (SD) offers a robust framework for analysing complex healthcare systems and informing strategic decision-making across multiple domains. A prominent application of SD lies in simulating the spread of infectious diseases, enabling policymakers to evaluate the effectiveness of interventions such as vaccination, quarantine, and social distancing, thereby supporting epidemic and pandemic response planning (Kou and Yang 2023). SD also facilitates the modelling of chronic disease progression and management, providing insights into the long-term impacts of interventions, patient behaviours, and policies on disease prevalence and associated healthcare costs (Kang *et al.* 2018).

In healthcare policy analysis, SD is instrumental for assessing the consequences of changes to insurance coverage, funding, and regulations, enabling evidence-informed policy development (Atkinson *et al.* 2015). Furthermore, SD supports the design and evaluation of behavioural health interventions, including smoking cessation and lifestyle modification programmes, by projecting their sustained effects on population health outcomes (Selya 2021). The methodology is also applied in strategic financial planning and risk management, contributing to the financial sustainability of healthcare organisations (Kurnianingtyas, Santosa and Siswanto 2020). Additionally, SD models the integration of care services across primary, secondary, and tertiary levels, thereby enhancing coordination and continuity of care delivery (Rashwan, Abo-Hamad and Arisha 2015). Collectively, these applications highlight SD's critical role in addressing complex healthcare challenges through dynamic and systemic analysis.

2.2.3 Agent-Based Simulation (ABS)

Agent-Based Simulation (ABS) dates back to the 1940s; it gained significant traction only in the 1990s (Klein, Marx and Fischbach 2018). It originated with John Von Neumann's theoretical “Von Neumann machine”, which could self-replicate. This concept evolved into Cellular Automata (CA), a grid-based system where agents follow local rules (Chen 2012).

Cellular automata are grids in which agents' decisions are influenced by neighbouring cells, with states typically “on” or “off” (Robertson 2019). In contrast, ABS allows agents to move freely and interact dynamically with their environment, focusing on the interactions within a system (Macal and North 2014; Macal and North 2005). Agents can represent various entities, such as people, institutions, or machines, and several names, including IBM, ABMS, ABS, and ABM.

There is no consensus on defining Agent or ABS, with varying interpretations emphasising computational aspects or social system simulations (Dignum, Gilbert and Wellman 2016; Wilensky and Rand 2015). The most cited definition by Macal and North (2010) describes ABM as a micro-level modelling approach that simulates autonomous agents' interactions and decision-making processes.

Critical characteristics of ABS include heterogeneity, autonomy, explicit spatial representation, local interaction, and bounded rationality (Epstein 1999). Macal and North (2014) highlighted four key attributes: autonomy, modularity, sociality, and conditionality. Agents are independent, self-contained, and capable of interaction, and their states change in response to other agents and the environment.

Agents also have explicit goals and can learn and adapt based on experiences (Macal and North 2005). Learning and adaptation can occur at the individual or population level through aggregate behavioural changes. Agent attributes can be either static or dynamic, and their

behavioural rules may range from simple conditional statements to complex systems such as neural networks (Macal and North 2014; Macal and North 2010b; Macal and North 2006).

All the properties in Figure 1 are essential for developing an Agent-Based Simulation (ABS) model. Macal and North (2010) referred to these as a 'typical agent structure'. These properties guide the design of tools to document agent-based models. The most widely used and discussed documentation tool in the literature is the ODD (Overview, Design Concepts, and Details) protocol, introduced by Grimm *et al.* (2006). It describes models using a three-part approach: overview, design concepts, and details, and covers seven elements: purpose, state variables and scales, process overview and scheduling, design concepts, initialisation, input, and sub-model.

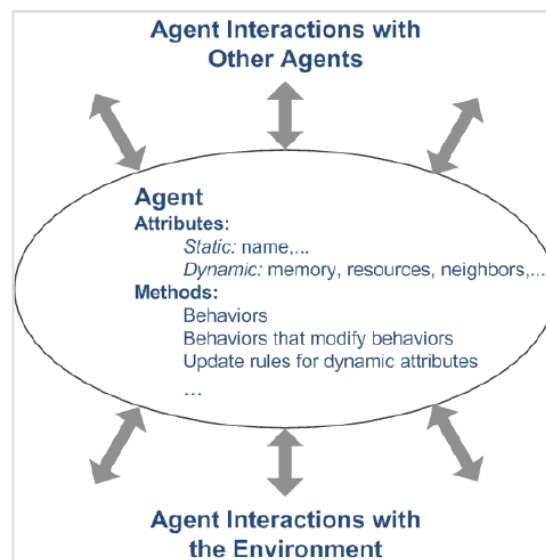


Figure 1: Properties of a typical agent (Macal and North 2014, page 10)

Monks *et al.* (2019) propose guidelines for reporting simulation studies using the ODD protocol as a reference. Macal and North (2014) also provided a set of questions, grouped into a six-part approach, to support modellers in developing ABS conceptual models, as shown in Table 1. The proposed questions help modellers to understand the problem, collect relevant data, and define the agent structure before developing the computer model.

Interaction is one of the most abstract aspects of an ABS model. To clarify interactions, Macal and North (2009) identified five types of agent interaction. The first is the "soup" model, where agents interact randomly with no specific location. The second type involves Cellular Automata (CA), where interactions occur between neighbouring cells. The third type, Euclidean Space, represents interactions within a two- or three-dimensional geometric space, such as a town or city, as illustrated in models examining COVID-19 propagation in Colombia (Gomez *et al.* 2021). The fourth type involves Geographic Information Systems (GIS), and the fifth type is network topology, where interactions are based on relationships rather than physical proximity.

Table 1: Questions to guide the development of an ABS (Macal and North 2014).

Perspectives	Questions
Model Purpose and Value-added of Agent-based Modeling	What specific problem is the model being developed to address?
	What specific questions should the model answer?
	What kind of information should the model provide to help make or support a decision?
	Why might agent-based modeling be a desirable approach?
	What value-added does agent-based modeling bring to the problem that other modeling approaches cannot bring?
All About Agents	Who should be the agents in the model?
	Who are the decision makers in the system?
	What are the entities that have behaviors?
	Where might the data come from, especially for agent behaviors?
Agent Data	What data on agents is simply descriptive (static attributes)?
	What agent attributes are calculated endogenously by the model and updated for the agents (dynamic attributes)?
	What is the agents' environment? How do the agents interact with the environment? Is agent mobility in space an important consideration?
Agent Behaviors	What agent behaviors are of interest?
	What decisions do the agents make and what information is required to make such decisions?
	What behaviors are being acted upon?
	What actions are being taken by the agents?
	How would we represent the agent behaviors? By If-Then rules? By adaptive probabilities, such as in reinforcement learning? By explicit heuristics? By regression models or neural networks?
Agent Interactions	How do the agents interact with each other?
	How do the agents interact with the environment?
	How expansive or focused are agent interactions?
Agent Recap	How do we design a set of experiments to explore the importance of uncertain behaviors, data and parameters?
	How might we validate the model, especially the agent behaviors and the agent interaction mechanisms?

The fourth interaction type in ABS involves Geographic Information Systems (GIS), where agents move across a geospatial landscape and interact with other agents during their movement. The fifth type is network topology, where interactions are based on relationships rather than physical proximity, meaning agents do not require a specific location to interact (de Farias and Dos Santos 2005). The principle underlying any topology is local interaction and

information transmission exchange between agents (Macal and North 2009). Despite its importance, Macal and North's topology classification is not widely used to describe agent interactions in ABS applications. Most studies focus on describing agents' behaviours or states rather than their interactions.

In terms of application, the simulation literature shows a growing popularity of Agent-Based Simulation (ABS) across different fields. For instance, Jing *et al.* (2020) reviewed the literature on transportation systems. They concluded that the interest in ABS for modelling autonomous vehicles (AVs) has increased considerably. Donovan *et al.* (2022) identified a similar upward trend in construction-related publications reporting the use of ABS. Nianogo and Arah (2015) and Lorig, Johansson and Davidsson (2021) also reported an increase in studies exploring disease management problems with ABS in healthcare. Unfortunately, this research did not identify any review papers examining the overall application of ABS to healthcare without focusing on a specific problem category, similar to the approach for DES (Vázquez-Serrano, Peimbert-García and Cárdenas-Barrón 2021).

A significant application of ABS is in disease spread and epidemic modelling, where it simulates the transmission of infectious diseases by capturing individual behaviours, mobility patterns, and social interactions, thereby elucidating the effects of public health interventions on outbreaks such as influenza and COVID-19 (Aleman, Wibisono and Schwartz 2011). ABS is also instrumental in examining patient behaviour and decision-making processes, including medication adherence, lifestyle choices, and responses to health interventions, which are critical for personalised healthcare strategies (Knight, Williams and Reynolds 2012).

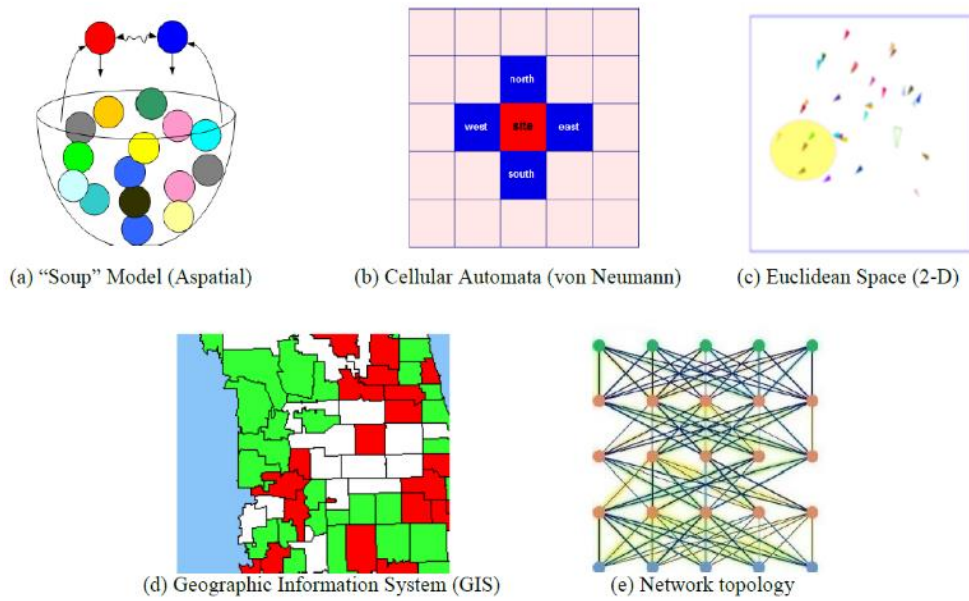


Figure 2: Topologies for agent interaction (Macal and North 2010, page 155)

Furthermore, ABS models healthcare workforce dynamics by simulating healthcare workers' behaviours and interactions, shedding light on factors such as job satisfaction, burnout, and mobility to inform workforce planning and retention strategies (Duggirala *et al.* 2016). In the management of chronic diseases, ABS enables the simulation of long-term patient-provider interactions, adherence to treatment protocols, and disease progression (Nianogo and Arah 2015). Additionally, ABS is applied to study the impact of health behaviour interventions, such as smoking cessation and exercise programmes, on individual health outcomes (Stephenson *et al.* 2020).

Importantly, ABS can incorporate social determinants of health, including socioeconomic status, education, and environmental factors, to assess their influence on health disparities and outcomes (Starr and Kain 2022). Collectively, these applications demonstrate ABS's capacity to capture complex, heterogeneous behaviours and interactions within healthcare systems, providing valuable insights for targeted interventions and policy development.

2.2.3.1 Advantages and Disadvantages of Agent-Based Modelling

The benefits and advantages of ABM over other modelling techniques were suggested by various authors (Badham *et al.* 2019; Hailegiorgis, Crooks and Cioffi-Revilla 2018; Macal and North 2005), and they can be grouped into three main features: (1) its ability to capture emergent behaviour, (2) flexibility, and (3) its capacity to describe a system naturally.

First, agent-based modelling can represent interactions and heterogeneity within processes (Badham *et al.* 2019). In other words, it can model systems with their various elements (agents), each with its own characteristics, objectives, properties, and decision-making abilities. Furthermore, it allows the study of those agents' micro-scale interactions. As a result, emerging behaviour or “complex macro-scale aggregative dynamics” (Chávez-Juárez 2017) mirrors real-world phenomena.

The second advantage of ABM lies in its flexibility and variable levels of aggregation. ABM can include multiple agents within the same model, allowing for the aggregation of individuals (e.g., city residents) or groups (e.g., families, generations X, Y, and Z, neighbourhoods) as needed to address specific modelling questions. It provides significant freedom in simulation design (Hunter, Mac Namee and Kelleher 2018). However, the authors note that this high flexibility can also be a limitation, as many models rely on the modeller's judgement regarding agent interactions, resulting in a lack of a universal definition for ABM. Additionally, flexibility allows agents to adapt and learn from experience at both individual and group levels, responding differently to identical stimuli and producing varied outcomes. This adaptability is linked to ABM's roots in Complex Adaptive Systems (CAS) and the principle that systems are built from the bottom up rather than top down, as in System Dynamics (SD) (Macal and North 2005).

ABM's third advantage is its ability to represent interactions between agents and their environments, offering a flexible and natural method for simulating real-world systems (Castle and Crooks 2006). This approach, which models components autonomously, provides a closer representation of reality and naturally describes systems (Badham *et al.* 2019). Furthermore, decentralising complex systems reduces the level of coupling between entities, leading to a more accurate depiction of reality (Chávez-Juárez 2017).

This flexibility also introduces challenges. ABM's ability to express real-world problems naturally can be problematic due to the lack of consensus on how to model agent behaviour. The arbitrary nature of the rules used to replicate human decision-making complicates the modelling process (Badham *et al.* 2019). Without clear guidance on defining key questions and behavioural rules, modellers often identify behaviour post hoc. Macal and North (2005) suggest using formal frameworks such as BDI (Belief-Desire-Intent) and engaging stakeholders to overcome these challenges.

Calibration and validation of ABM models present further challenges. Validation, essential for ensuring model accuracy, often lacks sufficient data and relies on subjective approaches. Unlike traditional models, ABM does not use statistical tools for validation; however, it depends on discovering and observing behavioural rules (Ormerod and Rosewell 2006).

The final challenge concerns the skills and background of modellers. Despite the availability of various ABM software packages, many require programming knowledge, which can create difficulties for new modellers without engineering or computing backgrounds (Eberlen, Scholz and Gagliolo 2017).

2.2.4 Hybrid Simulation (HS)

A few terms have been employed for Hybrid Simulation (HS). For example, researchers have referred to it as a mix of simulation methods (Morgan, Howick and Belton 2017), composite

models (Viana *et al.* 2014), a hybrid model (Chahal and Eldabi 2008), a modelling and simulation approach (Fakhimi *et al.* 2014), and a multi-paradigm model (Lynch and Diallo 2015).

Some authors have acknowledged a distinction between HS and the hybrid model or multi-methodology. Mustafee *et al.* (2015) distinguish HS from Hybrid System Modelling (HSM). According to these authors, HS involves the exclusive use of simulation methods. In contrast, HSM combines simulation with methods and techniques from applied computer science and system engineering throughout the modelling lifecycle. In other words, HS is “*a modelling approach that combines two or more of the following methods: discrete-event simulation, system dynamics, and agent-based simulation*”(Brailsford *et al.* 2019, page 721).

In addition, simulation methods can be categorised in several ways. Mustafee *et al.* (2017) identify three main simulation approaches: DES, SD, and ABS, resulting in four HS models: DES-SD, DES-ABS, SD-ABS, and DES-SD-ABS.

DES-SD is not a new topic in the OR community and has been widely explored, primarily until 2019.) Arisha and Rashwan (2016) showed that the DES-SD combination was the most widespread, representing 52 of the 135 publications within different fields (e.g., manufacturing, energy, healthcare, construction). SD-ABS and DES-ABS have not been as popular as DES-SD; however, they have been explored more often than DES-SD-ABS, according to data released by Brailsford *et al.* (2019).

In contrast to the work of Arisha and Rashwan (2016), which focused exclusively on case studies, Brailsford *et al.* (2019) adopted a broader perspective by proposing a conceptual framework comprising five key essential components for the evaluation of hybrid simulation studies. The following section is dedicated to discussing this framework.

2.2.4.1 Hybrid Simulation - areas of variability

Brailsford *et al.* (2019) developed a conceptual framework that groups areas of variability for a rigorous review of hybrid simulation studies. The authors proposed five components: (1) model hybridisation, (2) model integration process, (3) model input process, (4) verification and validation, and (5) implementation. Table 2 provides a brief explanation and classification of each framework variable. Moreover, it positions each component within one of the four stages of the simulation lifecycle. Including these variables or elements within the framework is essential for understanding the development of a hybrid simulation model. Some of these have been explored in earlier works by Chahal, Eldabi and Young (2013) and Zulkepli and Eldabi (2015), with different names.

Model hybridisation, identified as the first area of variability in Table 2, refers to the purposeful combination of different simulation methods. It describes how these methods are brought together and how they interact within a hybrid simulation model (Brailsford *et al.* 2019; Morgan, Howick and Belton 2017). Four model hybridisation categories are proposed:

- Enrichment, where one method is enhanced by incorporating parts of another without creating anything new.
- Integration, where elements from different methods are combined to produce something original.
- Sequential, where methods are used successively, often within their own frameworks; and
- Full integration, where complete methods or key components are merged to form a new, unified approach.

These categories build on earlier ideas and were later discussed by Morgan, Howick, and Belton (2017), who reviewed studies ranging from theoretical work (Mingers and Brocklesby 1997;

Schultz and Hatch 1996; Bennett 1985) to practical examples using methods like DES and SD (Morecroft and Robinson 2006; Brailsford *et al.* 2004; Venkateswaran and Son 2005).

The second component of the HS simulation framework is the model integration process, which concerns data exchange between software tools. This component applies to studies that employ two different software packages, each with its own language and structure, that are interconnected to ensure the HS model functions correctly. Brailsford *et al.* (2019) identified three different categories: automated, manual, or supported by intermediate tools.

The category automated is the gold standard for creating links within commercial software packages. Some studies have developed automated connections between the two simulation methods (Abdelghany and Eltawil 2017; Kolominsky-Rabas *et al.* 2015; Djanatliev and German 2013). The main advantage of automation lies in the speed and accuracy of data transfer between software packages. However, it can also pose a challenge for modellers lacking computer programming experience.

On the other hand, manual integration relies on the modeller's action. Although it can be a practical alternative for those without programming expertise, it is 'resource-intensive and error-prone' (Paganus, Honkoila and Karhela 2016), with a much higher likelihood of errors as information must be transferred manually between software packages. Furthermore, it can increase the time required to run a simulation model, which in some cases may be a significant limitation for the proposed model.

Finally, the third category involves using intermediate tools, such as Excel. Viana *et al.* (2014) used Excel to transfer data from Simul8 (DES software) to Vensim (SD software). Although this method reduces the likelihood of errors, it still depends on the modeller to manually transfer data between software tools to generate the simulation outcomes.

The third aspect refers to input data. Brailsford *et al.* (2019) argued that data can be classified into three categories: illustrative input, real-world, and a mixture of both. While real data is collected or measured from real systems, illustrative refers to the data from experts or previous publications, especially those discussing disease or parameters in an individual’s health.

The fourth element is validation and verification (V&V), the most discussed topic in HS and the main challenge for modellers in the HS field. V&V are critical activities in simulation, regardless of the method or the mixing of methods. *“Without thorough verification and validation, there are no grounds to place confidence in a study’s results”* (Robinson 2014, page 251). Modellers should be able to evaluate the outcomes of each simulation stage and ensure that the model accurately reflects reality, produces reliable results, and provides decision-makers with reliable information.

Table 2: Framework to explore variability in hybrid simulation based on Brailsford *et al.* (2019).

Areas of variability in HS	DEFINITION	CATEGORIES
Model Hybridisation (Stage 2: Model coding)	Defines how the simulation methods interact in an HS	H1 - Enriching H2 - Sequential H3 - Interaction H4 - Integration
Model Integration process (Stage 2: Model coding)	Defines how data exchange occurs between software that may be used for HS.	I1 - Automated I2 - Manual I3 - Supported by intermediate tools
Model Input Source (Stage 2: Model coding)	Defines if the model input data is primary (collected for this study) or secondary (collected not only for this study).	S1 - Real-world S2 - Illustrative S3 - Both real-world and illustrative
Verification & Validation (Stage 3: Experimentation)	States the approach used to ensure the accuracy of results and the model's adherence to the real system.	V1- Statistical approach checking V2 - Expert validity or qualitative validity V3 - Both - expert and statistical validation
Implementation (Stage 4: Implementation)	States whether the proposed model was implemented in real life or not.	IM1 - Proof of concept IM2 - Potential, but not real IM3 - Evidence of real implementation

Although publications often address verification and validation jointly, Robinson (2014) stated that both processes have distinct functions in simulation modelling. Verification involves inspecting whether the computer model is valid and correctly represents the system under study.

Sargent (2020) offered a similar definition, explaining that verification is synonymous with ensuring the accuracy of both the computer program of the model and the way it is implemented. Validation, on the other hand, is a more complex process concerned with ensuring that the model is robust and fit for its intended purpose, or '*substantiation that a computerised model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model*' (Sargent 2020, page 16).

A few techniques are commonly employed for V&V. Sargent (2020) identified three main approaches: model development team validation, user validation, and third-party or specialist validation. Model development team validation is based on tests (e.g., statistical tests) and comparisons with historical data. Its efficacy has already been demonstrated and accepted for DES models; however, its use for SD and ABS stand-alone models, or HS models combining both, remains questionable.

The main argument supporting the richness of SD and ABS lies in their ability to represent systems through qualitative variables or 'softer' skills (Eldabi *et al.* 2016). Their modelling relies on theory, assessments, and assumptions to create behavioural rules (Mustafee *et al.* 2015), all of which are, by nature, difficult to quantify. Kennedy (2011) argued that, for some aspects of human behaviour, relevant data may not exist, making the V&V process particularly challenging. In such cases, modellers rely on the second and third of Sargent's approaches, the involvement of stakeholders throughout the simulation lifecycle. Stakeholders may include users or other participants involved in the system, as well as third parties with sufficient expertise to assess whether the model is satisfactory at each modelling stage.

Finally, the last aspect is model implementation. During this stage, the simulation outcomes are put into practice. Robinson (2014) argued that implementation can take different forms: it may involve applying findings (lessons learned during model development) or implementing the model itself (the ideal scenario in real-world settings). However, the model implementation was defined in terms of the implementation status observed in the reviewed studies (from proof of concept to implementation in the real world with demonstrable changes to the organisation) (Brailsford *et al.* 2019).

Thus far, this chapter has discussed the theory of stand-alone and hybrid simulation methods, presenting their definitions, advantages, and disadvantages. The following sections will explore publications on hybrid simulation in healthcare.

The literature review was built upon previously published articles (Dos Santos, Kotiadis and Scaparra 2020). Using the same flow of information through four main phases - identification, screening, eligibility and inclusion, based on PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) guidelines (Shamseer *et al.* 2015; Cassidy *et al.* 2019). Unlike the approach adopted by Brailsford *et al.* (2019), only the main author in this research conducted the systematic review process, applying the PRISMA framework to identify relevant publications on hybrid simulation from two databases - Scopus and Web of Science, as shown in Figure 3.

The first phase was carried out using the search for the following keywords: ("discrete event simulation" OR "system Dynamics" OR "Agent-based simulation") OR [(“Discrete Event Simulation” AND “System Dynamics”) OR (“Discrete Event Simulation” AND “System Dynamics” AND “Agent-Based Simulation”) OR (“Discrete Event Simulation” AND “Agent-Based Simulation”) OR (“Agent-Based Simulation” AND “System Dynamics”)] OR ("multimethod*" OR "Hybrid model*" OR "mixed model*" OR "multi-model*" OR multi-

paradigm OR "coupled model" OR "composite model*" OR "multi-resolution model*" OR "multi-formalism model*" OR "hybrid simulation") AND health* across the two target databases.

As shown in Figure 3, Phases II to IV were dedicated to screening, eligibility checking, and inclusion. During the screening (phase II), several papers were excluded based on their title, keywords and abstracts. The main reasons were (1) the study was not related to healthcare or Operational Research, (2) hybrid simulation referred to the combination of simulation with other methodologies in Operational Research or other fields, (3) the article was proposing a comparison between stand-alone simulation, and (4) the proposed hybrid simulation was involving other simulation methods, such as Monte-Carlo Simulation (MC).

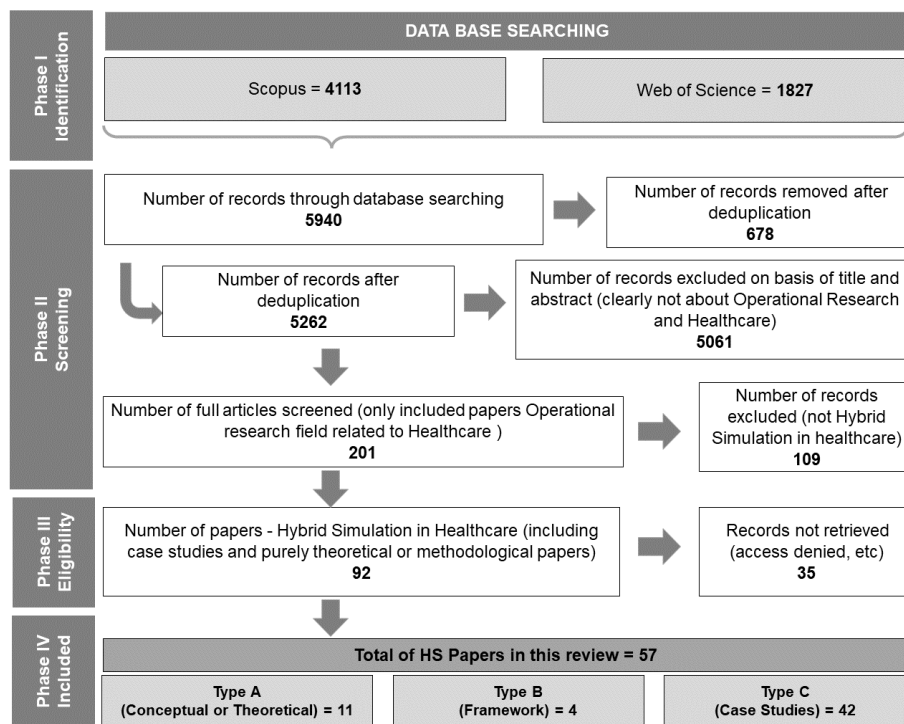


Figure 3: Phases through the systematic literature review.

As also shown in Figure 3, Phase III (eligibility) also resulted in eliminating papers. In this phase, ninety-two papers were reassessed to ensure that only papers proposing hybrid simulation in healthcare would be included in the review. Thirty-five papers have been

eliminated for not being exclusively dedicated to hybrid simulation according to the definition of Mustafee *et al.* (2015); instead of combining simulation approaches, they employed simulation methods alongside other operational research techniques, such as optimisation.

Additionally, several papers were inaccessible due to restricted access rights, and the author did not have the necessary institutional privileges to obtain them. No further action was taken on these papers as the abstract showed that the main goal of these papers was not purely related to HS in Healthcare, such as (Sinuany-Stern, Bitan and Kadosh 2023), which explores the impact of an Earthquake on the Location of Emergency Treatment.

Unlike the approach taken in previous studies (Dos Santos, Kotiadis and Scaparra 2020), this research aimed to review both case studies and theoretical or methodological papers. Hence, in phase IV, the 57 papers included in this review were classified into three groups, following a similar classification adopted by Brailsford *et al.* (2019), as outlined below:

- Group one (Type A) comprises purely theoretical/methodological papers that present the author's experiences and reflections on the application of hybrid simulation.
- Group two (Type B) refers to papers describing frameworks which other modellers could replicate. Some of these papers include a case study to illustrate the proposed framework.
- Group three (Type C) contains case studies or papers reporting the application of one of the four hybrid simulation models (DES-SD, DES-ABS, SD-ABS, and DES-SD-ABS) according to Mustafee *et al.* (2015).

The following sections present the findings from the systematic literature review, beginning with an overview of the fifty-seven papers across the three groups described above.

2.3 Literature Review Methodology

The literature on Hybrid Simulation (HS) shows an increasing trend, particularly in the number of case studies, as depicted in Figure 4. Among the three groups, case studies (Group 3) experienced the most significant increase in publications during the three periods mentioned above, as shown in Figure 4.

The data for HS publications indicate a higher prevalence of journal articles compared with conference papers. While twenty-five papers were published in conference proceedings, thirty-two were retrieved from academic journals. For journal papers, there was a marked increase in publications after 2019, twenty-one journal papers compared with nine conference papers.

Regarding the distribution of publications, the Winter Simulation Conference was the source of seventeen papers, while both the Journal of Simulation and the SIMULTECH Conference published three papers each. The academic journals European Journal of Operational Research, Healthcare (Switzerland), and Applied Simulation each published two papers.

A further thirty sources, including the Journal of the Operational Research Society, Simulation Conference, and Healthcare and Health Systems journals, are also represented in this review; however, each contributed only one publication.

The following paragraphs present further details about the papers included in this review, organised into the three groups discussed earlier. For Group 2, a comparison is made between the proposed frameworks for HS models and the frameworks used in stand-alone simulation (Robinson 2014). Group 1 findings summarise the reflections, lessons learned, and main topics addressed by papers classified as theoretical.

Group 3 was analysed using areas of variability as discussed in Table 2, together with other aspects of hybrid simulation development, such as the use of commercial software packages for

model building and the level of stakeholder engagement. The aim was to evaluate how simulation methods have been combined and to identify similarities and differences among studies that used the same hybrid model.

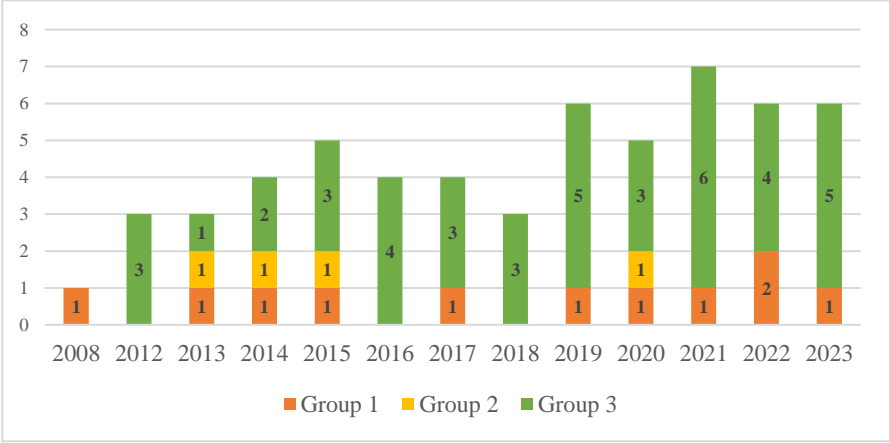


Figure 4: Evolution of HS in healthcare over time.

2.3.1 Group 1 - Survey and purely methodological papers (Type A)

Five articles reviewed the literature on hybrid simulation between 2019 and 2022, as shown in Table 3. Two were presented at the Winter Simulation Conference (WSC) (Kar, Eldabi and Fakhimi 2022; Dos Santos, Kotiadis and Scaparra 2020), both dedicated to healthcare literature. The remaining three were published in academic journals - BMC Health Services Research (Cassidy *et al.* 2019), American Journal of Infection Control (Nguyen, Megiddo and Howick 2022), Systems Research and Behavioural Science (Zhang *et al.* 2023).

The papers presented at the WSC reviewed HS literature in healthcare without restricting the focus to a specific HS model. Dos Santos, Kotiadis and Scaparra (2020) reviewed twelve case studies published after 2012, while Kar, Eldabi and Fakhimi (2022) included thirty-three studies. The former identified gaps in model development, particularly concerning human behaviour, and reported no evidence of stakeholder involvement throughout the HS lifecycle. Kar, Eldabi and Fakhimi (2022) corroborated this finding, emphasising that human interactions

play a crucial role and should be further explored in future research. Both reviews assessed the areas of variability in hybrid modelling.

Table 3: Summary of papers with reflections and tools for HS models.

Authors	HS model	Aim	Findings
(Chahal and Eldabi 2008)	DES-SD	Proposed an analysis of mixing DES and SD.	Briefly describe the hybrid approach applied to decision-making in various public health governance modes.
(Morgan, Howick and Belton 2017)	DES-SD	Proposing a toolkit for mixing DES and SD as a set of questions to guide the model development.	A table covers all model hybridisation types, outlining possible challenges and critical features of mixing DES and SD.
(Brailsford <i>et al.</i> 2013)	DES-ABS	Proposing reflections on developing a DES-ABS for a disease called age-related macular degeneration (AMD).	Hybrid simulation is appropriate for modelling social care systems. Challenges in model coding using AnyLogic. The validation process is possible, but it is a what-if scenario. It requires experts in the new simulation method for the first time.
(Brailsford 2015)	DES-SD DES-ABS	Presented a reflection on developing HS models.	There are reflections about the commercial packages, such as VENSIM and AnyLogic. There are different points of view between “system dynamists” and experts in DES modelling. It is still some way from the Holy Grail in the HS simulation.
(Viana 2014)	DES-SD DES-ABS	Presented a reflection on developing HS models.	Discuss the evolution of commercial packages and the differences between using two software tools for DES-SD and one software tool for DES-ABS.
(Nguyen, Megiddo and Howick 2021)	SD-ABS	Discussed the benefits of using HS rather than single simulation methods.	HS modelling is challenging due to a lack of comprehensive guidance and technical obstacles. Healthcare-associated infections (HAIs) would benefit from hybrid simulation to tackle their natural complexity.

Conversely, the other three reviews focused on specific problem domains. Nguyen, Megiddo and Howick (2020) examined simulation models addressing the transmission of healthcare-associated infections (HAIs). Zhang *et al.* (2023) conducted a systematic review of 372 papers

on COVID-19, identifying only eleven that proposed pure hybrid simulation models for COVID-19; their findings were therefore limited to pandemic-related healthcare impacts. Cassidy *et al.* (2019) reviewed SD-ABS studies and identified research gaps conducted in low- and middle-income countries (LMICs). In relation to the areas of variability discussed by Dos Santos, Kotiadis and Scaparra (2020), Cassidy *et al.* (2019) focused specifically on model verification and validation, as well as the software used in the reviewed studies. Their additional findings concerned the use of SD-ABS modelling in LMICs.

Furthermore, this research was also included in Group 1 papers that proposed reflections on the hybrid model, toolkits for mixing methods, or discussions about the challenges of developing an HS in healthcare. Table 3 summarises the six papers retrieved from both datasets, presenting the authors, hybrid models discussed, study aims, and main findings. Only one paper (Morgan, Howick and Belton 2017) was dedicated to introducing a toolkit designed to support the integration of different paradigms in simulation. The remaining five papers reflected on the evolution of commercial software packages for HS development (Brailsford 2015; Viana 2014; Brailsford *et al.* 2013), discussed the challenges of applying HS in public health (Chahal and Eldabi 2008), or explored the benefits and difficulties of simulating Healthcare-Associated Infections (HAIs) (Nguyen, Megiddo and Howick 2021).

2.3.2 Group 2 - Framework papers (Type B)

The second group comprises articles that propose conceptual models for developing an HS model, as shown in Table 4. This research compared the framework proposed in the papers with the conceptual framework proposed by Robinson (2014), which was also used by Brailsford *et al.* (2019) to develop the HS framework for reviewing HS studies across different fields. The first row of Table 4 presents the simulation lifecycle stages proposed by Robinson (2014), while Rows 2 to 5 outline the stages proposed by the four framework papers retrieved in this review.

In contrast to the stand-alone methods, limited work has been conducted on the conceptual or lifecycle frameworks for developing HS models. This review identified four conceptual model papers within the healthcare sector (Henchey, Ercolini and Klaus 2020; Zulkepli and Eldabi 2015; Chahal, Eldabi and Young 2013; Taylor *et al.* 2014).

Chahal, Eldabi and Young (2013) proposed a framework for a DES-SD model to study governance in UK healthcare. Regarding the stages of the HS lifecycle, this framework covers only the model conceptualisation stage, with most activities focused on understanding the interactions between DES and SD models. The authors introduced three different formats for combining both methods: hierarchical format, process-environment format, and mixed continuous and discrete format. In the hierarchical format, SD represents the strategic level of the system, while DES corresponds to operational-level decision-making. In the process-environment format, SD represents the environment surrounding a process or operation. The mixed continuous and discrete format corresponds to an integrated approach in which there is no clear distinction between the variables used in DES and SD.

As shown in Table 4, Zulkepli and Eldabi (2015) proposed a framework for large healthcare systems comprising three main phases: conceptual, modelling, and model communication. For each phase, the authors presented a flowchart outlining the main activities intended to guide modellers in hybrid simulation decision-making. Although the framework provides useful guidance, the authors acknowledged that implementing each phase is subjective and that breaking down overall objectives into smaller, specific goals can require considerable effort.

In contrast to Chahal, Eldabi and Young (2013) and Zulkepli and Eldabi (2015) extended their framework beyond the conceptual phase to include model coding and experimentation.

Table 4: Comparison between HS conceptual frameworks in healthcare and Robinson (2014) simulation lifecycle

Authors	Phase I	Phase II	Phase III	Phase IV
(Robinson 2014)	Conceptual modelling 1) Develop an understanding of the problem situation 2) Determine the modelling objectives 3) Design the conceptual model: inputs, outputs, and model content	Model coding 1) Convert the conceptual model into a computer model	Experimentation 1) Experiment with the model to examine its performance. 2) Find improvements to real-world problems.	Implementation 1) Implement the model
(Chahal, Eldabi and Young 2013)	A) Problem Identification 1) Identify the overall objective 2) Decompose into smaller objectives 3) Method selection B) Mapping between SD and DES models 1) Development of SD and DES models 2) Identification of interaction points 3) Formulation of the relationship between interaction points 4) Mapping of interaction points in SD and DES models. C) Identification of the mode of interaction 1) Identify the way SD and DES models are going to interact			
(Zulkepli and Eldabi 2015)	A) Conceptual Phase 1) Problem source definition and objective(s) identification; 2) Conceptual model and modularisation	B) Modelling phase 1) Development of SD and DES, which can be done simultaneously if expertise is available.	C) Models Communication Phase (cont.) 4) Model execution and	

Authors	Phase I	Phase II	Phase III	Phase IV
	process; 3) Identify affected modules; 4) Identification of the characteristics of each module 5) Identify the suitable technique for modelling	C) Models Communication Phase 1) Identifying the variables in both models that can be linked together 2) Define the last output from the linkage variable 3) Identify the initial influencing variable	data exchange 5) Evaluation of the outputs 6) Suggestions for improvements	
(Henchey, Ercolini and Klaus 2020)	A. Understand the Hypothesis and Objectives 1) Define the hypothesis and objectives for the new healthcare delivery service B. Map the Patient Journey 1) Define the patient journey (patient pathways)	C. Gather and Evaluate data 1) Identify data 2) Gather and analyse data D. Build and Calibrate Simulation 1) Develop the model for DES and ABS	E. Analyse Outcomes and Present Options 1) Address the hypothesis and objectives 2) Answer questions about the healthcare organisation's performance and patients' experiences 3) Visualise the results of the simulation	
Anagnostou and Taylor 2014)	A) Planning 1) Problem formulation B) Development 1) Distributed conceptualisation (interactions and semantic relationships) 2) Model conceptualisation	B) Development (cont.) 3) Model realisation 4) Data Collection 5) Verification and Validation 6) Define time advance strategy 7) Middleware implementation	Experimentation 1) Experimental design 2) Computer network selection 3) Result analysis	

Comparing this framework to Robinson (2014), this research found that Stage C (model communication) incorporates activities related to model coding and experimentation, but does not include any activities concerning model implementation.

Anagnostou and Taylor (2014) developed a three-stage methodology consistent with earlier publications on stand-alone simulation projects. In both cases, the stages of planning, development, and experimentation correspond to the phases involved in conducting a simulation study.

On the other hand, Henchey, Ercolini and Klaus (2020) proposed a five-stage framework for developing a DES-ABS model for implementing telehealth, a strand of telemedicine, in the treatment of post-traumatic stress disorder (PTSD), as shown in Table 4.

The first stage involves understanding the hypothesis and objective, which requires defining the goals and specific conditions for implementing a new healthcare delivery option. The authors suggested a template for articulating the hypothesis and objectives, illustrating its use through the contextualisation of PTSD treatment.

The first stage involves understanding the hypothesis and objective, which requires defining the goals and specific conditions for implementing a new healthcare delivery option. The authors suggested a template for articulating the hypothesis and objectives, illustrating its use through the contextualisation of PTSD treatment.

The second stage focuses on mapping the patient's journey, comparable to the model conceptualisation stage described by Brailsford *et al.* (2019) and in Robinson (2014). The purpose of this stage is to design the patient pathway and identify all connections between the patient and healthcare providers.

The third stage of the framework involves evaluating the data. Henchey, Ercolini and Klaus (2020) used demographic and health data to define agent demand, resource capacity, and the

services provided for the operational component of the model (the DES model). Finally, the fifth stage focuses on analysing outcomes and presenting options. However, Henchey, Ercolini and Klaus (2020) did not clearly describe this stage or clarify whether stakeholders were involved in the process.

2.3.3 Group 3 - Case Studies articles (Type C)

The following four sections analyse each type of Hybrid Simulation (HS) model, starting with the least common. DES-SD-ABS and SD-ABS were the least frequently used methods, with seven and two publications, respectively. In contrast, DES-SD appeared in fourteen publications, while DES-ABS was the most widely used combination, with nineteen papers. The subsequent sections discuss each combination in order of popularity, from the least common (DES-SD-ABS) to the most common (DES-ABS) hybrid model.

It is worth noting that the twelve papers reviewed in the previous work (Dos Santos, Kotiadis and Scaparra 2020) are included among the forty-two papers analysed in this review. These are highlighted in the tables below with a superscript (WSC20) following the respective author's name.

2.3.3.1 Discrete Event, System Dynamics, and Agent-Based Model

This review produced the same findings as those in Dos Santos, Kotiadis and Scaparra (2020) regarding the DES-SD-ABS. Only two papers applied the most comprehensive and complex approach within the HS spectrum: one addressing disease management (DM) (Viana *et al.* 2012) and the other focusing on health system planning (HM) (Gao *et al.* 2014), as depicted in Table 5.

Viana *et al.* (2012) developed a model in which DES represented the clinical setting, SD was used to model the process of sight loss in each eye, and ABS explored social care scenarios by

representing health, history, and other individual-level information. Gao *et al.* (2014), on the other hand, developed a model to evaluate the impacts of upstream and downstream interventions on patients diagnosed with diabetes. While DES captured the impact of available resources, SD described the evolution of health, body weight, and pre-diabetes diagnosis status among non-diabetic individuals, and ABS represented individuals with diabetes to capture social network effects and geographical information (Gao *et al.* 2014).

Both studies used the software AnyLogic. The model implementation was considered potential but not realised (IM2), and the model hybridisation was classified as interaction-based (H3) with an automated integration process (I1). The input data were identified as real-world (S1). Both articles reported using data from Canadian official databases, the English Longitudinal Study of Ageing, and the Royal National Institute for Blind People (Viana *et al.* 2012). Another similarity was observed in the conceptualisation phase, as shown in Table 5.

Table 5: Summary of DES-SD-ABS case studies included in this review.

Authors	Model variability					Category (problem)	Main problem	Management lens
	Hybridisation	Integration	Model Input	Validation and Verification	Implementation			
(Gao <i>et al.</i> 2014) ^{WSC20}	H3	I1	S1	V1	IM2	HM	Evaluating the treatment and progression of age-related macular degeneration (AMD).	S&O
(Viana <i>et al.</i> 2012) ^{WSC20}	H3	I1	S1	V1	IM2	DM	Comprehending the rising rates of diabetes and diabetic ESRD.	S

Note 1 Management lens: S&O - Strategic & Operational; S - Strategic.

For both studies, it was unclear how the authors collected their data. Viana *et al.* (2012) stated that a fully stakeholder-driven approach guided the model development; however, the methods of stakeholder involvement, such as interviews or workshops, were not described. In contrast, Gao *et al.* (2014) did not provide details regarding data collection methods or model

development. Finally, the model verification and validation were classified as a statistical approach checking (V1). Viana *et al.* (2012) used statistical methods to compare the results with a baseline model, while Gao *et al.* (2014) reported using sensitivity analysis to validate the outputs of their HS model.

2.3.3.2 System Dynamics and Agent-Based Model

This review resulted in seven SD-ABS case studies (Table 6), which differ from the findings in Dos Santos, Kotiadis and Scaparra (2020), who did not retrieve any papers employing this hybrid combination. Five papers focused on disease management (DM), while one addressed hospital management (HM) and another examined the healthcare system (HS).

For instance, Evenden *et al.* (2021) and Evenden *et al.* (2020) investigated dementia prevalence and outcomes within an ageing population, using SD to represent population-level ageing, dementia onset, and mortality, and ABS to model individual dementia severity progression. Nguyen, Megiddo, and Howick (2022) focused on the spread and outbreak of COVID-19 across multiple care homes, using SD to model COVID-19 transmission dynamics within each care home and ABS to represent the network connections between facilities through bank and agency staff. Similarly, Guo *et al.* (2021) studied the spread of COVID-19 in a Chinese community during the epidemic. Tuson *et al.* (2023) explored the role of social networks in obesity transmission using an HS model, with SD capturing social network interactions and ABS modelling individual health behaviours.

On the other hand, Kolominsky-Rabas *et al.* (2015) and Cernohorsky and Voracek (2012) explored problems associated with hospital management (HM) and the healthcare system (HS), respectively. The former examined the impact of the large-scale introduction of Mobile Stroke Units (MSUs) on the clinical outcomes of stroke patients in a large metropolitan area in Germany, while the latter investigated how information shortages in healthcare influence

patients' preferences for particular health facilities. In both cases, ABS represented patients or MSUs, whereas SD modelled population dynamics.

Table 6: Summary of SD-ABS case studies included in this review.

Authors	Model variability					Category (problem)	Main problem	Management lens
	Hybridisation	Integration	Model Input	Validation & Verification	Implementation			
(Tuson <i>et al.</i> 2023)			S1	V1		DM	Studying the impact of social networks on the spread of obesity.	S
(Nguyen, Megiddo and Howick 2022)	H3	I1	S1	V1		DM	Examining the spread of COVID-19 across multiple care homes.	S
(Evenden <i>et al.</i> 2021)	H3	I1	S1	V1	IM2	DM	Evaluating the dementia prevalence and outcomes within an ageing population.	S
(Guo <i>et al.</i> 2021)	H3	I1	S1	V1		DM	Exploring the impact of emotional contagion on the process of disease transmission.	S
(Evenden <i>et al.</i> 2020)	H3	I1	S1		IM2	DM	Evaluating the dementia prevalence and outcomes within an ageing population.	S
(Kolominsky-Rabas <i>et al.</i> 2015)	H3	I1				HM	Studying the impact of a large-scale introduction of MSUs (Mobile Stroke Units).	S
(Cernohorsky and Voracek 2012)					IM1	H	Evaluating how information (reputation, price) influences the patients' choice of facilities.	S

Note 2 Management lens: S - Strategic

Regarding the simulation software, five papers reported the use of AnyLogic (Nguyen, Megiddo and Howick 2022; Evenden *et al.* 2021; Guo *et al.* 2021; Evenden *et al.* 2020; Kolominsky-Rabas *et al.* 2015), one used programming language (Tuson *et al.* 2023), and another did not specify the commercial package or programming language employed (Cernohorsky and Voracek 2012). The five studies developed in AnyLogic were all classified

as having interaction-based model hybridisation (H3) and, consequently, automated integration (I1).

Five papers reported using real-world data (S1) as model input. For instance, Tuson *et al.* (2023) used longitudinal data from the United Kingdom, and Nguyen, Megiddo and Howick (2022) used datasets from the GOV.UK Coronavirus repositories, and Guo *et al.* (2021) employed data from official health commission websites in four Chinese cities. Conversely, Evenden *et al.* (2021) and Evenden *et al.* (2020) combined data from official repositories with information gathered from experts and previous publications. However, two studies did not report their data sources (Kolominsky-Rabas *et al.* 2015; Cernohorsky and Voracek 2012).

Only four papers explicitly stated the use of a statistical approach (V1) for verification and validation, as shown in Table 6. Evenden *et al.* (2021) and Nguyen, Megiddo and Howick (2022) compared their model outputs with previously published health data, Tuson *et al.* (2023) compared body mass index (BMI) results from the model with forecasting data, and Guo *et al.* (2021) employed sensitivity analysis to validate the model outcomes.

Stakeholder involvement was not a significant factor for SD-ABS models in this review; only two studies briefly mentioned stakeholder participation during data collection or model validation. Evenden *et al.* (2021) noted that several parameters were derived from expert judgement, while Kolominsky-Rabas *et al.* (2015) reported that expert group meetings were held to evaluate model structure, data sources, assumptions, and results. Although Evenden *et al.* (2020) explicitly report stakeholder engagement, this review considered the same level of involvement as in Evenden *et al.* (2021), as both works refer to the same case.

Finally, only three papers discussed implementation (Table 6). Evenden *et al.* (2021) and Evenden *et al.* (2020) described their models as potential but not real (IM2), while Cernohorsky and Voracek (2012) developed a model as a proof of concept (IM1). The remaining four papers

did not discuss implementation or appeared to interpret model implementation merely as the development of the computer model within a commercial software package.

2.3.3.3 Discrete Event Simulation and System Dynamics

Fourteen case studies applied the DES-SD model, making it the second most used hybrid combination in this review, double the number reported in the previous study by Dos Santos, Kotiadis and Scaparra (2020). These twelve papers addressed hospital management problems (HM), one was focused on disease management (DM) and another on the healthcare system (HS).

From a management perspective, eleven papers have explored the strategic and operational issues under analysis, while one adopted a purely strategic management focus (Mielczarek and Zabawa 2016a), and two others used a hybrid model focusing primarily on the operational aspects (Zulkepli and Eldabi 2019; Landa *et al.* 2017), as shown in Table 7.

Overall, all studies employed DES to represent a healthcare facility, while SD was used to examine population dynamics or behavioural processes. For instance, in Viana *et al.* (2014) and Tejada *et al.* (2014), the DES component represented a hospital outpatient clinic, whereas SD was used to model the infection process of Chlamydia in the community and the impact of policies on breast cancer screening and treatment in the United States, respectively. In both studies, the conceptual models clearly distinguished the DES component from the SD model and identified the key elements linking both methods within the HS model.

A similar conceptual structure was presented in the studies by He *et al.* (2013), Mielczarek and Zabawa (2016a), Mielczarek and Zabawa (2017), and Mielczarek, Zabawa and Dobrowolski (2018). Most papers reported the commercial software packages used, with notable variation in their selection. Three studies reported using Simul8 in combination with another software tool for modelling DES.

For instance, Zulkepli, Eldabi and Mustafee (2012), Viana *et al.* (2014), and Zulkepli and Eldabi (2019) combined Simul8 with VenSim. He *et al.* (2013) developed their DES model in Flexsim (SD software) to represent the orthopaedic clinic, and Tejada *et al.* (2014) modelled it in Arena. Mielczarek and Zabawa (2017) also used Arena, but in combination with ExtendSim9. Furthermore, one study reported using AnyLogic (Landa *et al.* 2017) to evaluate how emergency and elective patients interact within a hospital. However, three papers did not report the software or programming language used to build their computer models (Mielczarek, Zabawa and Dobrowolski 2018; Morgan, Belton and Howick 2016; Mielczarek and Zabawa 2016a)

Table 7: Summary of DES-SD case studies included in this review.

Authors	Model variability					Category(problem)	Main problem	Management lens
	Hybridisation	Integration	Model Input	Validation and Verification	Implementation			
(Mielczarek 2019)			S1	V1	IM2	HM	Determining the influence of demographic changes on the demand for inpatient hospital services.	S&O
(Zulkepli and Eldabi 2019)		I3	S2			HM	Assessing the viability of hybrid simulation over a single technique.	O
(Mielczarek, Zabawa and Dobrowolski 2018) ^{WSC20}			S1			HM	Evaluating the increase in demand for healthcare services, given the age structure of the Polish population.	S&O
(Hajjarsaraei, Shirazi and Rezaeian 2018)			S1	V1		HM	Evaluating the impact of implementing a fast track on the ED's key performance indicators.	S&O
(Mielczarek and Zabawa 2017) ^{WSC20}			S1	V2		HM	Estimating the level and structure of the demand for healthcare services.	S&O
(Landa et al. 2017)	H3	I1	S1	V1		HM	Analysing how emergent and elective patient flows interact inside the hospital.	O
(Mielczarek and Zabawa 2016a)		I1	S1			HM	Evaluating the relation between short-term demographic forecasts and health policy models.	S

Authors	Model variability					Category(problem)	Main problem	Management lens
	Hybridisation	Integration	Model Input	Validation and Verification	Implementation			
(Mielczarek and Zabawa 2016b) ^{wsc20}			S1			HM	Studying the influence of long-term population changes on the demand for healthcare services.	S&O
(Morgan, Belton and Howick 2016) ^{wsc20}	H2		S1			HM	Planning the radiotherapy treatment and possible changes in the treatment regime.	S&O
(Tejada <i>et al.</i> 2015)			S1	V1		HM	Analysing the problem of resource scheduling of emergency departments.	S&O
(Viana <i>et al.</i> 2014) ^{wsc20}	H2	I3	S1	V3	IM2	DM	Comprehend the relationship between the disease spread and the increase in clinic demand.	S&O
(Tejada <i>et al.</i> 2014) ^{wsc20}			S1	V1		HM	Evaluating the incidence and progression of untreated breast cancer.	S&O
(He <i>et al.</i> 2013) ^{wsc20}			S1		IM2	HM	Quantifying the potential impact of an overbooking policy.	S&O
(Zulkepli, Eldabi and Mustafee 2012)		I3	S2		IM2	HS	Evaluating the benefits of OR/Simulation techniques for modelling large systems.	S&O

Note 3 Management lens: S&O - Strategic & Operational; S - Strategic; O -Operational

Regarding the areas of variability, only three papers explicitly reported model hybridisation (Landa *et al.* 2017; Morgan, Belton and Howick 2016; Viana *et al.* 2014), as shown in Table 7. While the first reported the model hybridisation as interaction (H3), the last two were developed as sequential (H2). Most studies used real-world data (S1) as model input, while two relied on previous publications to determine model parameter values (Zulkepli and Eldabi 2019; Zulkepli, Eldabi and Mustafee 2012).

Three papers (Zulkepli and Eldabi 2019; Zulkepli, Eldabi and Mustafee 2012; Viana *et al.* 2014) reported integration between DES and SD as supported by intermediate tools (I3), while two described automated integration (I1). The remaining articles did not specify how model integration was conducted. Regarding model implementation, most studies did not discuss

implementation in real-world settings; however, four cases reported their models as potential but not realised (IM2) (Zulkepli, Eldabi and Mustafee 2012; He *et al.* 2013; Viana *et al.* 2014; Mielczarek 2019).

As shown in Table 7, none of the articles explicitly reported verification and validation processes. Fewer than half explained how they ensured the accuracy of model outcomes. For instance, five studies employed statistical analysis (V1) for validation, such as using a Student's t-test to compare empirical data with simulated outputs of monthly ward occupancy (Landa *et al.* 2017), comparing model results with historical data (Mielczarek 2019; Tejada *et al.* 2015; Tejada *et al.* 2014), and conducting sensitivity analysis (Hajjarsaraei, Shirazi and Rezaeian 2018). Viana *et al.* (2014) reported using both expert and statistical validation (V3), with key stakeholders performing face validation of the conceptual model.

Regarding stakeholder involvement during model development, the DES-SD combination had the highest number of studies engaging stakeholders, particularly during data collection and model conceptualisation. The methods for involving stakeholders varied across studies. For example, three papers stated that discussions with breast cancer experts supported the development of the conceptual model (Tejada *et al.* 2015; Tejada *et al.* 2014), while Viana *et al.* (2014) reported that discussions with clinic staff informed the understanding of the patient pathway through the outpatient clinic. He *et al.* (2013) and Hajjarsaraei, Shirazi and Rezaeian (2018) conducted interviews to collect data and develop the patient flow models. Similarly, Morgan, Belton and Howick (2016) used structured and unstructured interviews to collect data to build the conceptual model.

2.3.3.4 Discrete Event Simulation and Agent-Based Model

DES-ABS appears to have become the most popular hybrid model after 2019. Until 2018, only three works reported this combination (Dos Santos, Kotiadis and Scaparra 2020). However,

between 2019 and October 2023, sixteen case studies were published in conferences and academic journals. Overall, DES-ABS models addressed disease management (DM) in ten papers and hospital management (HM) in nine cases, as shown in Table 8.

Among the nine papers addressing disease management problems (DM), six examined the impact of COVID-19, with three focusing specifically on vaccination and testing centres. For example, Asgary *et al.* (2020) evaluated the design and operation of drive-throughs for future mass vaccination facilities for COVID-19. Bitencourt, Nikfar and Mykoniatis (2021) explored how vaccine distribution affects the spread of COVID-19 and hospitalisations in Alabama. Maïzi and Bendavid (2022) focused on improving COVID-19 testing centres in Montreal. The remaining three studies examined COVID-19 transmission. Possik *et al.* (2023) investigated the effects of parameters such as hospital capacity and vaccination policy on viral spread; while Anagnostou and Mykoniatis (2022) analysed virus transmission in a haemodialysis unit to optimise space and equipment layouts; Cimini *et al.* (2021) assessed COVID-19 containment measures in indoor environments to support businesses in implementing strategies to reduce transmission.

As shown in Table 8, four additional papers addressed distinct disease management problems (DM). Hajłasz and Mielczarek (2022) used DES to represent the educational process in primary schools, while ABS represented students to investigate the influence of peer environments on the effectiveness of dental caries prevention in Poland. Tofighi *et al.* (2022) integrated agent-based modelling and discrete-event simulation to capture risky contacts among pilgrims and assess different scenarios at Masjid-Al-Haram in Saudi Arabia. Elliott *et al.* (2020) modelled a hospital ward dynamic to replicate a real-life bacterial outbreak, using DES for the hospital environment, ABS for patients and static agents, such as beds, wards, and floors. Conversely, Penny, Bayer and Brailsford (2023) proposed a DES-ABS to study the impact of telecare on patients with dementia.

Hospital management (HM) has also been a common focus in several case studies. In general, DES represented the patient pathway within outpatient clinics or hospitals. For instance, Viana *et al.* (2017) and Viana *et al.* (2018) extended their earlier work on modelling an obstetrician department (Viana *et al.* 2016). In all studies, DES represented the healthcare facility, while ABS modelled the behaviour of patients.

Table 8: Summary of DES-ABS case studies included in this review.

Authors	Model variability					Category(problem)	Main problem	Management lens
	Hybridisation	Integration	Model Input	Validation and Verification	Implementation			
(Penny, Bayer and Brailsford 2023)	H3	I1	S1	V3		DM	Evaluating the impact of implementing telecare for people with dementia.	S&O
(Possik <i>et al.</i> 2023)	H3	I1	S1			DM	Analysing the COVID-19 transmission in an ICU unit.	O
(Terning, El-Thalji and Brun 2023)	H3	I1	S1	V1		HM	Evaluating the impact of changes on patient flow.	O
(Liu <i>et al.</i> 2023)	H3	I1	S3	V1	IM2	HM	Analysing alternatives to limited resource scheduling of emergency departments.	S&O
(Anagnostou and Mykoniatis 2022)	H3	I1	S1	V3	IM1	DM	Simulating the spread of the virus under various parameters (hospital capacities and vaccination policy).	S&O
(Hajłasz and Mielczarek 2022)	H3	I1	S2			DM	Investigating the impact of environments on strengthening or weakening the effectiveness of dental caries prevention.	S
(Tofighi <i>et al.</i> 2022)	H3	I1	S1			DM	Evaluating the spread of the virus in risky contacts among the pilgrims.	S
(Bitencourt, Nikfar and	H3	I1	S1		IM1	DM	Determine how the vaccine distribution affects	S&O

Authors	Model variability					Category (problem)	Main problem	Management lens
	Hybridisation	Integration	Model Input	Validation and Verification	Implementation			
Mykoniatis (2021)							the spread of COVID-19 and hospitalisation rates.	
(Maïzi and Bendavid 2021)	H3	I1	S1	V1		DM	Improving COVID-19 test centres located in the Montreal region	O
(Cimini <i>et al.</i> 2021)	H3	I1	S1	V3		DM	Evaluating the spread of COVID-19 in closed environments such as work and study places.	S&O
(Hamza, Majid and Hujainah 2021)	H3	I1	S3	V1		HM	Addressing the key challenge of the patient throughout time with HS.	S&O
(Asgary <i>et al.</i> 2020)	H3	I1	S2	V1	IM1	DM	Evaluating the design and operation of drive-through mass vaccination facilities for COVID-19.	S&O
(Elliott <i>et al.</i> 2020)	H3	I1	S1			DM	Assessing hospital ward dynamics and pathogen transmission.	S&O
(Elliott <i>et al.</i> 2019)	H3	I1	S1	V1		HM	Investigating the impact of using a risk assessment tool (RAT) to improve the selection of patients.	O
(Viana <i>et al.</i> 2018) ^{WSC20}	H3	I1	S1	V1	IM2	HM	Evaluating changes in patient flow at the outpatient clinic.	S&O
(Lee <i>et al.</i> 2019)	H3	I1	S1	V1		HM	Simulating the examination workflow at an MRI department in a medical centre.	O
(Ying and Kittipittaya korn 2018)	H3	I1	S1	V1		HM	Evaluating waiting time on the draftees' physical examination service.	O
(Viana <i>et al.</i> 2017) ^{WSC20}	H3	I1	S1	V1	IM2	HM	Evaluating the effectiveness of the home hospital service.	S&O
(Viana <i>et al.</i> 2016) ^{WSC20}	H3	I1	S1	V1	IM2	HM	Evaluating the benefits of hybrid simulation.	S&O

Note 4 Management lens: S&O - Strategic & Operational; S - Strategic; O - Operational

Three articles examined emergency departments (EDs) operations. Terning, El-Thalji and Brun (2023) and Liu *et al.* (2023) used DES to model ED processes and ABS to represent patients. The former compared patient flow under three intervention policies: (1) adding extra treatment rooms, (2) introducing a waiting zone, and (3) combining both interventions. The latter focused on resource scheduling under uncertain conditions. Hamza, Majid and Hujainah (2021) developed a patient-flow model (SIM-PFED) to address patient throughput time, using DES for the ED process and ABS to represent participants such as nurses, doctors, and laboratory staff.

The remaining three papers were examined in hospitals and medical centres, considering the behaviour of agents involved in care delivery. Ying and Kittipittayakorn (2018) evaluated ways to improve draft physical examination services by reducing waiting times, with DES modelling the examination process and ABS representing hospital staff. Similarly, Lee *et al.* (2019) analysed process improvements in the MRI department, while Elliott *et al.* (2019) investigated the impact of using a risk assessment tool (RAT) to enhance patient selection for colonoscopy procedures in detecting bowel disease (SBD). In these cases, DES effectively modelled system processes involving resource constraints and queues, whereas ABS captured patient behaviour.

In general, most studies used AnyLogic software, which enabled all simulation methods to be modelled within the same environment. Only Penny, Bayer and Brailsford (2023) and Hajlasz and Mielczarek (2022) reported using Simul8 and Arena, respectively. Furthermore, as shown in Table 8, all articles classified their model hybridisation as interaction-based (H3) and their model integration process as automated (I1).

A further similarity across the studies concerned data usage. Sixteen papers reported using real-world data (S1), and one employed illustrative data (S2) (Liu *et al.* 2023), and two used a mix of real and illustrative data (S3) (Possik *et al.* 2023; Hajłasz and Mielczarek 2022).

Seven papers made explicit statements regarding model implementation. Three studies (Anagnostou and Mykoniatis 2022; Bitencourt, Nikfar and Mykoniatis 2021; Asgary *et al.* 2020) proposed a proof of concept (IM1) model, while five others described their model as potential but not real (IM2) (Liu *et al.* 2023; Viana *et al.* 2018; Viana *et al.* 2017; Viana *et al.* 2016).

Model validation and verification were predominantly a statistical approach (V1). Eleven papers reported using statistical methods to compare model results with historical data (Terning, El-Thalji and Brun 2023; Liu *et al.* 2023; Maïzi and Bendavid 2021; Viana *et al.* 2018). Two studies used sensitivity analysis (Asgary *et al.* 2020; Elliott *et al.* 2019), while another two applied t-tests (Hamza, Majid and Hujainah 2021; Ying and Kittipittayakorn 2018). Three studies made general statements about their method for validating the model. For instance, Viana *et al.* (2016) ran empirical data through the model as a form of validation, and Viana *et al.* (2017) stated that verification and validation of the base model were conducted.

Conversely, three papers reported using combined expert and statistical validation (V3) (Penny, Bayer and Brailsford 2023; Anagnostou and Mykoniatis 2022; Cimini *et al.* 2021). Five additional studies did not provide any statement regarding their model verification and validation procedures, such as Bitencourt, Nikfar and Mykoniatis (2021) and Elliott *et al.* (2019).

2.4 Conceptual Model in Hybrid Simulation in Healthcare

Conceptual modelling is one of the most critical and yet least understood stages in developing a simulation model (Jones *et al.* 2022; Tako *et al.* 2019). As the first stage in the simulation

lifecycle (Robinson 2014), conceptual modelling addresses one of the most challenging issues in simulation modelling as it determines “...*the content of the simulation model.*” (Robinson 2013, page 377). In other words, during this stage, modellers face the challenge of understanding the real system and translating it into a non-software-specific description of the computer simulation model (Robinson *et al.* 2015). The design of a conceptual model influences all aspects of a simulation study, particularly data requirements, model development time, model validity, speed of experimentation, and the level of confidence placed in model results (Robinson 2006).

Despite extensive research, there is no agreed definition of the conceptual model in simulation (Jones, Kotiadis and O’Hanley 2019; Robinson *et al.* 2015). A widely cited definition is that of Robinson (2008), who described the conceptual model as the abstraction of a real-world system, independent of coding or software, outlining the objectives, inputs, outputs, content, assumptions, and simplifications of a simulation model (Jones *et al.* 2022; Tako *et al.* 2019; Brailsford *et al.* 2019; Kotiadis and Robinson 2008).

The literature on conceptual modelling in stand-alone simulation already presents established methods and philosophical viewpoints. Several studies have introduced frameworks supporting the development of DES (Robinson *et al.* 2015), SD (Vennix 1999; Forrester 1961), and ABS (Grimm *et al.* 2020; Müller *et al.* 2013) conceptual models. According to Jones *et al.* (2022), these frameworks reflect distinct philosophical perspectives and facilitate model documentation, improving understanding, replication, and reusability in future research (Laatabi *et al.* 2018).

However, in the hybrid simulation (HS), the literature on conceptual modelling remains underdeveloped and underreported. Recent reviews have identified conceptual modelling as one of the least addressed areas in HS studies (Brailsford *et al.* 2019; Tako *et al.* 2019).

Brailsford *et al.* (2019) found that only 63% of reviewed papers provided evidence of conceptual model development. Similarly, Kar, Eldabi and Fakhimi (2022) and Dos Santos, Kotiadis and Scaparra (2020) highlighted a lack of generic guidance for model development as a major gap in HS research. This finding was confirmed by the current review, in which only half of the analysed papers demonstrated evidence of conceptual model development, as discussed in the following paragraphs.

Table 9 summarises the findings regarding evidence of conceptual model development in HS. Since there is no universal definition of an HS conceptual model (Brailsford *et al.* 2019), this research adopted the generic definition proposed by Robinson (2008), which was also used as a reference in a panel discussion on conceptual modelling in HS (Tako *et al.* 2019). For each case study, this research examined whether the authors have included a discussion of the four CM components: (1) model objective, (2) model inputs, (3) model outputs, (4) model content, and (5) assumptions for the whole hybrid simulation, as well as the (6) model representation (Tako *et al.* 2019; Robinson 2008). Each component was classified with Y (Yes, clear evidence provided), P (Partial - brief discussion provided), or N (No - no discussion or evidence found in the paper).

As shown in Table 9, only one conceptual modelling component was consistently discussed across all papers - the model objectives. All reviewed studies described their objectives, preceded by either a brief (Guo *et al.* 2021; Mielczarek and Zabawa 2016b; Mielczarek and Zabawa 2017) or in-depth (Penny, Bayer and Brailsford 2023; Hamza, Majid and Hujainah 2021; Tejada *et al.* 2015) discussion of the problem context.

The model context was the second most discussed aspect, with nineteen articles detailing the model's scope and 23 partially approaching this component. For instance, Anagnostou and Mykoniatis (2022) used the Reporting of Empirical Simulation Studies (STRESS) framework

(Monks *et al.* 2019) and the Multi-paradigm Modelling and Simulation Framework (MPMF) (Mykoniatis and Anagnostou 2020) to describe the ABS and DES modules, outlining details of the overall simulation and describing the interaction points between each stand-alone method in the HS model.

Table 9: Overview of the conceptual model in healthcare case studies.

HS model	Authors	Conceptual model components (Robinson 2008)							Model representation
		Objective	Inputs	Outputs	Model Content	Assumptions	HS Model illustration	Stakeholder engagement	
DES-SD-ABS	(Gao <i>et al.</i> 2014) wsc20	Y	P	Y	Y	P	N	N	HS Computer model
	(Viana <i>et al.</i> 2012) wsc20	Y	P	P	P	P	P	Y	Macro view for a CM
SD-ABS	(Tuson <i>et al.</i> 2023)	Y	Y	Y	Y	N	N	N	Single methods
	(Nguyen, Megiddo and Howick 2022)	Y	Y	Y	Y	Y	P	N	No clear illustration for CM.
	(Evensden <i>et al.</i> 2021)	Y	Y	Y	Y	Y	Y	Y	Hybrid CM.
	(Guo <i>et al.</i> 2021)	Y	N	P	Y	Y	Y	N	No clear illustration for CM.
	(Evensden <i>et al.</i> 2020)	Y	Y	Y	Y	Y	Y	N	Hybrid CM.
	(Kolominsky-Rabas <i>et al.</i> 2015)	Y	P	P	P	P	N	Y	No representation
	(Cernohorsky and Voracek 2012)	Y	P	P	Y	N	N	N	Computer model
DES-SD	(Mielczarek 2019)	Y	Y	P	P	Y	Y	N	Schematic Hybrid CM.
	(Zulkepli and Eldabi 2019)	Y	N	P	P	N	N	N	Single methods
	(Mielczarek, Zabawa and Dobrowolski 2018) wsc20	Y	P	P	P	N	N	N	Single methods
	(Hajjarsaraei, Shirazi and Rezaeian 2018)	Y	Y	Y	Y	Y	N	Y	Single methods

HS model	Authors	Conceptual model components (Robinson 2008)							Model representation
		Objective	Inputs	Outputs	Model Content	Assumptions	HS Model illustration	Stakeholder engagement	
	(Mielczarek and Zabawa 2017) wsc20	Y	Y	Y	P	N	N	N	Single methods
	(Landa et al. 2017)	Y	N	N	P	N	P	N	Macro view for a CM
	(Mielczarek and Zabawa 2016a)	Y	P	P	P	P	P	N	Macro view for a CM
	(Mielczarek and Zabawa 2016b) wsc20	Y	N	N	P	N	N	N	Single methods
	(Morgan, Belton and Howick 2016) wsc20	Y	P	N	P	N	N	Y	Single methods
	(Tejada et al. 2015)	Y	P	P	P	Y	N	Y	Single methods
	(Viana et al. 2014) wsc20	Y	N	Y	Y	P	N	Y	Single methods
	(Tejada et al. 2014) wsc20	Y	P	P	P	N	N	Y	No representation
	(He et al. 2013) wsc20	Y	P	P	P	P	N	Y	Single methods
	(Zulkepli, Eldabi and Mustafee 2012)	Y	N	Y	P	N	N	N	Single methods
DES-ABS	(Penny, Bayer and Brailsford 2023)	Y	Y	Y	Y	Y	P	Y	Macro view for a CM
	(Possik et al. 2023)	Y	N	P	P	N	N	Y	Computer & and single models
	(Terning, El-Thalji and Brun 2023)	Y	P	P	Y	P	N	N	Single methods
	(Liu et al. 2023)	Y	P	P	Y	P	N	N	Single methods
	(Anagnostou and Mykoniatis 2022)	Y	Y	Y	Y	Y	N	N	Computer and single-model
	(Hajłasz and Mielczarek 2022)	Y	P	Y	Y	N	P	N	Macro view for a CM
	(Tofighi et al. 2022)	Y	N	P	P	N	N	N	Computer model
	(Bitencourt, Nikfar and Mykoniatis 2021)	Y	N	P	Y	Y	N	N	Computer model
	(Maïzi and Bendavid 2021)	Y	P	Y	P	N	N	N	Computer model

HS model	Authors	Conceptual model components (Robinson 2008)							Model representation
		Objective	Inputs	Outputs	Model Content	Assumptions	HS Model illustration	Stakeholder engagement	
	(Cimini et al. 2021)	Y	Y	Y	Y	Y	N	Y	Single methods
	(Hamza, Majid and Hujainah 2021)	Y	Y	Y	Y	P	P	N	Macro view for a CM
	(Asgary et al. 2020)	Y	P	P	Y	P	N	N	Computer model
	(Elliott et al. 2020)	Y	Y	Y	P	P	Y	Y	Hybrid CM.
	(Elliott et al. 2019)	Y	Y	P	P	N	N	N	No representation
	(Viana et al. 2018) wsc20	Y	P	P	P	P	N	Y	No representation
	(Lee et al. 2019)	Y	Y	Y	Y	P	N	N	Single methods
	(Ying and Kittipittayakorn 2018)	Y	N	Y	P	N	Y	N	Hybrid CM.
	(Viana et al. 2017) wsc20	Y	P	P	P	Y	P	Y	Macro view for a CM
	(Viana et al. 2016) wsc20	Y	P	P	P	N	N	Y	Single methods

Likewise, Nguyen, Megiddo, and Howick (2022) used the ODD protocol (Grimm *et al.* 2020; Müller *et al.* 2013; Grimm *et al.* 2010) to describe the SD-ABS hybrid model. In both papers, model input, model output, and assumptions were comprehensively provided. Conversely, other studies did not use a formal protocol but offered detailed documentation of all CM components, often using the appendices to include supplementary material (Penny, Bayer and Brailsford 2023; Evenden *et al.* 2021; Evenden *et al.* 2020).

As shown in Table 9, model input was reported in most papers. In total, eighteen papers provided partial input descriptions, generally emphasising methodology development and scenario design (Terning, Brun and El-Thalji 2022; Morgan, Belton and Howick 2016; Viana

et al. 2012) or model representation using schematic diagrams and figures (Liu *et al.* 2023; Maïzi and Bendavid 2021; Asgary *et al.* 2020; Viana *et al.* 2016; Cernohorsky and Voracek 2012), which may explain the lack of input detail. Ten papers did not include input information (Bitencourt, Nikfar and Mykoniatis 2021; Guo *et al.* 2021; Tofighi *et al.* 2022; Possik *et al.* 2023; Viana *et al.* 2014; Ying and Kittipittayakorn 2018; Zulkepli and Eldabi 2019; Zulkepli and Eldabi 2015), while fourteen provided a comprehensive description of their model inputs (Tuson *et al.* 2023; Penny, Bayer and Brailsford 2023; Evenden *et al.* 2021; Evenden *et al.* 2020; Elliott *et al.* 2020; Hamza, Majid and Hujainah 2021; Cimini *et al.* 2021; Lee *et al.* 2019).

Similarly, most papers only partially described model outputs. Fourteen papers provided detailed outputs, while twenty-one partially reported them (Viana *et al.* 2016; Viana *et al.* 2017; Viana *et al.* 2012; Tejada *et al.* 2014). These papers typically emphasised results presentation through graphics (Asgary *et al.* 2020; Bitencourt, Nikfar and Mykoniatis 2021; He *et al.* 2013) or model representation diagrams (Asgary *et al.* 2020; Bitencourt, Nikfar and Mykoniatis 2021; Cernohorsky and Voracek 2012; Gao *et al.* 2014; Maïzi and Bendavid 2021; Possik *et al.* 2023; Zulkepli and Eldabi 2019; Viana *et al.* 2016; Viana *et al.* 2012), often providing only a few graphics outputs at the end of the paper (Liu *et al.* 2023; Bitencourt, Nikfar and Mykoniatis 2021; Viana *et al.* 2018; Mielczarek 2019). Three papers did not discuss simulation outputs, whereas eighteen used graphics, tables, and detailed numerical results (Cimini *et al.* 2021; Tuson *et al.* 2023; Evenden *et al.* 2021; Anagnostou and Mykoniatis 2022; Nguyen, Megiddo and Howick 2022; Hamza, Majid and Hujainah 2021; Lee *et al.* 2019; Ying and Kittipittayakorn 2018; Hajjarsaraei, Shirazi and Rezaeian 2018; Gao *et al.* 2014).

The model assumptions were among the least reported CM components. Seventeen papers did not report assumptions (Tuson *et al.* 2023; Tofighi *et al.* 2022; Viana *et al.* 2018; Landa *et al.* 2017), and thirteen provided partial information (Liu *et al.* 2023; Terning, El-Thalji and Brun 2023; Asgary *et al.* 2020; Elliott *et al.* 2020; Elliott *et al.* 2019). Only twelve papers included a

comprehensive list of assumptions, either in the main text (Anagnostou and Mykoniatis 2022; Evenden *et al.* 2021; Hamza, Majid and Hujainah 2021; Hajjarsaraei, Shirazi and Rezaeian 2018; Tejada *et al.* 2015) or in appendices (Evenden *et al.* 2020).

The final component assessed was model representation, as shown in Table 9. The concept of model representation, or the pictorial interface, was first introduced by Hurrion initially and later discussed in Robinson (2005). Hurrion's work pioneered the visual representation of Operational Research models, enabling analysts and users to explore system dynamics and gain an understanding of expected operational behaviour (Hurrion 1986). Since then, visual interactive simulation has become essential for enhancing communication between modellers and decision-makers (Onggo 2010; Bell *et al.* 1999).

Despite five decades since Hurrion's initial work, model representation in simulation, particularly in Hybrid Simulation, remains underdeveloped (Brailsford *et al.* 2019). This review supports that view. Only five papers fully represented their integrated models, using different notations. Guo *et al.* (2021) applied the multi-layer network concept (Mustafee *et al.* 2015; Ficco *et al.* 2014) to depict the model, aiming to show both macro- and micro-level views, though neither the SD nor ABS components were fully integrated in the diagram. Evenden *et al.* (2020) used stock-flow notation for SD and UML state diagrams for ABS, combining both with text boxes describing inputs. Mielczarek (2019) illustrated a DES-SD model using basic blocks, including the inputs for each method and the model output. Elliott *et al.* (2020) and Ying and Kittipittayakorn (2018) produced schematic DES-ABS diagrams with directional arrows to indicate information transfer, though DES elements were absent. Evenden *et al.* (2021), however, however, integrated icons, shapes, and arrows to depict the SD and ABS modules as a unified model.

Eight papers partially represented their conceptual model, often through screenshots. For instance, Penny, Bayer and Brailsford (2023) included a Simul8 screenshot and schematic icons, while Nguyen, Megiddo and Howick (2022) used geometric illustrations, though both lacked intuitive visual clarity.

In addition, five papers offered partial visualisations that provided an overview of the HS model. For instance, Landa *et al.* (2017) used connected DES and SD diagrams, but the integration links were unclear. Mielczarek and Zabawa (2016a), Hajłasz and Mielczarek (2022), Hamza, Majid and Hujainah 2021, and Viana *et al.* (2017) used combinations of blocks, arrows, and flowcharts, though integration remained visually ambiguous.

Twenty-eight papers provided no proper model illustration, classified as “N” in Table 9. Three papers lacked any representation (Kolominsky-Rabas *et al.* 2015; Tejada *et al.* 2014; Elliott *et al.* 2019; Viana *et al.* 2018). Four used a screenshot of the 2D or 3D computer model (Cernohorsky and Voracek 2012; Maïzi and Bendavid 2021; Tofighi *et al.* 2022; Terning, El-Thalji and Brun 2023). Eleven depicted stand-alone models separately (Viana *et al.* 2012; Brailsford *et al.* 2013; Zulkepli and Eldabi 2019; Hajjarsaraei, Shirazi and Rezaeian 2018; Mielczarek 2016; Morgan, Belton and Howick 2016; Tejada *et al.* 2015; Viana *et al.* 2014; He *et al.* 2013; Zulkepli, Eldabi and Mustafee 2012; Lee *et al.* 2019). Cimini *et al.* (2021) represented only single methods, combining an AnyLogic state chart for ABS and a flowchart for DES. Gao *et al.* (2014) used a screenshot of their AnyLogic model with two state charts representing the diabetes progression and the treatment pathways. However, neither provided a full DES-SD-ABS view. Finally, Possik *et al.* (2023) and Anagnostou and Mykoniatis (2022) illustrated flowcharts and state charts separately, without integration links.

Regarding stakeholder engagement, Table 9 shows that only sixteen out of forty-two HS case studies reported any stakeholder involvement, revealing a significant gap in participatory

practice. In DES-ABS studies, stakeholder participation was most frequent but largely limited to interviews for data collection and parameter definition (Penny, Bayer and Brailsford 2023; Terning, El-Thalji and Brun 2023; Elliott *et al.* 2020; Hajjarsaraei, Shirazi and Rezaeian 2018; Fan and Geerts 2012). Some studies mentioned stakeholder involvement during the conceptual modelling phase (Cimini *et al.* 2021; Viana *et al.* 2016), though methodological details were often missing. This indicates a consultative rather than participatory approach, where stakeholders act as informants rather than co-developers.

DES-SD studies showed slightly more structured engagement, with stakeholders contributing during problem structuring and model design, including discussions with health experts (Tejada *et al.* 2015; Viana *et al.* 2014; Tejada *et al.* 2014) and data collection interviews (Hajjarsaraei, Shirazi and Rezaeian 2018; Morgan, Belton and Howick 2016; He *et al.* 2013). However, these interactions were typically informal and lacked methodological consistency.

Limited stakeholder involvement was also observed in SD-ABS studies. Only two reported participation, mainly during data collection (Evenden *et al.* 2021; Kolominsky-Rabas *et al.* 2015). These lacked clear descriptions of engagement methods or qualitative processes used.

Finally, DES-SD-ABS studies offered minimal evidence of stakeholder contribution. Although Viana *et al.* (2012) described their work as fully stakeholder-driven, it lacked detail on the engagement process across model development stages.

Stakeholder engagement is widely recognised as crucial for successful simulation implementation (Jones, Kotiadis and O’Hanley 2019; Brailsford *et al.* 2009; Harper and Pitt 2004). This involvement can occur throughout various stages of model development, including conceptualisation, coding, experimentation, and implementation (Brailsford *et al.* 2019; Robinson 2014). Some studies restrict stakeholder participation to conceptualisation (Pessôa *et al.* 2015; Jun, Jacobson and Swisher 1999; Lehaney, Clarke and Paul 1999), while others

advocate continuous engagement across the simulation lifecycle, known as the facilitated modelling approach (Tako and Kotiadis 2018a; Vennix 1999).

Facilitation approach, though well established, has only recently gained emphasis in Operational Research (OR), particularly simulation. Its benefits have been widely demonstrated in SD and DES healthcare studies (Zimmerman *et al.* 2016; Jahangirian *et al.* 2015; Robinson *et al.* 2014; Rouwette *et al.* 2011; Robinson and Pidd 1998). However, there remains little to no literature addressing stakeholder engagement in ABS and HS (Jones *et al.* 2022; Powell and Mustafee 2017). Reviews consistently highlight this gap across DES (Jahangirian *et al.* 2015) and HS (Dos Santos, Kotiadis and Scaparra 2020; Powell and Mustafee 2017; Mustafee *et al.* 2015).

The findings of this research corroborate previous studies, reinforcing that stakeholder engagement in HS remains limited. Across all hybrid modelling types, evidence of engagement is restricted in scope and detail, with minimal adoption of facilitated approaches or participatory frameworks. These findings echo prior research noting the absence of methodological structure in stakeholder engagement within HS (Jones *et al.* 2022; Dos Santos, Kotiadis and Scaparra 2020; Jones, Kotiadis and O’Hanley 2019). The results emphasise the need for systematic, inclusive approaches to stakeholder involvement - particularly as model complexity increases.

2.5 PartiSim - a multi-methodology framework to support facilitated simulation modelling

PartiSim, short for “Participative Simulation”, is a structured, multi-methodological framework developed to support stakeholder involvement across the lifecycle of discrete event simulation (DES) studies. The methodology represents a deliberate departure from conventional, modeller-centric simulation practices. It was conceived to address the modelling challenges encountered in complex environments - particularly in healthcare - where multiple actors, each with their

own perspectives, expertise, and tacit knowledge, must contribute to the articulation of the problem and the development of a usable simulation model (Tako and Kotiadis 2015). By incorporating elements of Soft Systems Methodology (SSM) into the predominantly positivist tradition of DES, PartiSim provides a mechanism for engaging stakeholders through structured facilitation, model co-construction, and joint reflection.

At a philosophical level, PartiSim is grounded in a multi-paradigm perspective that integrates both 'hard' and 'soft' approaches within Operational Research. The DES component is aligned with the hard OR paradigm, which privileges objectivity, quantification, and the formal modelling of structured systems. In contrast, the incorporation of SSM introduces a soft OR orientation, one that acknowledges the interpretative nature of organisational problems and the importance of multiple worldviews. One of PartiSim's distinguishing features lies in its explicit recognition of these paradigms and its guidance on when and how to adopt an appropriate epistemological stance. This methodological reflexivity supports a more inclusive, context-sensitive modelling process and enhances both the relevance and credibility of the model in practice.

The framework comprises six stages: initiating the study, defining the problematic situation, creating the conceptual framework, model coding, experimentation, and implementation, as displayed in Figure 5 (Tako and Kotiadis 2015; Tako and Kotiadis 2018a). Each stage comprises specific activities and outputs designed to support participatory model development and facilitate its eventual use. Four of these stages take place within facilitated stakeholder workshops, which serve as the primary vehicle for knowledge elicitation, sense-making, and consensus-building. Modellers act as facilitators, guiding discussions through four workshops using Soft Systems Methodology (SSM) tools. As shown in Figure 5, workshops occur in stages 2, 3, 5 and 6. This participative approach ensures stakeholders are involved throughout the simulation lifecycle, from problem definition to implementation (Tako and Kotiadis 2018b).



Figure 5: PartiSim modelling framework (Tako and Kotiadis 2018, page 8).

As shown in Table 10, the first stage, “Initiate Simulation Study,” involves gathering preliminary information about the system under investigation, establishing the scope and objectives of the study, and identifying the relevant stakeholder group. This stage typically involves informal interviews, site visits, and meetings with key stakeholders and results in the articulation of initial objectives, study timelines, and definition of key names to join the study (Tako and Kotiadis 2018b).

The second stage, “Define System,” marks the first facilitated workshop and represents a transition into the soft paradigm. During this stage, stakeholders are invited to collaboratively explore the boundaries of the system, articulate the problem situation, and reflect upon its cultural and political dimensions. Tools derived from SSM, such as CATWOE (Customers, Actors, Transformation, Weltanschauung (Worldview), Owners, Environmental constraints) analysis and Root Definitions (Checkland 2000; Checkland and Scholes 1999), are employed to assist stakeholders in identifying the key elements of the system and defining its purpose. This stage culminates in a shared system map and an agreed-upon understanding of the system’s structure and behaviour (Tako and Kotiadis 2015). By engaging stakeholders in framing the

problem and delineating the system's boundaries, this stage enhances the model's relevance and legitimacy.

The third stage, "Specify Conceptual Model," builds upon the outputs of the second workshop and is dedicated to refining the simulation study's objectives and developing a conceptual model that can subsequently be translated into a computational DES model. This stage involves the construction of purposeful activity models (PAMs), process flow diagrams, and the formulation of key performance measures (Tako and Kotiadis 2018b). As with the previous stage, this activity is conducted within a facilitated workshop setting and remains anchored in a mixed paradigm. The soft paradigm supports articulating stakeholder concerns and values, while the hard paradigm informs structuring system elements into formal representations. A sub-stage follows the workshop, during which the modelling team consolidates the results and prepares the groundwork for model coding.

Stage four, "Develop Computer Model," is primarily technical and firmly situated within the hard OR tradition. It involves coding the conceptual model into a simulation software platform, collecting and analysing data, and executing model verification and validation procedures. Stakeholders are typically not involved in this stage, as it requires specialist modelling expertise and is time-intensive (Tako and Kotiadis 2018b). Nonetheless, some interaction may occur, particularly in the provision and interpretation of data or in clarifying modelling assumptions (Tako and Kotiadis 2018a).

The fifth stage, "Experimentation," presents stakeholders back into the process through a third facilitated workshop. Here, the validated simulation model is employed to evaluate alternative scenarios, each reflecting different configurations of system variables and policies (Tako and Kotiadis 2018b).

Multi-Criteria Decision Analysis (MCDA) is commonly used to guide the discussion and help stakeholders assess the desirability and feasibility of different options across multiple dimensions (Tako and Kotiadis 2018a). This stage is undertaken from a soft paradigm perspective, where the emphasis shifts from optimisation to deliberation. Rather than seeking a singular ‘optimal’ solution, the aim is to explore a range of acceptable solutions that reflect the diverse preferences and priorities of the stakeholder group.

The final stage, “Implementation,” also occurs within a facilitated workshop and aims to translate the findings of the study into concrete actions. Stakeholders review the results, reflect on the learning generated through the process, and identify changes that are both feasible and desirable within their organisational context (Tako and Kotiadis 2018a). Attention is given to risk analysis, feasibility assessments, and the formulation of an implementation plan or action trail (Tako and Kotiadis 2018b). The paradigm adopted in this stage is mixed: the soft paradigm ensures stakeholder ownership of proposed actions, while the hard paradigm supports the structuring of implementation efforts.

Table 10: Summary of PartiSim methodology stages based on (Tako and Kotiadis 2018b).

Stage	Purpose & Activities	Key Tools	Outputs
1. Initiate Study	Identify stakeholders and understand the problem situation via meetings, interviews, and observations.	- Situation of Interest Tool- Recording Observations Tool- Stakeholder Details Tool- Bank of Questions (script)	Stakeholder roles list, preliminary problem understanding, study proposal
1. a Pre-Workshop (Sub-stage)	Prep for Workshop 1: define roles, set logistics, send invitations.	-	Prepared materials, scheduled workshop
2. Define Problem (Workshop 1)	Agree on the problem and wider system; draw the system model.	- Define the System Tool- Draw the System Model Tool	Problem statement, system map, study objectives
2a. Post-Workshop 1 / Pre-Workshop 2 (Sub-stage)	Refine and disseminate Workshop 1 outputs.	-	Refined system map, materials for Workshop 2

Stage	Purpose & Activities	Key Tools	Outputs
3. Define Conceptual Model (Workshop 2)	Identify objectives, draw models (PMM, communicative), and data needs.	- PMM Tool- Communicative Model Tool- Study Objectives Tool	Simulation objectives, model inputs/outputs, process flow, data requirements
3a. Post-workshop 2 (Sub-stage)	Refine the conceptual model, validate outputs.	-	Report of refined conceptual model
4. Model Coding	Data collection, build and validate the simulation model.	-	Simulation model, validation, scenarios
4a. Pre-Workshop 3 (Sub-stage)	Review model, prepare scenarios and materials for Workshop 3.	-	Preliminary results and scenarios
5. Experimentation (Workshop 3)	Validate model, assess scenarios, rate outputs, debate solutions.	- Model Validation Tool- Rating Performance Measures Tool (e.g. VISA)- Debate Scenarios Tool	Validated model, performance ratings, preferred scenarios
5a. Post-Workshop 3 / Pre-Workshop 4 (Sub-stage)	Refine scenarios and the model based on feedback.	-	Updated scenarios and model
6. Implementation (Workshop 4)	Define the implementation plan, assess feasibility and risks.	- Feasibility and Risk Scale Tool- Barriers to Change Tool- Action Plan Tool	Agreed scenario(s), action plan with responsibilities and deadlines

In practice, PartiSim has been most prominently applied in healthcare service redesign (Tako and Kotiadis 2015). Healthcare systems are often typified by decentralised decision-making, professional silos, and complex interdependencies, making them particularly well-suited for participative simulation approaches (Carey *et al.* 2015; Best *et al.* 2012). Within these settings, PartiSim has demonstrated its utility in fostering engagement, eliciting tacit knowledge, and promoting consensus among clinicians, managers, and other key stakeholders (Kotiadis, Tako and Vasilakis 2014). The framework's emphasis on facilitation roles is critical; the modelling team typically comprises a facilitator, modeller, and recorder, while stakeholder teams include project champions and subject-matter experts. Facilitated workshops are carefully structured,

drawing on techniques such as sticky-dot voting, group reflection, visual mapping, and small-group discussion to ensure inclusivity and encourage constructive interaction (Kotiadis and Tako 2021; Tako, Kotiadis and Vasilakis 2010a). Recommendations include holding workshops in neutral and comfortable venues to create a conducive environment for dialogue and learning.

The advantages of PartiSim, as evidenced by empirical studies, include increased stakeholder commitment, improved model transparency, and a greater likelihood of successful implementation. Among the benefits are its capacity to increase stakeholder ownership, improve model validity and transparency, and enhance the likelihood of implementation success. Empirical evidence from case studies has substantiated many of these claims, demonstrating that the participative approach leads to a deeper understanding of problem contexts, greater commitment to change initiatives, and improved integration of diverse forms of knowledge (Kotiadis and Tako 2021). The framework also aligns well with established quality criteria in conceptual modelling, such as validity, credibility, utility, and feasibility (Harper, Mustafee and Yearworth 2021; Pessôa *et al.* 2015; Kotiadis, Tako and Vasilakis 2014). Moreover, by structuring engagement at each stage of the process, PartiSim mitigates common risks associated with top-down interventions, such as stakeholder disengagement, resistance, and misalignment with organisational realities.

Although PartiSim has been applied solely to discrete event simulation (DES) modelling, its underlying principles and methodological structure render it well-suited for adaptation to other simulation approaches (Tian *et al.* 2022; Jones, Kotiadis and O'Hanley 2019). PartiSim's core features - namely, its structured facilitation, explicit engagement with multiple paradigms, and strong emphasis on stakeholder involvement - position it as a potential methodology for supporting hybrid simulation studies (Dos Santos, Kotiadis and Scaparra 2020). In hybrid contexts, where different simulation methods may be employed at various stages or in parallel to model distinct system components, PartiSim could provide a coherent participatory structure,

enabling modellers to align methodological choices with stakeholder perspectives, facilitate cross-paradigm dialogue, and systematically integrate both quantitative data and qualitative insights. As such, while originally designed for DES, PartiSim may offer a flexible and robust foundation for more comprehensive and inclusive simulation practices that span multiple modelling paradigms.

2.6 Chapter Conclusion

This chapter has examined the simulation literature, discussing the advantages and disadvantages of using stand-alone simulation methods such as Discrete-Event Simulation (DES), System Dynamics (SD), and Agent-Based Simulation (ABS). Additionally, it has explored the application of these methods in four combinations: DES-SD, DES-ABS, SD-ABS, and DES-SD-ABS applied to healthcare. This review also showed that DES-ABS was the most frequently applied. These findings contradict earlier reviews (Arisha and Rashwan 2016; Brailsford *et al.* 2019; Dos Santos, Kotiadis and Scaparra 2020), which found that DES-SD was the most popular hybrid model. SD-ABS emerged as the third most common approach, whereas DES-SD-ABS remains the least explored, consistent with observations by Kar, Eldabi and Fakhimi (2022).

In terms of the areas of variability, over 60% of the reviewed studies classified their model hybridisation as interaction-based (H3) and their integration as automated (I1). This fact may be explained by the fact that AnyLogic was the most commonly used software across the papers. Only two studies reported the use of Simul8 and Arena in DES-ABS models. Model input predominantly relied on real-world data (S1), while model verification and validation were typically statistical (V1). However, several studies employed expert validation (V2) or combined statistical and expert validation (V3), particularly in DES-ABS and DES-SD models. Conversely, model implementation was rarely addressed, reaffirming that hybrid simulation

(HS) modelling in healthcare remains challenging (Dos Santos, Kotiadis and Scaparra 2020). Only 16 of 42 papers described their models as potential but not implemented in practice.

Another significant finding concerns the limited attention given to conceptual modelling. Only twenty-two studies fully or partially addressed the key components of a conceptual model (Robinson 2008). However, all papers specified their model objectives, inputs, and/or outputs; most provided incomplete or no discussion of assumptions and model content. Similarly, hybrid model representation appeared in only five studies. In most cases, authors included screenshots of the coded model or separate schematic illustrations of each simulation method, without integrating them into a unified HS representation.

Stakeholder engagement in hybrid model development received insufficient attention. Of the forty-two case studies reviewed, half did not report stakeholder involvement at any stage, while ten studies reported stakeholder participation only during data collection or model validation. These findings corroborate earlier observations (Dos Santos, Kotiadis and Scaparra 2020). Moreover, the review identified a major gap in the HS healthcare literature: the absence of a conceptual framework that guides modellers in systematically involving stakeholders throughout model development. None of the frameworks reviewed in this chapter explicitly incorporated stakeholder engagement into the HS lifecycle (Tako *et al.* 2019).

The insights from the literature review provide the theoretical foundations for the Brazilian context discussed in Chapter 3, the research design outlined in Chapter 4, and the conceptual framework developed in Chapter 5.

Chapter 3 - Overview of Healthcare System in Santo Amaro and Cidade Ademar (SACA)

3.1 Chapter Introduction

This chapter examines the Brazilian health system, with a particular focus on the structure available to the population residing in the southern area of São Paulo, comprising the districts of Santo Amaro and Cidade Ademar, known collectively as SACA. It begins with a concise overview of the social and geographic characteristics of SACA in Section 3.2, followed by a discussion of the key features of the Unified Health System (SUS) in São Paulo and SACA in Section 3.3. The current policies and strategies for the care of older people are in Section 3.4. Section 3.5 considers the organisation of healthcare for older adults in São Paulo, and Section 3.6 outlines the main challenges associated with population ageing in Brazil and in SACA. This contextual understanding shapes the methodological decisions presented in Chapter 4 and directly informs the development of the participatory hybrid conceptual modelling framework in Chapter 5.

3.2 Santo Amaro and Cidade Ademar (SACA) - demographic profile

Santo Amaro and Cidade Ademar are two of São Paulo's ninety-six districts. São Paulo is the most populous city in Brazil and in the Southern Hemisphere, with an estimated 11.45 million residents in 2022 (IBGE n.d.). The city is divided into five zones, North, South, Centre, East, and West, and each zone comprises thirty-two sub prefectures. Subprefectures function similarly to boroughs in English-speaking countries and consist of districts or wards that encompass one or more neighbourhoods (Prefeitura da Cidade de São Paulo 2021).

Figure 6 presents the location of Brazil, the state of São Paulo, and the São Paulo municipality, with SACA highlighted. The population of SACA is 691,566 residents within a territory of 37.70 km², representing 5.8 per cent of the city's population (SEADE 2023). The Human

Development Index values are 0.941 in Santo Amaro and 0.825 in Cidade Ademar (Prefeitura da Cidade de São Paulo 2000)¹.

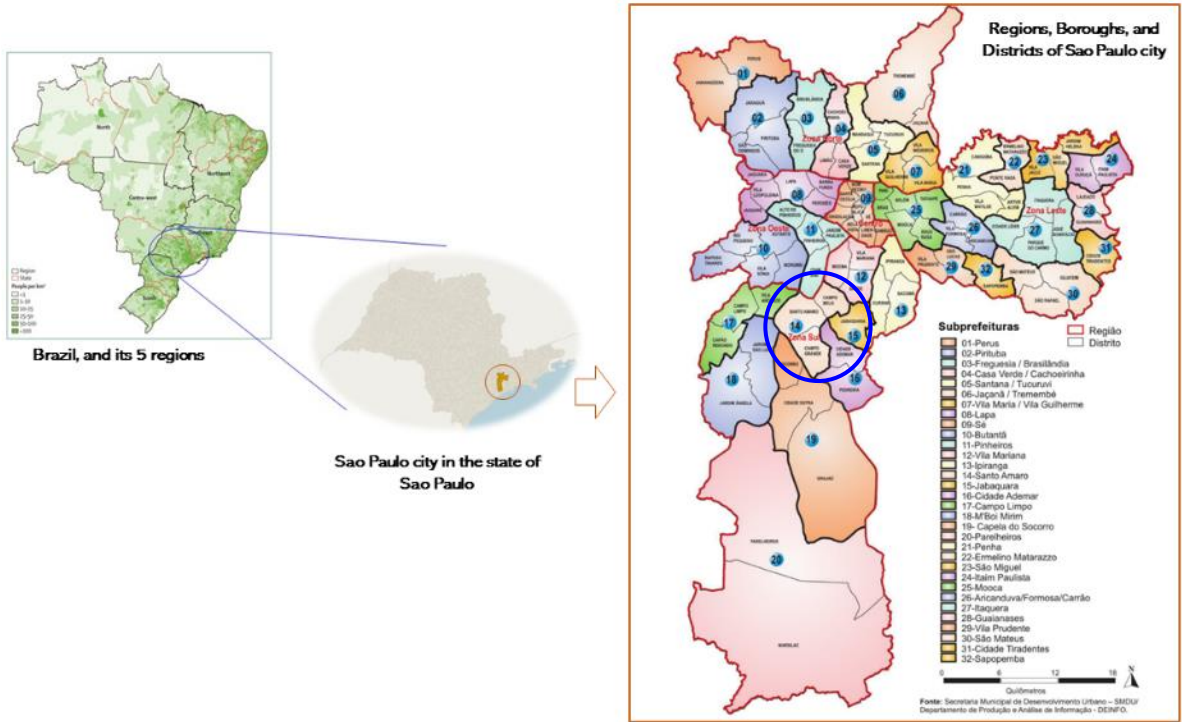


Figure 6: Map of Brazil, São Paulo state and municipality.

Although both districts lie within the most economically prosperous city in Latin America, marked disparities in social and income indicators persist. In Cidade Ademar, 81.38 per cent of residents have only primary education (SEADE 2024), and the average income is equivalent to three minimum wages (Negocios SP 2021). A further 16.03 per cent receive up to half of the national minimum wage (SEADE 2024). Formal employment declined by 2.2 per cent between 2011 and 2021, reducing access to employer-provided health insurance and increasing dependence on public healthcare.

Santo Amaro presents comparatively stronger social indicators and a growing population of individuals aged over sixty. The average monthly income is close to five minimum wages, rising

¹ HDL of 0.8 or greater stands for very high human development. Data available on the website in 2024, however numbers refer to reports from 2000.

to approximately six minimum wages for those aged over fifty (Negocios SP 2021). Only 3.31 per cent receive up to half of the minimum wage, and 45.31 per cent of older adults have only a primary education (SEADE 2024).

The ageing index also differs significantly. Santo Amaro displays advanced demographic ageing with an index of 112.02, compared to 37.76 in Cidade Ademar and 57.19 in São Paulo overall (SEADE 2024). This demographic shift has raised concerns about growing demand for healthcare services and increased associated costs (Minayo 2012; Carvalho and Garcia 2003). Projections suggest that population ageing in SACA will intensify. By 2050, the older population is estimated to reach approximately 168,200 residents, representing 11.51 per cent of São Paulo's population (SEADE 2023).

3.3 The healthcare system in São Paulo and SACA

The Unified Health System, Sistema Único de Saúde, SUS, established by the 1988 Constitution, is founded on the principles of universality, equity, and integrality (Lewis, Penteadó and Malik 2015). Universality ensures that all individuals have access to care, equity seeks the fair distribution of services, and integrality requires coordination of preventive and curative actions (Marques, Piola and Carrillo Roa 2016). Health is defined constitutionally as a right of the citizen and a duty of the state.

SUS comprises primary, secondary, and tertiary levels of care. Primary care centres, known as Unidades Básicas de Saúde, UBS, function as the main point of entry to the health system (Mello, Fontanella and Demarzo 2009). In contrast to the UK, where primary care is mainly general practice, community pharmacy, dentistry, and eye care (NHS England 2024), Brazilian UBS facilities might include additional services more commonly associated with secondary care elsewhere, such as dietetics, social work, community nursing, laboratory tests,

vaccinations, minor procedures, and urgent inhalation therapies (Giovanella, Franco and Almeida 2020; Almeida *et al.* 2018).

São Paulo has three primary care models: the traditional UBS, integrated emergency centres, AMA, and Family Health Strategy (FHS) centres. Their distribution varies across regions and depends on decisions by municipal authorities and sub-mayors, who have discretion in how national guidelines are implemented (Pinto, Tanaka and Spedo 2009). Consequently, service provision differs across districts, although SUS principles remain in place.

The organisation of primary care influences the range of services available. Traditional centres rely on the classic triad of general practitioners, paediatricians, and gynaecologists, supported by nurses and dentists (Santos *et al.* 2018). The AMA UBS model merges traditional primary care with urgent care capacity and manages both scheduled and unscheduled consultations (Prefeitura da Cidade de São Paulo 2021).

On the other hand, Family Health Strategy centres (FHS) are designed to provide comprehensive, continuous, and preventive healthcare through multidisciplinary teams responsible for a defined population. They serve as the backbone of Brazil's primary healthcare system, emphasising health promotion, disease prevention, and strong patient-provider relationships within local communities (Ignacio, De Lima Barata and De Moraes Neto 2018). These centres attend to low- and medium-complexity conditions, reducing unnecessary referrals to emergency departments (Associação Paulista para o Desenvolvimento da Medicina 2021).

Santo Amaro and Cidade Ademar contain sixty-eight health facilities across primary, secondary, and tertiary care (INTS 2024). Twenty-six are primary care centres, of which twenty-one are located in Cidade Ademar and five in Santo Amaro. Most centres in Cidade Ademar operate under FHS guidelines, whereas those in Santo Amaro follow the traditional model.

3.4 Health and Ageing in Brazil: Funding, Policy and Regional Disparities

Brazil's health system, particularly regarding the care of older people, reflects the combined pressures of demographic transition, fiscal constraints, and uneven policy implementation. Although SUS guarantees universal coverage, the coexistence of public and private sectors has contributed to unequal access and quality across regions, with older adults mainly affected (Melo *et al.* 2021). Funding for elderly care remains insufficient given the pace of population ageing. Brazil is entering a post-demographic bonus period without having made sustained investments in health infrastructure or long-term care (Saraiva *et al.* 2020). As a result, formal long-term care provision is limited, and most care is delivered informally (Miranda, Mendes and Silva 2016).

The decentralised system introduced by the 1988 Constitution assigns responsibilities across federal, state, and municipal levels, yet disparities persist (Massuda *et al.* 2018). Wealthier municipalities, such as São Paulo, provide more advanced services, including URSI centres and home care programmes, while poorer municipalities struggle with limited resources (Mitre, Andrade and Cotta 2012). Although legislation such as the Estatuto do Idoso [Statute of Older Person, author's translation from Portuguese to English] mandates specialised geriatric care, shortages of trained professionals and inadequate infrastructure hinder implementation (Saraiva *et al.* 2020).

São Paulo offers a comparatively well-developed model of integrated care for older people. With more than 4.9 million residents aged over sixty (SEADE 2020), the city has implemented Centros de Referencia do Idoso CRIs [Reference Centres for Older People (CRIs), author's translation from Portuguese to English], Unidades de Referencia na Saude do Idoso (URSI) [Older Adult Health Reference Units, author's translation from Portuguese to English], and the Caregiver Programme, PAI, reflecting a multi-sectoral approach to active ageing. However,

these initiatives are not universal across Brazil, and national-level support has not been sufficient to enable broader replication (Melo *et al.* 2021). The Brazilian health system, particularly regarding older adults' care, stands at a complex intersection of demographic change, policy responses, and funding challenges (Massuda *et al.* 2018).

3.5 Health care for older people in São Paulo

São Paulo has acknowledged the implications of demographic ageing and introduced policies to guide service provision. The Municipal Health Secretary, ATSPI, has emphasised active ageing, prevention, and enabling older adults to remain in their communities (Secretaria Municipal da Saúde de São Paulo 2016). Older adults are expected to attend annual assessments at UBS and primary care facilities. The Multidimensional Assessment of Older People, AMPI AB, supports early identification of geriatric syndromes and helps define care plans (Saraiva *et al.* 2020). This tool classifies older adults into three risk categories: robust (or healthy), at risk/frail (or pre-frail), or dependent (or frail), based on their combined clinical, functional, cognitive, and social assessment scores (Secretaria Municipal da Saúde de São Paulo 2016). It supports primary care teams in identifying vulnerabilities and guiding personalised care plans for ageing populations (Ramos *et al.* 2016).

Depending on frailty, individuals may be referred to secondary centres. São Paulo has two types of secondary facilities dedicated to older adults, Reference Centres for Older People, CRIs, and Older Adult Health Reference Units, URSIs. Ten such centres operate across the city (Prefeitura da Cidade de São Paulo 2021), providing multidisciplinary care. Patients may also be referred to the PAI programme, which supports individuals with social vulnerability.

Since 2010, municipal health plans have prioritised expanding services, strengthening primary care, and promoting multidisciplinary work. Progress has been uneven, and waiting times for secondary care remain long (Melo *et al.* 2021; Mitre, Andrade and Cotta 2012). The distribution

of facilities varies across districts and is partly determined by local political arrangements. For example, CRIs are present only in the North and West zones (Cidade de São Paulo Saude 2023).

In SACA, only one secondary care centre is available for approximately 78,606 older residents (SEADE 2024). It has fifteen staff members, including two geriatricians. Home care is available but limited to individuals with social vulnerability due to capacity constraints.

3.6 Challenges of the Ageing Population from Brazil to SACA

São Paulo, despite its economic status, faces substantial socioeconomic inequalities. These inequalities have deepened since 2020 as Brazil has left its demographic bonus period, during which higher proportions of working-age individuals could have supported economic growth and investment in public infrastructure (Braga and von Mutius 2023; Porsse and Bistafa 2020). Brazil did not capitalise on this period, and investment levels remain low (Barbosa and Prates 2020; OECD 2018). Consequently, long-standing disparities in education, income, and access to services persist.

Brazil is ageing at a faster pace than many European countries did, yet without parallel improvements in social protection and healthcare (Marques, Piola and Carrillo Roa 2016; Pereira 1998). Public investment continues to prioritise maternal, child, and infectious disease programmes, while investment in geriatric services and infrastructure remains limited (Marques, Piola and Carrillo Roa 2016).

In SACA, the ageing index in Santo Amaro is more than double the national figure, yet health and social care provision has not adapted accordingly. Limited access to services combined with pronounced socio-economic inequalities may hinder healthy ageing and increase pressure on an already stretched health system (Plouffe, Pereira and Sivaramakrishnan 2013). It is crucial to take immediate steps to establish a service system that safeguards the rights of older adults and promotes healthy ageing. (Oliveira *et al.* 2024; Louvison *et al.* 2008). These challenges

reinforce the motivations outlined in Section 1.2 and directly inform the modelling priorities and the structure of the participatory hybrid framework introduced in Section 5.2.

3.7 Chapter Conclusion

Although São Paulo is the wealthiest city in Latin America, significant socioeconomic inequalities persist across its districts. The analysis of SACA illustrates contrasting conditions within a single sub-prefecture. In Cidade Ademar, the majority of residents lack formal employment and earn on average three minimum wages, approximately £649.12 before tax (Negocios SP 2021). Given an estimated monthly living cost of £505.50, excluding rent (NUMBEO 2024). Many residents may struggle to meet healthcare costs privately. In Santo Amaro, incomes are higher, yet the ageing index is substantially greater than in Cidade Ademar, indicating a need for expanded services for older adults.

São Paulo has not experienced the advantages of rapid economic growth and has not made the level of investment required to prepare for the demographic profile projected for 2050. Secondary care for older adults is limited. SACA has one URSI with 15 staff members serving approximately 78,000 older residents, leading to waiting times of 12 months or longer. The mismatch between demand and capacity is expected to intensify as the population ages. Without investment in social determinants and health services, there is a risk of further strain on the public system (Oliveira *et al.* 2024; Paúl, Ribeiro and Teixeira 2012). Healthcare professionals and researchers have called for reforms to address these pressures. Delayed action may jeopardise the sustainability of care provision in SACA.

Chapter 4 - Methodology and Research Design

4.1 Chapter Introduction

This chapter presents the methodological foundation and overall design of the research. It explains how the study was structured to address the research aims and questions introduced in Chapter 1. The chapter begins by outlining the research design, detailing the conceptual and methodological foundations (Section 4.2) and integration between Action Research and PartiSim (Section 4.3), before setting the background for the case study in Brazil (Section 4.4), providing details on the main researcher's role in this study.

Furthermore, this chapter provides an overview of the research process, data collection techniques, and analytical methods employed in Section 4.5, and the choice for using Simul8 as the simulation software is explained in Section 4.6.

4.2 Research design (Conceptual and Methodological Foundations)

This study adopts a qualitative, exploratory research design, grounded in Critical Participatory Action Research (CPAR) (Kemmis, McTaggart and Nixon 2013) and situated within an in-depth single case study. This research design was selected to facilitate the iterative development of the participatory hybrid simulation conceptual framework, comprising its stages, activities, and tools, by enabling their systematic creation, refinement, and assessment in collaboration with stakeholders. By embedding the study within a participatory and cyclical inquiry process, the research ensures that the framework is grounded in practice, responsive to stakeholder needs, and shaped by real-world contexts rather than predetermined assumptions.

Framed by the principles of Action Research (AR), the study uses a cyclical and collaborative process of planning, action, observation, and reflection. Action Research was adopted as the comprehensive methodological framework, supporting both practical problem-solving and

theoretical development through collaborative inquiry. Its iterative and participatory nature makes it suitable for examining complex healthcare systems (Koshy, Waterman and Koshy 2010), and aligns with soft OR and participatory modelling contexts, to support method development and stakeholder engagement (Eden and Ackermann 2018; Franco 2013; Howick and Ackermann 2011).

Healthcare environments are characterised by dynamic interactions between people, policies, and constrained resources (Eldabi 2009; Brailsford *et al.* 2009). Action Research meets these demands by enabling co-learning, surfacing tacit knowledge, and supporting systemic improvement (Coughlan and Shani 2015; Reason and Bradbury 2001). As Warmington (1983) noted, Action Research is practice-oriented and designed to generate change through action, making it suited to the development of a conceptual simulation framework grounded in stakeholder experience.

The pluralistic and multi-methodological character of AR further strengthens its suitability. AR accommodates diverse forms of data collection and analysis, which is essential for the hybrid simulation approach adopted in this study, combining Discrete Event Simulation (DES) and Agent-Based Modelling (ABM). Its methodological flexibility allows the research process to adapt as new insights emerge, ensuring contextual relevance and coherence. This adaptability reflects an open-systems perspective (Barton, Stephens and Haslett 2009), which is particularly important in healthcare settings that are often fragmented and shaped by political and organisational complexities. Action Research therefore provides a structured yet flexible pathway for collaborative inquiry, organisational learning, and conceptual model refinement (Coughlan and Coughlan 2002).

Within this methodological framing, the use of a single case study (Yin 2009) allows for an in-depth and context-rich examination of a healthcare system facing demographic pressures

associated with population ageing. The case provides a bounded environment in which participatory modelling activities can be implemented and observed in detail, drawing on the organisational and demographic characteristics outlined in Chapter 3.

The facilitation of participatory modelling activities is guided by the PartiSim methodology (Kotiadis and Tako 2018; Tako and Kotiadis 2015), which offers a structured methodology for stakeholder engagement, model building, experimentation, and implementation in simulation studies. Although originally developed for Discrete Event Simulation (DES), PartiSim is adapted in this study to support hybrid simulation. This adaptation is justified for several reasons.

First, PartiSim provides a rigorously structured, participatory process. It incorporates Soft Systems Methodology (SSM) (Powell and Mustafee 2017; Checkland and Scholes 1999) into the early stages of simulation studies, enabling collaborative problem structuring, conceptual modelling, and stakeholder reflection (Tako and Kotiadis 2015). These activities occur through facilitated workshops. Four of the six stages are workshop-based, making it highly compatible with the participatory cycles of Action Research (Kemmis, McTaggart and Nixon 2013)

Second, the structure of PartiSim is a multi-paradigm approach and methodologically flexible, making it adaptable for hybrid simulation approaches. As Chiasson, Germonprez and Mathiassen (2009) argue, action research that embraces methodological pluralism can effectively accommodate multiple modelling paradigms, and PartiSim embodies this pluralism by integrating hard and soft OR techniques within a single architecture. This structure provides an ideal launch point for incorporating additional methods such as SD and ABM. Moreover, the adaptability of PartiSim has been demonstrated in subsequent methodological extensions. For example, Noorain (2024) shows how it can be expanded towards facilitated optimisation, further evidencing its flexibility and suitability as a foundation for methodological innovation.

Third, the methodology provides not only the step-by-step instructions for engaging stakeholders, but also toolsets for each stage and defines the role of each participant. It provides facilitation guidance, manuals and toolsets (e.g. CATWOE, Root Definitions, purposeful activity models) to support the engagement of stakeholders and capture information about the system under study (Tako and Kotiadis 2015). By using these tools, the modelling team can interact with stakeholders to capture their knowledge of the system, clarify assumptions, and explore the implications of different viewpoints. This process encourages richer discussions and mutual understanding, both of which are essential for developing a conceptual model that reflects the complexity of the system under study.

Fourth, PartiSim has been applied to different healthcare contexts such as obesity (Tako *et al.* 2012) and ambulance service (Kotiadis and Tako 2021), demonstrating its practical validity and transferability to this study's context. Although the ageing population in a developing country presents a compelling and relevant area for research, the development of such studies is often surrounded by challenges, particularly as simulation has been rarely applied in these contexts (Vecillas Martin, Berruezo Fernández and Gento Municipio 2025; Forbus and Berleant 2022). In this proposed research, the ageing population provides an opportunity to investigate complex patient journeys, shifting service demands, and workforce constraints. Nevertheless, the lack of accurate and comprehensive data may compromise the ability to develop a computer model that reliably represents the reality of the Brazilian healthcare context (Massuda *et al.* 2018). In this setting, the PartiSim engagement structure assumes a crucial role in eliciting tacit knowledge and institutional memory, thereby enabling a more faithful representation of these complex flows.

Finally, using PartiSim as a foundation allows this research to innovate while building on a proven participatory methodology. As hybrid simulation increasingly seeks participatory approaches to bridge technical models and stakeholder realities (Brailsford *et al.* 2019), this

study contributes by extending PartiSim into hybrid simulation, enhancing methodological rigour and relevance.

4.3 Integrating Action Research and PartiSim

Figure 7 illustrates how the PartiSim framework (in green) aligns with, and is embedded within, the broader Action Research (AR) cycle (in blue). Each green stage, initiating the study, defining the problem, developing a conceptual model, building a computer model, experimenting with the model, and implementing findings, sits within a corresponding AR phase of acting and observing, with the overall process framed by the AR phases of planning at the top and reflecting at the bottom.

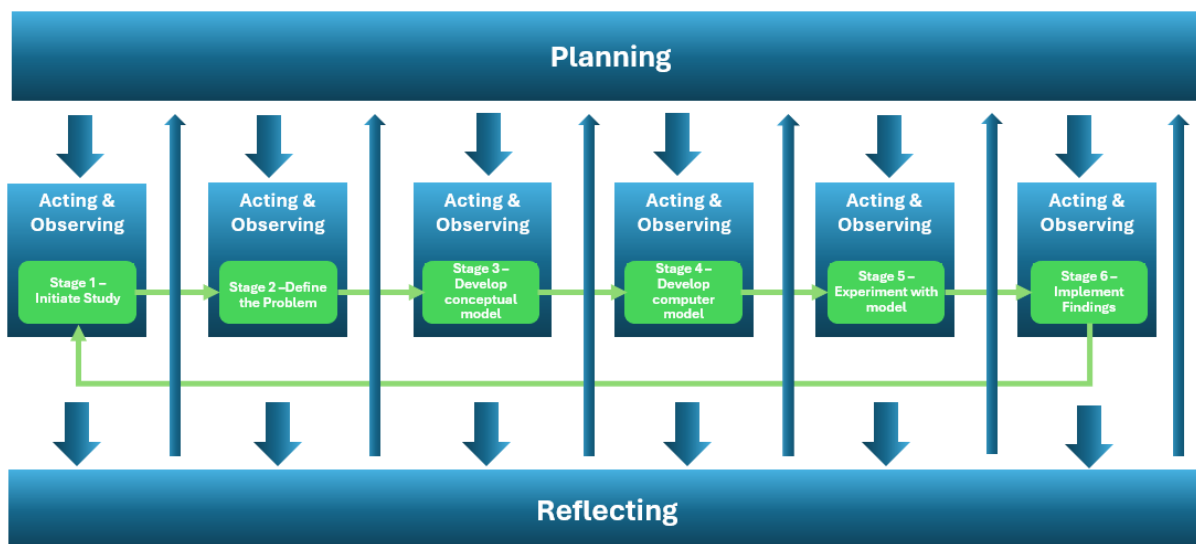


Figure 7: Integration between PartiSim and Action Research (author's own work)

The horizontal green flow shows the sequential progression of PartiSim activities, while the vertical blue arrows indicate how action, observation, planning, and reflection interact continuously at every stage. Together, the diagram shows that PartiSim provides the structured modelling activities within each AR cycle, while Action Research offers the iterative learning and improvement framework that integrates these steps. Merging both approaches ensures continuous stakeholder involvement and reflection throughout the framework's development.

Taken together, the combined use of Action Research and the PartiSim framework provides a strong methodological foundation for this study. AR offers a participatory and cyclical process that supports the co-creation of knowledge and practical change in complex healthcare environments, while PartiSim provides structure, facilitation tools, and methodological flexibility for participatory hybrid simulation modelling. Their integration ensures that the research remains contextually grounded, pluralistic, and responsive to both stakeholder needs and theoretical development.

4.4 Background to the case study

This research was conducted as part of the author's doctoral studies, with the researcher assuming multiple roles throughout the process. In addition to acting as the primary modeller, the researcher was responsible for coordinating stakeholder engagement, facilitating workshops, and managing data collection. These responsibilities required both technical expertise and strong interpersonal skills, diverging from the structured role separation recommended in PartiSim, where these duties are divided across the modelling team.

In PartiSim, modelling and stakeholder teams are distinct: the modeller develops the simulation, the recorder documents discussions, and the facilitator guides workshops, while stakeholders provide input as project champions, sponsors, key stakeholders, or other contributors (Tako and Kotiadis 2018c; Tako and Kotiadis 2018b). Further implications of adopting an alternative approach to PartiSim will be examined in Chapter 9.

The case study engaged diverse actors from the Brazilian healthcare system, including managers, frontline professionals, policy representatives, and technical staff. Their participation informed the model's scope, assumptions, and interpretation through structured facilitation. All participants received one of the four key roles in PartiSim: the project champion, the sponsor, key stakeholders, and other stakeholders (Tako and Kotiadis 2018b).

The project began in September 2019 with a duration of 4.5 years. The COVID-19 pandemic disrupted the original timeline, with travel restrictions cancelling the first field trip and delaying workshops until April-May 2023. Brazil's ongoing public health measures further limited in-person engagement, and conditioned how workshops could be conducted with the use of masks and keeping a minimum distance between participants. In July 2024, a three-month health-related interruption led to revising the project scope, removing the final two PartiSim stages to meet doctoral deadlines while preserving core research aims.

Despite these disruptions, the research maintained its focus on applying hybrid simulation to address complex challenges in the Brazilian healthcare system, including ageing populations, patient flow, and workforce constraints. Academically, it contributes to understanding stakeholder engagement in hybrid simulation. Practically, it supports evidence-based decision-making in a resource-constrained context, particularly during the initial stages when the conceptual model for a hybrid simulation is developed.

4.5 Research Methods: Data Collection, Modelling Procedures, Evaluation and Validity

This section describes the methods used to collect data, develop the hybrid simulation model, and evaluate the credibility of the research. The methodological choices were shaped by the Action Research cycle and the practical requirements of applying a participatory hybrid simulation approach in the Brazilian healthcare context. A combination of qualitative techniques and simulation-specific procedures was used to ensure that the modelling process was informed, transparent, and grounded in stakeholders' experience.

Data collection was carried out iteratively and closely aligned with the activities in each Action Research cycle. The primary method was a series of facilitated stakeholder workshops, structured using adapted tools from the PartiSim (Tako and Kotiadis 2018b), including root definitions, CATWOE analysis, and Analysis One-Two-Three (Checkland and Scholes 1999).

These workshops provided a collaborative environment for defining the problem, co-producing the conceptual model, and discussing model assumptions and performance measures. Semi-structured interviews (Kvale 2009) with healthcare professionals, managers, and local community representatives supplemented the workshop data, offering additional insight into system operations, ageing-related challenges, and stakeholder views on service delivery. Direct observation during meetings and workshops further enriched the dataset, with field notes and recordings used to document interactions, emerging issues, and modelling decisions. Documentary analysis, including policy documents, demographic data, system descriptions, and administrative records, supported the interpretation of stakeholder input and informed the development of model parameters.

The hybrid model was developed following the conceptual model co-created with stakeholders. Modelling procedures included the identification and organisation of data requirements, translation of conceptual structures into a DES-ABS computational model in Simul8, and the systematic implementation of model logic, parameters, and behavioural rules. Simulation artefacts, such as evolving diagrammatic representations and intermediate model versions, were used both as analytical materials and as tools for communicating progress to stakeholders. Model development followed an iterative process, with verification and preliminary testing conducted throughout to ensure consistency and technical correctness.

Evaluation of the model involved both verification and validation. Verification focused on checking the internal accuracy of the model implementation, including logic, flows, parameters, and code structure (Sargent 2020; Robinson 2014). Validation assessed the model's credibility in representing the real system (Balci 1995). Structural validation was achieved through stakeholder review sessions, where participants confirmed whether the model logic, pathways, and assumptions reflected their understanding of healthcare delivery in Santo Amaro and Cidade Ademar. Quantitative validation compared model outputs with available system

indicators, assessing how closely the simulated behaviour matched historical data and expected performance patterns to ensure the model's accuracy and predictive credibility.

Several forms of validity were considered to strengthen the overall credibility of the study. Construct validity was supported through extensive stakeholder involvement in defining the problem, shaping the conceptual model, and evaluating model structure. Internal validity is enhanced through transparent documentation of assumptions, data gaps, and simplifications, particularly given the limited availability of empirical data for the ABS component. External validity was acknowledged as constrained due to the model's reliance on local conditions and datasets; applying the model to other settings would require additional calibration and data collection. Throughout the research process, the integration of participatory methods with simulation procedures ensured that the model was both technically sound and contextually grounded.

4.6 Simul8 - the software choice for developing a hybrid simulation

For this research, SIMUL8 was selected as the primary software tool for developing the hybrid simulation model. This choice is justified by three key factors. First, SIMUL8 provides free access to its full professional license for PhD students, granting unrestricted use of all advanced features necessary for comprehensive simulation modelling. After presenting this research to SIMUL8 following the initial stage of the study, the researcher was awarded a full license to support the development of the hybrid simulation model, which combines discrete-event simulation (DES) and agent-based simulation (ABS) as the selected hybrid approach for the Brazilian case study.

Second, SIMUL8 supports hybrid modelling capabilities, allowing the integration of DES with ABS, an essential feature for accurately representing the complexities of the healthcare environment in Brazil. This hybrid approach enables the model to capture both detailed process

flows and individual agent behaviours effectively. The choice of SIMUL8 is also reinforced by its successful application in similar research contexts, as evidenced in Penny, Bayer and Brailsford (2023), who have similarly employed SIMUL8 for hybrid simulation modelling.

Third, the researcher's prior experience and familiarity with SIMUL8 for discrete-event simulation potentially enhances the efficiency and quality of the model development process. This existing knowledge of SIMUL8's interface, functionalities, and modelling tools would enable the modeller to navigate the software more confidently, reduce the learning curve, and minimise errors during simulation construction. Further discussions on the Simul8 model will be conducted in Section 7.2.2.

4.7 Chapter conclusion

This chapter established a methodological foundation by integrating Action Research and the PartiSim methodology into a coherent and context-sensitive research design. This synergy enables participatory, iterative model development while grounding it in real-world healthcare challenges associated with ageing populations. The qualitative, multi-method approach- anchored in stakeholder engagement, empirical observation, and simulation artefacts- ensures both rigour and relevance. Through this integrated design, the study advances a participatory hybrid simulation framework that is not only theoretically informed but also practically usable and adaptable to complex healthcare systems, setting the stage for the framework's development in Chapter 5.

Chapter 5 - Conceptual Framework for Participatory Hybrid Simulation: Stages, Activities and Tools.

5.1 Chapter Introduction

This chapter presents a four-stage conceptual framework designed to guide the development of a hybrid simulation model for evaluating the health system serving the older population in Santo Amaro and Cidade Ademar (SACA), two districts in São Paulo, Brazil, as discussed in Chapter 3. Grounded in the PartiSim methodology (Tako and Kotiadis 2015), the framework introduces several methodological extensions and adaptations to address the distinctive requirements of participatory hybrid simulation. It builds directly on the methodological choices outlined in Chapter 4, which provides the foundation for structuring participatory activities, data collection, and model development in this study.

For clarity, throughout this chapter, any reference to the modelling team or the facilitator refers exclusively to the author, who acted as the sole researcher responsible for the design, facilitation, and implementation of all modelling activities.

The chapter begins with an overview of the adjustments made to the original PartiSim stages, sub-stages and tools (Section 5.2), followed by a discussion of each of the four stages in Sections 5.3 to 5.9, as applied to the Brazilian case study. The reasons for confining this research to the first four stages of PartiSim were outlined in Chapter 4. Detailed tools, manuals, and templates referenced in this chapter are provided in Appendix A.

5.2 Overview of the Conceptual Framework for Facilitated Hybrid Simulation.

The conceptual framework for facilitated hybrid simulation aims to support the development of a hybrid model through stakeholder participation. The framework addresses the conceptual modelling limitations identified in Section 2.4. It was adapted from the PartiSim methodology (Tako and Kotiadis 2015; Tako and Kotiadis 2018b), and unlike previous conceptual

frameworks for hybrid simulation (Nguyen, Howick and Megiddo 2024; Zulkepli, Eldabi and Mustafee 2012; Chahal and Eldabi 2008), it sets out the steps and tools required to develop a hybrid model with active stakeholder engagement.

The framework focuses on model conceptualisation and incorporates the same first four stages as PartiSim: (1) Initiate study, (2) Define problem (workshop), (3) Define conceptual model (workshop), and (4) Model coding. These stages are based on the typical phases of OR studies (Tako, Kotiadis and Vasilakis 2010b) and the simulation modelling process outlined in the literature (Brailsford *et al.* 2019; Robinson 2014; Pidd 2004a). Additionally, three sub-stages are included between the four stages. These involve activities designed to support and facilitate workshops and to refine outputs generated during workshop discussions (Tako, Kotiadis and Vasilakis 2010b).

Each stage has a well-defined set of activities, tools, and manuals (Kotiadis, Tako and Vasilakis 2014; Tako and Kotiadis 2018a). Following PartiSim, activities are classified into workshop activities and modelling activities (Kotiadis and Tako 2021; Tako, Kotiadis and Vasilakis 2010a). Workshop activities support stakeholder engagement during workshops, while modelling activities are undertaken by the modelling team between workshops. These activities are crucial for developing the simulation model or, where generic to project management, are essential to ensure the smooth organisation of the project.

Tools consist of scripts and forms that may be shared with the stakeholder team or used exclusively by the modelling team (Tako and Kotiadis 2018a). Their main functions are to: (1) ensure the requirements of each stage of the simulation project are met, (2) provide traceability of actions taken at each stage, and (3) keep the collected information recorded and accessible to the whole team (Pidd 2004b). Manuals offer additional guidance on how to use these tools or conduct certain activities (Tako and Kotiadis 2015).

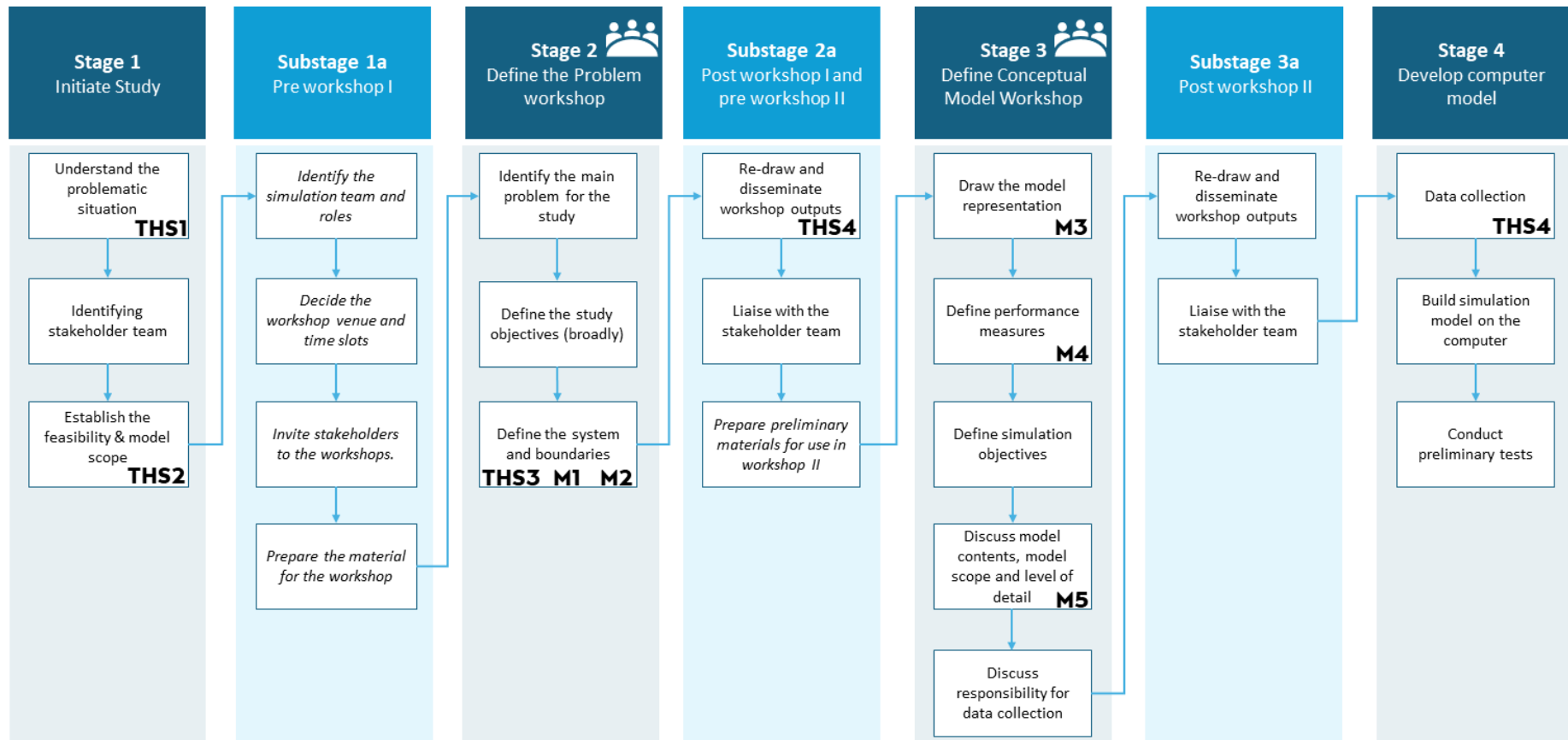


Figure 8: Participative Hybrid Conceptual Modelling Framework² (author’s own work)

² THS denotes the “Tool for Hybrid Simulation”, and the label “M” indicates that there is an available manual to support the activity.

Although the framework adopts the typical stages of simulation studies, PartiSim was initially designed for DES modelling (Tako and Kotiadis 2012; Tako and Kotiadis 2018b). The proposed conceptual framework for hybrid simulation retains similar nomenclature and purposes for all PartiSim stages and sub-stages. However, to meet the specific requirements of hybrid simulation, PartiSim tools and activities were reviewed and, where necessary, extended. New tools were introduced at various stages, as shown in Figure 8.

Figure 8 presents the proposed Participative Hybrid Conceptual Modelling Framework, which comprises four stages and three sub-stages, each with specific activities. Activities in Stages 2 and 3 are conducted during facilitated workshops (workshop activities), while activities in Stages 1 and 4 are primarily carried out by the modelling team (modelling activities). Sub-stage activities focus on project management procedures essential for preparing the facilitated workshops.

PartiSim tools were evaluated for each stage and adjusted for hybrid simulation where required, as indicated in Figure 8. Some activities include abbreviations after their names to indicate the introduction of new tools (THS) or manuals (M) for hybrid simulation. For example, in Stage 1, two new tools were proposed: THS1 Initiate Study Tool HS1: Bank of questions and THS2 Initiate Study Tool HS2: Feasibility of hybrid simulation modelling and scope of the model.

Similarly, Stage 2 incorporates three new tools: THS3 Conceptual Modelling Tool HS3: Analysis One, Two, and Three for Hybrid Simulation and two supporting manuals, M1 and M2. Four additional tools were introduced in later stages, including the THS4 HS Inputs Form in sub-stage 2a, supporting the documentation of data collection for DES-ABS models, and further manuals for Stage 3. THS4 is again used in Stage 4 to verify information before model building begins.

Complementing Figure 8, Table 11 summarises the tools used at each stage of the Participative Hybrid Conceptual Modelling Framework. The highlighted text indicates modifications to the original PartiSim framework. Eleven new tools were integrated across the four stages, with Stage 2 undergoing the most significant changes. Sub-stages remained largely unchanged, except for activity 1 in sub-stage 2a, which required the addition of THS4. Existing PartiSim tools were retained where no adjustments were necessary for their application in hybrid simulation.

Table 11: List of Tools in the Participative Hybrid CM (author’s own work)

Stages	Activities in each stage	Tools proposed to each stage
Stage 1 - Initiate Study	Understand the problematic situation.	Initiate Study Tool HS1: Bank of questions (THS1) PartiSim Toolset 1 Initiate Study Tool 4: List of reading materials PartiSim Toolset 1 Initiate Study Tool 1: Situation of Interest
	Identifying stakeholder team	PartiSim Toolset 1 Manual for Initiate Study Tool 3: Stakeholders' Contact details
	Establish the feasibility and the scope of the simulation study	Initiate Study Tool HS2: Feasibility of hybrid simulation modelling and scope of the model (THS2)
	Identify the modelling team and the stakeholder team roles.	
Substage 1a - Pre workshop I	Decide the workshop venue and time slots	
	Invite stakeholders to the workshops	
	Prepare preliminary materials for use in workshop I	
	Identify the main problem for the study	
Stage 2 - Define the Problem Workshop	Define the study objectives (broadly)	
	Define the system and boundaries	Conceptual Modelling Tool HS3: Analysis One, Two, and Three for Hybrid Simulation (THS3) (M1) Manual for employing the Tool HS3: Analysis One, Two, and Three for hybrid simulation. (M2) Manual for employing the Tool HS3: Tips for Developing a Rich Picture
	Re-draw Workshop I outputs	Conceptual Modelling Tool HS4: HS Inputs Form (THS4)
Substage 2a Post workshop	Liaise with the stakeholder team	
	Prepare preliminary materials for use in workshop II	
	Draw the model representation	(M3) Manual for Conceptual Modelling: Drawing a Communicative Model with UML notation.
Stage 3 - Define Conceptual Model Workshop	Define performance measures	PartiSim Toolset 3 Conceptual Modelling Tool 3: Drawing the Performance Measurement Model (M4) Manual for Conceptual Modelling : Identifying the Performance Measurement in HS Model
	Define simulation model objectives	PartiSim Toolset 3 - Stakeholder Form 1: Brainstorm study objectives PartiSim Toolset 3 Conceptual Modelling Tool 4: Study Objectives
	Discuss model contents, model scope and level of detail	(M5) Manual for Conceptual Modelling: Discussing elements in Hybrid Conceptual Model.
	Discuss responsibility for data collection	
	Re-draw Workshop II outputs	
Substage 3a - Post	Liaise with the stakeholder team	
	Data collection	Refer to Conceptual Modelling Tool HS4: HS Inputs Form
Stage 4 - Develop computer model	Build simulation model on the computer	
	Conduct preliminary tests	

Thus far, this chapter has provided an overview of the Participative Hybrid Conceptual Modelling Framework. The remainder of the chapter discusses each activity in Stages 1 to 4 in detail.

5.3 Stage 1 - Initiate study

The initial stage is crucial for planning the simulation project and establishing its boundaries. It also marks the first formal interaction between the modelling team and stakeholders. As in PartiSim, this stage comprises three activities: (1) understanding the problematic situation, (2) identifying the stakeholder team, and (3) establishing feasibility and scope for a simulation study with key stakeholders (Tako and Kotiadis 2015).

The modelling team is responsible for managing all three activities. Activities 1 and 2 have the same objectives as in PartiSim. The first supports the modelling team in understanding the situation of interest, while the second ensures that the project team is identified (Kotiadis, Tako and Vasilakis 2014; Tako, Kotiadis and Vasilakis 2010b). Minor modifications were made to the tools used in Activity 1. Activity 2, which involves identifying stakeholders, remained unchanged. The details of both activities are elaborated in Sections 5.3.1 and 5.3.2, respectively. Significant changes were introduced in Activity 3. In PartiSim, this activity assesses whether DES (Discrete Event Simulation) is appropriate for the study, considering other modelling approaches that may also be suitable (Tako and Kotiadis 2018b). A similar activity was proposed by Vennix (1996a), who argued that the initial stage should include a situational analysis to understand the nature of the problem. For hybrid simulation projects, unlike those using a single method, the modelling team must conduct a situational analysis to determine whether a hybrid approach is best suited to represent different aspects of the system. Accordingly, substantial adjustments were made to the tools used in this activity. Further details are provided in Section 5.3.3.

5.3.1 Activity 1 - Understand the problematic situation.

This activity represents the initial point of contact between the stakeholders and me, as the sole member of the modelling team. It may involve informal discussions, interviews, group

meetings, or site visits aimed at developing an initial understanding of the situation (Kotiadis, Tako and Vasilakis 2014; Tako, Kotiadis and Vasilakis 2010b). As no two simulation projects are identical (Vennix 1996a), a range of engagement approaches may be required. Methodological flexibility is therefore important to ensure that the study responds to stakeholders' needs (Vennix 1999; Vennix 1996b).

During these early interactions, the modelling team gathers broad and exploratory information rather than attempting to define problems or solutions at an early stage. In the original PartiSim methodology, this process is supported by a Bank of Questions organised around three themes: the problem situation, potential improvements, and people's roles (Tako and Kotiadis 2018b). These questions are particularly suited to discrete-event simulation studies, where the focus is often on services, processes, and operational performance.

In hybrid simulation studies, however, the modelling team must consider a wider range of system characteristics from the outset. In addition to services and operations, early discussions should allow stakeholders to reflect on how system structures change over time, how behaviours and interactions emerge, and how rules, norms, and policies influence outcomes at different levels of the system. Keeping discussions open and exploratory at this stage also supports the early identification of suitable hybrid modelling approaches.

To support this broader perspective, the original PartiSim Bank of Questions was reviewed and adapted to reflect the requirements of hybrid simulation. The resulting Initiate Study Tool HS1: Bank of Questions provides a structured but flexible starting point for exploring macro-, meso-, and micro-level system features relevant to hybrid models (Eldabi *et al.* 2018). Most of the original PartiSim questions were retained, while additional prompts were introduced to capture system structure, societal influences, rules, behaviours, and interactions.

The detailed content of this adapted question set is provided in Appendix A (Section A.1, Table 29). This tool aims to support early stakeholder engagement, with the emphasis placed on facilitating discussion and understanding rather than on the specific questions themselves.

This study guides the sequencing of questions during early interactions. Initial meetings often involve a small number of influential stakeholders whose views may shape early interpretations of the problem. To preserve the exploratory nature of this activity, discussions should begin with system-focused questions before addressing the problematic situation or potential improvements. This approach allows the modelling team to develop an overall understanding of the system before examining specific issues in detail.

In addition to stakeholder interaction, modellers may also supplement these interactions with background reading, which is particularly useful when stakeholder time is limited (Vennix 1999). Relevant materials—such as white papers, reports, guidelines, policies or procedural documents—can provide valuable context (Tako and Kotiadis 2018b). These documents should be shared with the modelling team to support their understanding of the system.

All background materials should be recorded in a single place. PartiSim’s Initiate Study Tool 4: List of Reading Materials is suitable for this purpose (Kotiadis and Tako 2021; Tako and Kotiadis 2021; Tako and Kotiadis 2018b). It helps document sources that may assist the project team, and it is adopted here without modification. Guidance on its use is provided in PartiSim Toolset 1.

Finally, this research also adopts the Initiative Study Tool 1: Situation of Interest. In PartiSim, this tool captures information provided during initial stakeholder interactions (Tako and Kotiadis 2018b). The modelling team should use it to record early inputs, which subsequently inform the assessment of feasibility for a hybrid simulation study (Section 5.3.3 - Activity 3).

5.3.2 Activity 2 - Identifying stakeholder team.

Identifying stakeholders is the second activity in this stage. This framework follows the same approach as PartiSim. Stakeholders are individuals or groups who may directly influence the future dynamics of an organisation or system (Brailsford *et al.* 2009) or who can provide valuable insights into model structure, variables of interest and their values.

The modelling team is encouraged to consider identifying and discussing ‘internal and external, positive and negative, and performing and advising stakeholders’ (Stackpole 2013) who can contribute to simulation model development. Identifying key stakeholders is considered important for conceptual and operational model validity and for successful implementation (Tako and Kotiadis 2015; Jones, Kotiadis and O’Hanley 2021). To support this process, Table 1 from the PartiSim Toolset 1: Manual for Initiating Study is adopted, outlining roles, descriptions and personal traits to help select appropriate workshop participants and assign suitable roles.

5.3.3 Activity 3 - Establish the feasibility and the scope of the simulation study.

The purpose of this activity is to assess whether hybrid simulation is an appropriate approach for the problem under study and to define a realistic initial scope for the modelling work. Building on the information gathered during earlier stakeholder interactions, the modelling team must decide whether the system characteristics, available data, and study objectives justify the use of a hybrid simulation approach rather than a single-method model.

Assessing feasibility at this stage is particularly important in hybrid simulation, as combining multiple simulation methods introduces additional complexity in terms of data requirements, model integration, skills, and time (Eldabi *et al.* 2018; Mustafee *et al.* 2015). Without an early and explicit assessment of feasibility, there is a risk of developing an overly complex model that cannot be supported by available resources or stakeholder input. This activity, therefore,

acts as a decision point, helping the modelling team to balance analytical ambition with practical constraints.

To support this assessment in a structured and transparent way, this research reviewed the respective Feasibility tool in PartiSim (Tako and Kotiadis 2010) and proposed the Initiate Study Tool HS2: Feasibility of Hybrid Simulation Modelling and Scope. The tool is designed to guide the modelling team in reflecting on key feasibility considerations, including the nature of the problem, the suitability of hybrid simulation, data availability, stakeholder engagement, and practical constraints such as time and expertise. In addition, the tool supports the definition of an initial model scope, which is used to prepare materials for the first facilitated workshop.

Tool HS2 does not aim to prescribe whether hybrid simulation should or should not be used. Instead, it provides a systematic way of documenting assumptions, uncertainties, and constraints, enabling informed judgement and discussion within the modelling team. It also supports transparency by recording the rationale behind early modelling decisions, which can be revisited and refined as the study progresses.

The detailed structure and content of Tool HS2, including the specific questions and assessment criteria, are presented in Appendix A. In this chapter, the focus is on the role of the tool within the overall framework, rather than on its detailed content.

The outputs of this activity feed directly into subsequent stages of the framework. In particular, they inform the preparation and focus of the first facilitated workshop, ensuring that discussions with stakeholders are aligned with what is feasible and meaningful within a hybrid simulation context. They also provide an early reference point for revisiting scope and feasibility decisions later in the study, should system understanding or project constraints change.

5.4 Substage 1a - Pre-workshop

After completing Stage 1, preparation for the facilitated workshop begins. According to PartiSim, this stage involves four key activities: (A) identifying the roles of the modelling and stakeholder teams, (B) selecting the workshop venue and time, (C) inviting stakeholders, and (D) preparing workshop materials (Tako and Kotiadis 2018b).

Activity A complements Activity 2 in Stage 1. Based on the list of potential participants, the modelling team allocates individuals to either the modelling team or the stakeholder team. Further guidance on roles and responsibilities is provided in the PartiSim Toolset 1 Manual for Initiating Study Tool 3: Stakeholders' Contact Details (Tako and Kotiadis 2018c)

Activities B and C focus on organising the workshop. The choice of venue is important, as a comfortable and well-arranged environment can influence the quality of facilitation (Mingers and Rosenhead 2004). Factors such as seating layout, access to walls and tables, and space for group work affect workshop dynamics and participant interaction (White, Burger and Yearworth 2016; Ackermann *et al.* 2011)

Activity D concerns the preparation of preliminary materials for Workshop I. Participatory simulation workshops may begin either from preliminary material or from scratch (Vennix 1996b). The modelling team must therefore assess the complexity of the problem and stakeholder expectations to decide on the most appropriate approach. While some studies have successfully used preliminary models to structure early discussions (Tako, Vasilakis and Kotiadis, 2010), starting entirely from scratch can be time-consuming and less productive (Kotiadis, Tako and Vasilakis, 2014).

5.5 Stage 2 - Define the Problem workshop.

The second stage explores the situation of interest and the system under study through a facilitated workshop. A facilitated workshop is a structured meeting with clear objectives, in

which selected and empowered participants contribute their perspectives on a specific issue (Franco and Montibeller 2010). In this framework, stakeholders identified in Stage 1 are invited to discuss the system in which they operate and the problematic situation affecting them. The session is led by a member of the modelling team acting as facilitator.

The facilitator plays a neutral role and requires strong interpersonal and communication skills to guide group interaction effectively (Tako and Kotiadis 2012). Given the complexity of managing workshop dynamics, support from other modelling team members, as recorders or co-facilitators, can be beneficial (Tako and Kotiadis 2012; Ackermann 1996).

The first workshop includes three activities: identifying the main problem, broadly defining the study objectives, and defining the system and its boundaries (Tako and Kotiadis 2015). These activities are largely retained from PartiSim. Minor adjustments were made to Activity 1 to encourage exploration of the system from multiple perspectives, while Activity 2 required no modification, as the existing PartiSim tools adequately support objective definition in a hybrid simulation context (Tako and Kotiadis 2018d).

In contrast, Activity 3 required adaptation. Its tools were reformulated using concepts from Soft Systems Methodology, including Rich Picture, CATWOE, and Analysis One, Two, and Three (Checkland and Scholes 1999; Checkland and Poulter 2020). The resulting Analysis One, Two, and Three for Hybrid Simulation was developed to support a DES-ABS hybrid model. This tool was refined after the feasibility assessment for the Brazilian case study, which indicated DES and ABS as the most suitable methods. Consequently, the tool focuses on elements relevant to these simulation approaches. Further details on each activity and the new tool are provided in the following sections.

5.5.1 Activity 1 - Identify the main problem for the study.

The first activity in the facilitated workshop is identifying the problem. Like in PartiSim, the facilitator leads the group to brainstorm and discuss the possible problems in the system (Tako and Kotiadis 2015). Brainstorming techniques allow participants to engage in discussions and reach a consensus on problem statements (Ritter and Mostert 2018).

The facilitated workshop starts with the facilitator providing stationery, such as post-it notes, pens and A4 paper, to all participants. Then, they are invited to contribute their views regarding the problem (Kotiadis, Tako and Vasilakis 2014).

In the DES context, the proposed question is highly relevant as it aims to pinpoint significant challenges the group encounters that lack the necessary numerical data to aid in effective planning and decision-making. Restricting this question to one system dimension (e.g., DES) drives the group to think about specific areas without sufficient quantitative data (such as statistics, metrics, or measurable evidence) to make informed decisions or develop plans.

Hybrid simulation, however, empowers modellers to scrutinise inherent issues in the system from different perspectives (Eldabi *et al.* 2019). Exclusively applying the question proposed in PartiSim in a hybrid simulation context might drive the group to cover one system perspective or lead to unproductive discussions. This approach could cause the group to concentrate on aspects of the system directly related to their interests rather than exploring it holistically or investigating the root causes of issues, which might be linked to services, individuals or regulations. Hence, this study proposes expanding the PartiSim approach for directing the group through an open-ended activity that explores the complex system through different perspectives.

The session starts with the questions proposed in PartiSim: “What major problems are you facing where quantitative information is not available to support your planning and decision-

making?” (Tako and Kotiadis 2018b). Answers to this broad exploratory question allow the facilitator to learn which dimension of the system drives the group thinking process. Based on the participant's answer, the facilitator should use questions from the Initiate Study Tool HS1: Bank of questions (Table 29, section 5.3.1) to guide the discussion and explore potential problems within other perspectives of the system.

During the brainstorming process, the facilitator reminds the participants to consider potential issues connected to policies and regulations. Posing questions on understanding society and rules might support facilitators in this task. Likewise, people-related issues could be explored by employing questions related to people and roles. By encouraging a comprehensive and inclusive discussion, the facilitator aids in the identification of a wide range of potential issues, ensuring that no crucial system perspective is disregarded in this session.

5.5.2 Activity 2 - Define the study objectives (broadly)

The purpose of this activity is to define the study objectives at a broad level. As in PartiSim, this stage does not aim to establish final objectives (Tako and Kotiadis 2015), but instead encourages participants to reflect on the outputs of previous activities and agree on initial goals for the study. Guiding questions, such as “Considering the discussions so far, what could be the objective of this study?”, help structure this discussion.

Although the formal definition of objectives takes place in the second workshop (Tako and Kotiadis 2015), an initial discussion is included in the first workshop. Establishing broad objectives at this stage supports post-workshop activities by helping the modelling team understand stakeholders’ perspectives and refine materials and facilitation plans for the subsequent workshop.

5.5.3 Activity 3 - Define the system and boundaries.

This session aims to define the system in which the problematic situation exists. The facilitator leads the group through the task of identifying the elements of the system. In PartiSim, this activity refers to identifying the elements using the SSM tool called CATWOE and root definition (Tako and Kotiadis 2015; Tako and Kotiadis 2018b). CATWOE is a mnemonic, and each letter corresponds to the initials of five elements in the system, namely Customer (beneficiaries of the transformation), Actors (who will do the transformation process), Transformation (the conversion of input to output), Weltanschauung (worldview which makes the Transformation process meaningful in its context), Owner (who stop the transformation), and Environmental constraints (elements outside the system which is taken as given) while root definition stands as a statement which contains all components in CATWOE mnemonic (Bergvall-Kåreborn, Mirijamdotter and Basden 2004; Checkland 2000).

Undoubtedly, CATWOE is a powerful SSM tool for defining key elements in the system. Combining these elements into a root definition provides a comprehensive system definition, enhancing comprehension of the problem situation (Tako, Kotiadis and Vasilakis 2010a) and in PartiSim, using CATWOE as one of the SSM tools created a friendly dynamic in which participants are involved in discussing the system without being challenged with the technical aspects of DES simulation modelling (Tako and Kotiadis 2015).

Although the approach in PartiSim demonstrated its efficacy for defining the system and boundaries in a facilitated workshop environment, this research recognises that its use alone would not tackle the challenges in a hybrid modelling scenario. In a hybrid simulation, the elements in the system that need to be discussed extend beyond those in the CATWOE (Customers, Actors, Transformation process, Worldview, Owners, and Environmental constraints). Key aspects, such as the aggregate behaviour of systems, the behaviours and

interactions of individual agents, the characteristics and attributes of agents, behavioural rules, and interactions between agents and their environments, should also be addressed.

Hence, significant adjustments were made to the tools used in this session, incorporating other SSM tools into CATWOE. This research began by considering three powerful SSM tools - CATWOE, Analysis One Two Three, and Rich Picture. CATWOE, as discussed above, encapsulates six essential elements in a hybrid system. It helps to define who is affected by the problem (Customers and Actors), what the system does (Transformation process), how stakeholders perceive the system (Worldview), who has responsibility for the system (Owners), and what external constraints impact the system (Environmental constraints).

Analysis One Two Three is a well-known framework for examining roles and social and political aspects within a system (Checkland 2000). Initially, the first analysis delves into the clients' roles, focusing on who initiated the study, who is responsible for solving the problem, and who ultimately owns the problem. Analysis Two, on the other hand, concentrates on roles, norms, and values. Lastly, Analysis Three aims to comprehend how power manifests in a specific problematic scenario (Kotiadis 2010; Checkland and Scholes 1999). By clarifying these foundational aspects, Analysis One sets the stage for a deeper exploration of the system's dynamics. At the same time, Analysis Two helps to understand how people interact within the system and how cultural and social norms influence these interactions. Analysis Three focuses on political aspects. Together, these three analyses provide a holistic view of the system, highlighting the operational aspects and the social and political dimensions that influence the system's behaviour and outcomes.

Analysis One Two Three and CATWOE are integral parts of Soft Systems Methodology (SSM), offering complementary perspectives to understand and analyse complex systems.

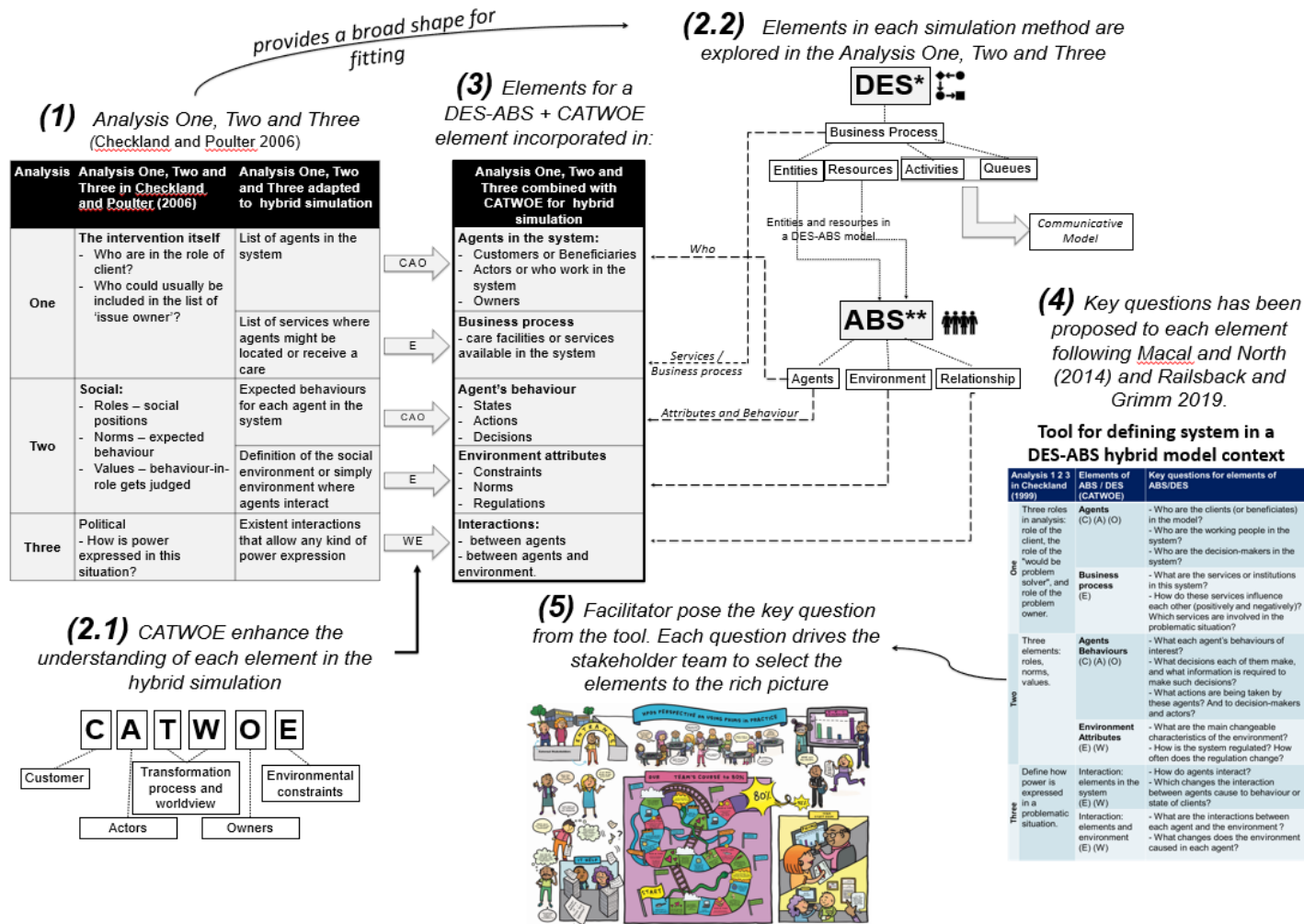


Figure 9: Elements and steps in the proposed Analysis One, Two, and Three for Hybrid Simulation (*author's own work*)

By merging both tools, this research aims to provide a robust tool for comprehensively understanding and analysing the multifaceted nature of systems, encompassing structural and behavioural dimensions and stakeholders' perspectives and influences.

The merged tool was structured as a checklist with key questions distributed over the three Analysis One Two Three levels. As depicted in Figure 9, the original Analysis One Two Three (number 1) provides the structure for fitting the elements in hybrid simulation models.

The analysis expected for each level was reviewed to fit the hybrid simulation needs, and elements of the hybrid simulation were allocated to each level. Elements primarily originate from CATWOE (number 2.1), complemented by elements in DES and ABS (number 2.2), outlined in Figure 9.

Analysis one incorporated three elements (Customers, Actors, Owners) of CATWOE (number 2.1), which are also elements in ABS (agents). This level also incorporates the elements in DES, services or business processes, outlined in Figure 9 (number 2.2). Analysis Two also covers the same CATWOE elements as Analysis One. However, it is dedicated to exploring agents' behaviours, attributes, or essential characteristics from the agents' ABS.

Still, this analysis also explores the definition of a social environment where agents interact with each other or with the element Environment. Environment is another essential element in ABS (number 2.2) and CATWOE (number 2.1), explored in Analysis Two and Three. Figure 9 also outlines the new design for Analysis Three. Instead of focusing on political power between stakeholders, hybrid simulation explores the existing interactions that allow any power expression through analysing two elements of CATWOE - Environment and worldview.

Table 12 displays the proposed Analysis One Two Three for Hybrid Simulation. The first column presents the elements for DES and ABS distributed over the three levels. As discussed

above, Analysis One covers Agents and Entities, while Analysis Two explores Agent Behaviours and Environment attributes. Finally, Analysis Three discusses interactions between agents and between agents and the environment.

The second column in Table 12 presents the questions. Questions were formulated based on previous works in agent-based simulation (Macal and North 2010b; Macal and North 2014; Railsback and Grimm 2019), as well as in DES (Tako and Robinson 2009; Robinson 2014) and the original PartiSim Bank of Questions (Tako and Kotiadis 2010). The last column in Table 12 summarises the outputs for each Analysis, outlining the elements from CATWOE and hybrid DES-ABS that are expected to be identified by posing the respective questions.

The new tools were designed to support the facilitator in guiding participants through discussions to define the system and its boundaries. By posing questions using these tools, the facilitator encourages the group to respond with images that will form a rich picture.

Table 12: Analysis One, Two, and Three for Hybrid Simulation.

Tool 1: Analysis One, Two, and Three for Hybrid Simulation			
Elements of ABS/DES	Key questions	Output	
One	Agents	<ul style="list-style-type: none"> ○ Who are the clients (or beneficiaries) in the model? ○ Who are the decision-makers in the system? ○ Who are the working people in the system? 	- Definition of customers (C), actors (A), and decision-makers (O) in the system.
	Entities	<ul style="list-style-type: none"> ○ What are the services or institutions in this system? ○ How do these services influence each other (positively and negatively)? ○ Which services are involved in the problematic situation? 	- Map of all services or institutions in the system relevant to the problematic situation.
Two	Agent behaviours	<ul style="list-style-type: none"> ○ What are the client's (or beneficiaries') behaviours of interest? ○ What decision-makers' behaviours are of interest? ○ What actors' behaviours are of interest? ○ What decisions do the clients (or beneficiaries) make, and what 	- Identification of the relevant states assumed by customers (C), decision-makers (O), and actors (A) over time.

Tool 1: Analysis One, Two, and Three for Hybrid Simulation			
Elements of ABS/DES	Key questions	Output	
	<p>information is required to make such decisions?</p> <ul style="list-style-type: none"> ○ What decisions do the decision-makers make, and what information is required to make such decisions? ○ What decisions do actors in the system make, and what information is required to make such decisions? ○ Under which circumstances or conditions do clients state changes? How about decision-makers and actors who work in the system? ○ What actions are being taken by these agents? And to decision-makers and actors? 		
Environment attributes	<ul style="list-style-type: none"> ○ What are the main changeable characteristics of the environment? ○ How is the system regulated? ○ How often does the regulation change? 	- Description of the environmental factors and constraints (E) that might influence the problematic situation.	
Three	Interaction between elements in the system	<ul style="list-style-type: none"> ○ How do clients interact with decision-makers? ○ How do clients interact with those who work in the system? ○ How do decision-makers interact with those who work in the system? ○ Which changes in the interaction between clients and decision-makers cause the behaviour or state of clients? ○ Which changes in the interaction between clients and those who work in the system cause the behaviour or state of clients? ○ Which changes the interaction between decision-makers and those who work in the system, causing the behaviour or state of decision-makers? 	- Definition of the interaction between autonomous agents in the system and the effect of these interactions on the agent's decision or world view (W) regarding the problematic situation.
	Interaction between elements and the environment	<ul style="list-style-type: none"> ○ What are the interactions between clients and the environment? ○ What are the interactions between decision-makers and the environment? ○ What are the interactions between those who work in the system and the environment? ○ What changes does the environment cause in the clients? 	Definition of the interaction between autonomous agents and the environment and the changes these interactions can cause (E).

Tool 1: Analysis One, Two, and Three for Hybrid Simulation		
Elements of ABS/DES	Key questions	Output
	<ul style="list-style-type: none"> ○ What changes does the environment cause in those who work in the system? And in the decision-makers? 	

To conduct the rich picture session using the proposed Analysis One, Two, and Three, this study introduced two manuals: the "Manual for Running the Proposed Tool HS3 Analysis One, Two, and Three" and the "Manual for Conceptual Modelling Tool HS3: Rich Picture," which includes tips for developing a rich picture. Both manuals aim to provide comprehensive guidance on creating a rich picture with the new tool. The following paragraphs provide further details on these tools and their application.

5.5.3.1 Manual for employing the Tool HS3: Analysis One, Two, and Three for hybrid simulation.

This manual accompanies the Conceptual Modelling Tool HS3: Analysis One, Two, and Three for hybrid simulation, bringing further guidance in using Table 12 through three main steps, while Figure 9 displays how this session is conducted in three main steps.

Step 1: Exploring Transformation (T)

To start the discussion, the facilitator invites participants to contribute their views about the transformation in the system by discussing element T, the transformation of CATWOE.

Key questions, such as "what is the transformation that lies at the heart of the system?" or "Which processes or systems are affected by the issue?" (Tako and Kotiadis 2018c), could be thought-provoking questions to encourage the stakeholders to share their views. The stakeholder team should be given 10 to 20 minutes to brainstorm about the transformation before the facilitator leads the group in prioritising the transformation for the study.

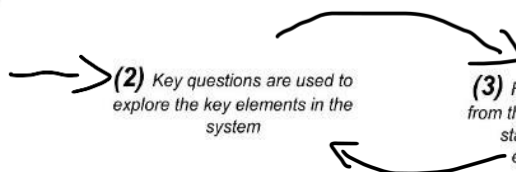
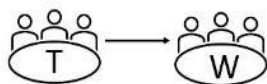
Step 2: Exploring Worldview (W)

The group carry on with the discussion regarding a second element in CATWOE - W or worldview. This element summarises the participant’s beliefs about the system. In other words, the reasons for the system or organisation's existence and its primary purpose (Checkland and Poulter 2020; Checkland and Scholes 1999).

For this element, the main question for engaging the stakeholder team in its discussion could be: “What are the worldviews (or beliefs) that explain the existence of the transformation?” (Tako and Kotiadis 2010). Like the discussions about transformation, the facilitator invites the group to brainstorm about their worldview of the system. PartiSim Toolset 2, Manual for Conceptual Modelling Tool 2, can support the discussion on T and W in this session³.

On the day of the workshop...

(1) Transformation and Worldview are discussed before the facilitator start using the tool for building rich picture is discussed ...



Tool for defining system in a DES-ABS hybrid model context

Analysis 1 2 3 in Checkland (1999)	Elements of ABS / DES (GATWOE)	Key questions for elements of ABS/DES
One	Agents (C) (A) (O)	- Who are the clients (or beneficiaries) in the model? - Who are the working people in the system? - Who are the decision-makers in the system?
	Business process (E)	- What are the services or institutions in this system? - How do these services influence each other (positively and negatively)? Which services are involved in the problematic situation?
Two	Agents Behaviours (C) (A) (O)	- What each agent's behaviours of interest? - What decisions each of them make, and what information is required to make such decisions? - What actions are being taken by these agents? And to decision-makers and actors?
	Environment Attributes (E) (W)	- What are the main changeable characteristics of the environment? - How is the system regulated? How often does the regulation change?
Three	Interaction: elements in the system (E) (W)	- How do agents interact? - Which changes the interaction between agents cause to behaviour or states of clients?
	Interaction: elements and environment (E) (W)	- What are the interactions between each agent and the environment? - What changes does the environment caused in each agent?



Figure 10: Three steps in conducting activity 2 (author’s own work)

Step 3: Developing Rich Picture with Analysis One Two Three for HS.

³ Toolset 2 can be downloaded from PartiSim website: <https://www.partisim.org/get-partisim/>

After agreeing on the transformation and worldview, the stakeholder team built the rich picture by following analyses one, two, and three proposed in this framework (Step 2 in Figure 9). The facilitator should begin by inviting participants to review the pre-printed pictures available for the activity and explain the process. These pictures should be printed before the workshop and accessible to all participants at this stage.

Next, the facilitator poses the questions from Analysis One, Two, and Three for the hybrid simulation (Table 12). For each question, the group selects the pictures that best represent their perspectives and places them on a flipchart or whiteboard. This process is repeated for all questions across the three levels of Analysis One, Two, and Three. After all questions have been covered, the facilitator should ensure the group agrees on the session's outcome.

5.6 Substage 2a - Post workshop

After the first facilitated workshop, I have a few activities to complete. The modelling team should document the findings from the workshop and liaise with stakeholders to ensure the correctness of the model (Tako and Kotiadis 2012). This framework adopts the same three activities in PartiSim (Tako and Kotiadis 2015) for this substage with minor adjustments. They are (1) re-draw and disseminate workshop outputs to stakeholders, (2) liaise with the stakeholder team over the correctness of workshop one outputs, and (3) prepare preliminary materials for use in workshop II. The following paragraphs will describe each activity.

5.6.1 Activity 1 - Re-draw and disseminate workshop outputs to stakeholders.

After the workshop, the modelling team thoroughly reviews all the materials generated. It includes gathering and discussing recordings, drawings, and notes. The team ensures that the recorders are actively involved in this process, incorporating their notes and perceptions into the final report and workshop outputs. The resulting report is then shared with key stakeholders for further analysis and consideration.

Different from the original PartiSim, the modelling team was faced with the task of managing the extensive amount of information collected during Activity 2, defining the system and boundaries supported by the tools Conceptual Modelling Tool HS3: Analysis One, Two, and Three for Hybrid Simulation (THS3).

To effectively handle this information overload, the team uses the Conceptual Modelling Tool HS4: HS Inputs Form (THS4), proposed by this research as a complementary tool HS3: Analysis One, Two, and Three for hybrid simulation, described in Section 5.5.3.

Conceptual Modelling Tool HS4, referred to as the HS Inputs Form (THS4), is used to record and organise information gathered during Activity 1. The tool supports the systematic documentation of stakeholders' initial views of the system, key contextual factors, and early perceptions of the problematic situation. Capturing this information in a structured way helps ensure continuity between early stakeholder engagement and subsequent feasibility, scoping, and conceptual modelling activities.

The detailed structure and content of the HS Inputs Form, including example fields and guidance on its use, are provided in Appendix A. In the main framework, the tool is referenced to indicate its role in supporting the modelling process rather than to describe its detailed format.

5.6.2 Activity 2 - Liaise with the stakeholder team over the correctness of workshop one output.

The modelling team might contact the project champion or sponsor to ensure that their findings during the workshop are correct. Additionally, key stakeholders might be involved in informal meetings to assist the modelling teams with possible questions or doubts regarding the discussions during the workshop. Ideally, all activities in stage 2 should be completed during the workshop, and stakeholders' involvement in post-workshop activities should be restricted to one-off questions (Tako and Kotiadis 2015).

5.6.3 Activity 3 - Prepare preliminary materials for use in workshop II.

The final post-workshop activity involves planning and preparing for the next facilitated workshop, covering three tasks: (1) deciding the venue and time slots, (2) inviting stakeholders, and (3) preparing workshop materials. Preliminary materials, including outputs from the first workshop and relevant information collected, should be structured for use in the second workshop. This preparation helps the modelling team avoid prolonged and unproductive sessions during the development of the conceptual model. The benefits of engaging in preparatory activities are also documented in previous works (Kotiadis, Tako and Vasilakis 2014; Vennix 1996a).

5.7 Stage 3 - Define Conceptual Model Workshop.

This stage corresponds to the second facilitated workshop and focuses on engaging stakeholders in defining the key elements of the conceptual model, including objectives, inputs, outputs, and model representation (Tako and Kotiadis 2015; Robinson 2014; Tako *et al.* 2019). As shown in Table 13, the activities proposed in PartiSim were considered sufficient to support participatory hybrid simulation; however, new tools were introduced to adapt the methodology to a DES-ABS hybrid context.

At this stage, Draw the Model Representation is introduced as the first activity. Significant adaptations to the original PartiSim tools (Tako and Kotiadis 2018e) were required to support the identification of elements within each module of the hybrid model. Unlike stand-alone simulations, hybrid models consist of multiple distinct modules, each with its own elements (Zulkepli and Eldabi 2019; Onggo 2014). As a result, new tools were developed for selected activities, as summarised in Table 13.

In the hybrid simulation field, discussions about modules within the model are held (Onggo 2014; Zulkepli 2012). Modules in a hybrid model refer to distinct components that integrate

different simulation methods to capture the complexity of a system more effectively (Zulkepli 2012). A module in a hybrid simulation model is considered an independent simulation model (Eldabi *et al.* 2016). Each module operates autonomously, with its own set of inputs, outputs, objectives, assumptions, and simplifications. Given this independence, modellers need to define the elements of each module individually. This process involves identifying each module's objectives, inputs, outputs, and other pertinent components before integrating them into the broader hybrid model.

Table 13: Activities in the Participative Hybrid Conceptual Modelling Framework versus PartiSim

Towards a Participative Hybrid Conceptual Modelling Framework		PartiSim (Tako and Kotiadis 2015)	
Activities	Tools	Activities	Tools
Draw the model representation.	(M3) Manual for CM: Drawing a Communicative Model with UML notation.		
Define performance measures	(M4) Manual for Conceptual Modelling: Identifying the Performance Measurement in the HS Model PartiSim Toolset 3 Conceptual Modelling Tool 3: Drawing the Performance Measurement Model	Put forward and agree on performance measures to address the problem identified in the workshop I	PartiSim Toolset 3 Manual for Conceptual Modelling Tool 3: Drawing the Performance Measurement Model
Define simulation model objectives.		Define simulation model objectives.	Manual for Conceptual Modelling Tool 4: Conceptual Modelling Tool 4: Study Objectives
Discuss model contents, model scope and level of detail	(M5) Manual for Conceptual Modelling: Discussing elements in a Hybrid Conceptual Model.	Discuss model contents, model scope and level of detail.	
Discuss the responsibility of data collection.		Discuss the responsibility of data collection.	

To illustrate how modules operate within a hybrid model and how the elements of a conceptual model can be identified, this research reviewed Robinson's framework for conceptual

modelling (Robinson 2008) and adapted it for hybrid simulation, as shown in Figure 11. In this adapted structure, the problematic situation appears at the top and informs the definition of the overall objectives, which are explored during stages 1 and 2 of the participatory hybrid simulation framework proposed in this research. These initial stages focus on understanding the real-world issue and clarifying what the model must achieve, in line with Robinson's original guidance for discrete-event simulation. The remaining elements of the conceptual model are then developed in stage 3, where the complexity of hybrid simulation becomes apparent.

Figure 11 presents a central hybrid model composed of several modules (Module 1, Module 2, ... Module N), each with its own inputs, internal logic, and outputs. Although these modules may use different simulation methods, they are connected through information flows, where the output of one module can become the input to another. Inputs on the left represent experimental factors that feed into the hybrid model, while outputs on the right represent system responses used to assess whether the overall objectives have been met. The curved arrows linking outputs back to objectives show how results are interpreted to evaluate success or identify reasons for failure.

Overall, Figure 11 demonstrates how Robinson's structured approach can be extended to support the interconnected and multi-method nature of hybrid simulation. For example, outputs from Module 1 may become inputs for Module N (Input N.1) and Module 2 (Input 2.1), while other outputs—such as Output N.1 or Output N.Z—remain final simulation results used for analysis rather than feeding into other modules. Recognising these information exchanges helps identify which inputs originate as outputs from other modules and clarifies how the components of the hybrid model influence one another. This understanding is essential for building an integrated and effective hybrid simulation model.

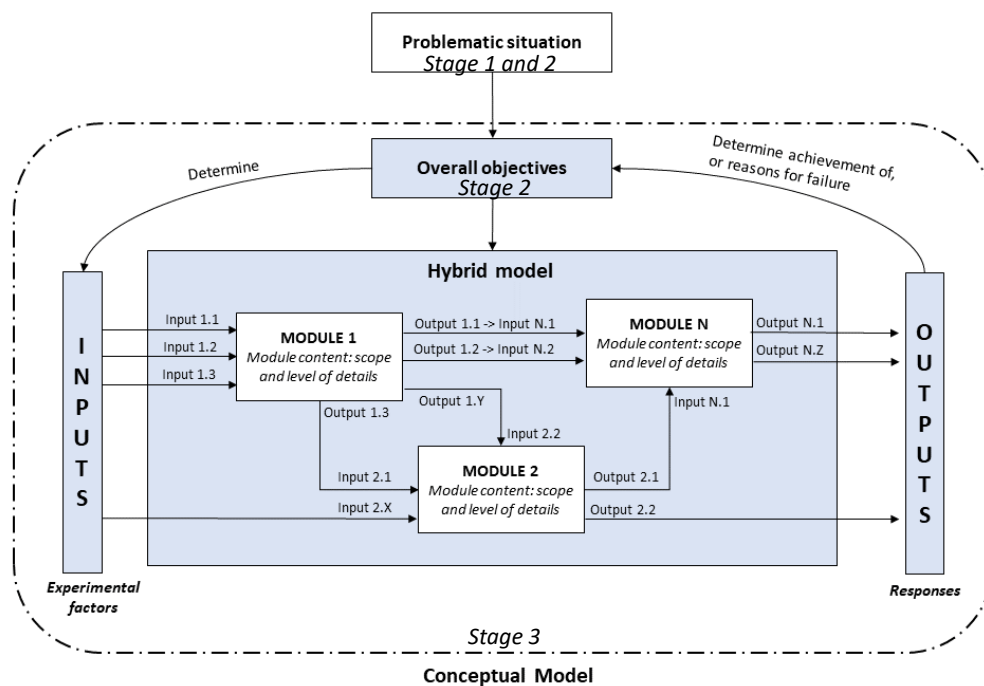


Figure 11: Overview of a conceptual model for hybrid simulation, based on Robinson (2008) (author's own work)

The following paragraphs provide further detail on each activity within this stage 3, aimed at developing the conceptual hybrid simulation model and ensuring that all elements are clearly identified, recognising that modules in hybrid simulation operate as distinct components, each functioning as an independent model with its own objectives, inputs, outputs, assumptions, and simplifications, which must be defined individually before being integrated into the overall hybrid model (Eldabi *et al.* 2016; Onggo 2014; Zulkepli 2012).

5.7.1 Activity 1 - Draw the model representation.

The first activity is to develop the communicative or visual representation of the simulation model. Drawing a model representation is an activity in PartiSim. However, it offers tools and guidance on representing a DES model (Tako and Kotiadis 2018b). Hence, this research reviewed this activity to accommodate the hybrid simulation requirements for a model representation that includes DES and ABS.

Two main adjustments were proposed. First, in PartiSim, this activity is presented as the final step in the facilitated workshop, following the inputs, outputs, and objectives discussion. (Tako and Kotiadis 2010). However, the researcher chose to reverse the sequence of the tasks, with the visual representation taking precedence over the initial activity. The visual representation is used as the foundation for the discussions proposed in the following activities, serving as an instrument to support the stakeholders' reflection on how the system should be presented. This concept aligns with previous research that emphasised the significance of visual representation in communicating the simulation model (Jebeile 2018; Onggo 2010) and also with the researcher's belief that using a visual representation would enhance the interactions between the facilitator and stakeholder team.

The second significant adjustment was the language used to develop the model representation. In PartiSim, a Process Flow Diagram (PFD) represents a series of queues and activities. The PFD uses squares to represent activities, circles for waiting times, and arrows to connect them. While other simulation studies have explored the use of BPMN (Business Process Model and Notation), which is a more detailed graphical language than PFD (Wagner 2021; Onggo *et al.* 2018), BPMN also focuses on elements that represent events, activities, and flow. Although both PFD and BPMN effectively represent a DES model, they fall short in illustrating a hybrid model, particularly those incorporating ABS.

ABS models have three main elements: agents, environment, and interactions (Macal and North 2010b), and all elements should be included in the model representation, as discussed in Chapter 2, Section 2.2.3. Therefore, this research recognised that tools in PartiSim might not be suitable for hybrid simulation, and a new tool was proposed. The new tool was the Manual for Conceptual Modelling Tool 4: Drawing a Communicative Model with UML notation - the manual combined two concepts to represent a hybrid model - UML notation and a multi-layered system.

The UML diagram notation is an extensive modelling language in the software engineering domain, and guidelines include several types of UML diagrams (Odell, Van Dyke Parunak and Bauer 2000). UML stands for Unified Modelling Language (Torre *et al.* 2018), comprising fourteen different UML diagram types that address different software development aspects.

UML has been frequently used to represent ABS (Odell, Van Dyke Parunak and Bauer 2000; Bauer and Odell 2005; Leombruni and Richiardi 2006; Masad and Kazil 2015). They mainly focus on state diagrams, which effectively capture agents' states and their transitions in a simulation. Likewise, other studies have considered the UML notation ideal for representing states and transitions in ABS (Siebers and Klügl 2017; Ahmed, Robinson and Tako 2014); however, none have discussed interactions.

The multi-layered concept is a framework that organises a complex system into distinct, hierarchical layers, each with specific functions and interactions (Kempkens and Rosch 2000). While the multi-layered system has found extensive application in software development (Kempkens and Rosch 2000), its implementation in hybrid simulation remains unexplored. Thus far, the multi-layered system has only been suggested as a potential alternative for representing hybrid models in a few hybrid simulation studies (Guo *et al.* 2021) and conferences, such as the Winter Simulation Conference Panel (Mustafee *et al.* 2015).

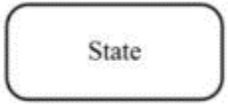


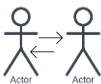

Combining the strengths of UML and multi-layer systems, this research aims to provide essential guidance for communicating a hybrid model through a unique representation. This approach addresses the gap in hybrid system (HS) simulation representation identified in previous studies (Brailsford *et al.* 2019) and confirmed by the literature review, as discussed in Chapter 2. Given the lack of guidance on representing a hybrid simulation model, this research proposes a manual for constructing a communicative model using UML notation grounded in a multi-layer system. This method is discussed in detail in the subsequent section.

5.7.1.1 Manual for Conceptual Modelling Tool 4: Drawing a Communicative Model with UML notation.

This manual was developed to support modellers in representing the conceptual model. It has two-fold objectives. First, it details the notation introduced by this study as ideal for representing the DES-ABS model, explaining the graphical notation selected from UML. Second, it presents the idea of representing the hybrid model using a multi-layer system.

The diagramming notation proposes the use of graphical elements for ABS and DES. Table 14 contains the notations for ABS. Elements (a) and (b) represent the state assumed by agents and the event or transition between the states, respectively. Both notations were already used in former studies that attempted to introduce the UML state machine diagram to represent ABS (Siebers and Onggo 2014; Ahmed, Robinson and Tako 2014; Onggo 2010).

Table 14: Notation - ABS module in a hybrid model representation.



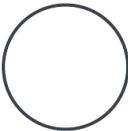
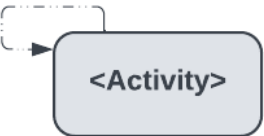
ID	Graphical element	Description
(a)		It represents the condition of a single object at an instant of time. It can also mean the behaviour of an object in response to an event in a system.
(b)		Transformation. It connects one state to the other. It indicates the transition or transformation from one state to another.
(c)		It represents agents in the model. The subtitle below the agent replaces the word “actor” with the agent’s name.
(d)		It represents agents’ interaction along the model. The symbol should be placed above or below the interaction activities.
(e)		Arrows between the agent's representation (c) indicate the interaction between agents or between agents and the environment.

In this research, the UML notation for ABS is expanded, and elements from another UML diagram, such as the Use Case Diagram (Fauzan *et al.* 2019; Ibrahim *et al.* 2010), are included to represent interactions between agents and interactions between agents and the environment.

In Table 14, the graphical elements (c), (d) and (e) are used to represent agents and agent interaction over a DES-ABS hybrid model. Element (c) represents agents, while element (d) was adapted from UML and should be used to indicate where in the model the interaction between agents occurs, while element (e) is used to indicate the interaction itself. The first two elements are derived from the UML State chart diagram. In contrast, the others originate from the UML Use Case diagram.

Complementary Table 15 introduces the graphical elements for representing DES. Elements (a) and (b) are commonly used. They are also part of other pictorial representations, such as BPMN (Business Process Modelling and Notation) and Activity Cycle Diagram (ACD) (Onggo 2010; Nizioł *et al.* 2021), and they represent activities or stages in an organisation's process and the connection between these activities, respectively. Element (c) is not part of UML but comes from ACD and represents waiting time in the organisation's process. A similar graphical notation is found in UML but is employed to represent interfaces. Furthermore, element (d) is adapted from UML and outlines activities requiring multiple reiterations.

Table 15: Notation for the DES module in a hybrid model representation.

ID	Graphical element	Description
(a)		Round corner-shaped rectangles indicate the activities or stages in an organisation's process to represent steps in services or facilities.
(b)		The connection between activities indicates the activity's directional or control flow.
(c)		It comes from the Activity Cycle Diagram (ACD) and represents queues or waiting lists. The words queue and waiting list should be written inside the circle.
(d)		The arrow coming out of the rectangle indicates a recurring activity. Above the arrow, the time for a repeating activity is registered.

Beyond the notation, the present research also adopted the concept of layers to represent the hybrid model. Multi-layer system design is a structural methodology employed in software engineering to arrange complex systems into separate tiers, with each tier accountable for specific functionalities (Kempkens and Rosch 2000).

In a hybrid simulation, each tier or layer will stand for a module in the hybrid simulation model. Figure 12 shows an example of what would stand as layers in a DES-ABS hybrid simulation. The multi-layer system approach allows for visualising the various components and interactions within the hybrid model. The DES components can be visualised in one layer, showing the sequence and timing of events. In contrast, the ABS components can be detailed in another layer, focusing on the autonomous behaviours displayed in Figure 12. Interactions can be outlined over the representation, especially in the DES layer, where staff and patients, for instance, are likely to interact.

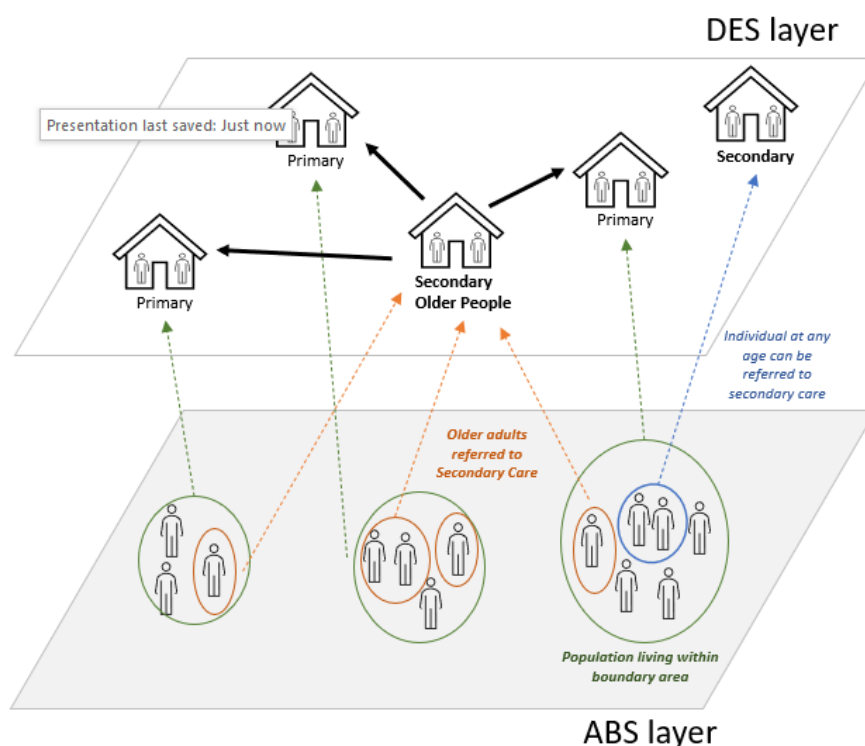


Figure 12: Multi-layered system in hybrid simulation (author's own work)

The multi-layered system representing the model allows for a clear mapping of interactions between DES and ABS components. This approach provides a unique and comprehensive representation of the entire model, utilising standard graphical elements with the necessary notation to cover all essential aspects of DES and ABS. This unified representation clarifies the hybrid model's functioning and enhances stakeholder engagement by offering an accessible and intuitive visual tool. To the best of the researcher's knowledge, no studies have proposed a unified approach for representing all elements in DES and ABS hybrid models. As discussed in Chapter 2, the literature review revealed that most studies represent each simulation separately or use an image of the computer model to communicate the conceptual model.

5.7.2 Activity 2 - Define performance measures.

This activity aims to identify the performance measures for the system in the study. In PartiSim, the definition of performance measures is accomplished by the development of the Performance Measurement Model (PMM), which follows three steps: (1) identifying the performance measures, (2) identifying how efficiency, effectiveness and efficacy can be monitored, and (3) completing the Performance Measurement Model (PMM) (Tako and Kotiadis 2018b; Kotiadis 2007).

Identifying measures in a hybrid DES-ABS model extends beyond the scope explored in PartiSim. For DES, performance measures often focus on efficiency and operational metrics, such as wait times and resource utilisation. For ABS, the focus shifts to the behaviours and interactions of agents, tracking metrics like agent decision-making processes, adaptability, and emergent phenomena. Adjustments were proposed to include measurements for the ABS modules to adapt this activity for hybrid simulation. As discussed in Chapters 2 and 5, agents in an agent-based model can represent any autonomous entity in a system, requiring specific performance measures related to the agents or their behaviours. For example, Shamil *et al.*

(2021) used the total number of infected people as a key indicator in a COVID-19 ABS study, while Jindal and Rao (2017) used cumulative cases and mosquito population size as KPIs in their ABS study on mosquito-borne disease transmission.

Therefore, this research introduces a manual for identifying the measurements in a hybrid simulation model to support the modelling team in conducting this activity during the facilitated workshop. This manual is detailed in the subsequent section.

5.7.3 Activity 3 - Define simulation model objectives

This activity is adopted directly from PartiSim and requires no modification, as its structure and tools are suitable for simulation studies, including hybrid simulation. The session begins with the facilitator reviewing the outcomes of the brainstorming exercise conducted in Workshop I to confirm that the study objective remains valid. Brainstorming is then used again to support participants in reflecting on and refining the objective (Tako and Kotiadis 2015). PartiSim tools, such as Stakeholder Form 1: Brainstorm Study Objectives, may also be used to record stakeholders' views (Tako and Kotiadis 2018b).

5.7.4 Activity 4 - Discuss model contents, model scope and level of detail.

The fourth activity focuses on defining the elements of the conceptual hybrid simulation model. A conceptual model typically includes objectives, inputs, outputs, content, assumptions, and simplifications (Tako *et al.* 2019; Robinson 2008). Following the PartiSim approach, outputs and inputs are identified first, followed by discussions of model content, assumptions, and simplifications (Tako and Kotiadis 2015).

While PartiSim provides clear guidance for this activity, adaptations are required for hybrid simulation, where multiple simulation modules coexist within a single model. This activity must therefore be repeated for each module to capture its specific characteristics and requirements. This iterative process supports coherent integration by ensuring that interactions and

dependencies between modules are systematically identified. Further guidance on conducting this activity is provided in the revised PartiSim manual, *Manual for Conceptual Modelling: Discussing Elements in the Hybrid Conceptual Model*, introduced in the following section.

5.7.4.1 Manual for Conceptual Modelling: Discussing elements in the Hybrid Conceptual Model (M5).

The manual guides leading discussions to identify the hybrid model's inputs, outputs, content, assumptions, and simplifications. This manual proposes four key steps to be undertaken:

1. Identify the modules in the model representation (output of activity 1)
2. Identify the model inputs and outputs to each module.
3. Agree on the model content of each module.
4. Agree on assumptions and potential simplifications to the hybrid model.

Like in PartiSim, this activity is conducted in an interactive session with stakeholders, or the modelling team can optionally undertake it as part of post-workshop stage 3 (Tako and Kotiadis 2018b). The following paragraphs explain how to accomplish each step:

Step 1: Identify the modules in the model representation

The modelling team first identifies the modules within the model representation developed in Activity 1. Modules are defined as independent components that can be developed using different simulation methods, guided by the broad objectives agreed upon in Workshop I. Each module is identified before stakeholders discuss its elements, beginning with inputs and outputs. A module represents a single logical part of the model, with defined input and output interfaces connecting it to other modules or the external environment Onggo (2014). A module can produce two types of outputs: model output and input for other modules (as illustrated in Figure 11: Overview of a conceptual model for hybrid simulation, based on Robinson (2008) in Section 5.4).

Step 2: Identify the model inputs and outputs to each module.

Building on the performance and behavioural measures identified earlier, outputs are first linked to their respective modules. These outputs reflect system performance and agent behaviour, such as waiting times or resource utilisation in DES modules, and behavioural or health outcomes in ABS modules. Once outputs are defined, inputs are identified as the data and parameters required for each module to operate, including resources and demand rates for DES, and agent attributes and decision rules for ABS. Examples from the literature may be used to support this process (Robinson 2014).

Step 3: Agree on the model content of each module.

The content and scope of each module are then discussed separately to clarify what is included in the model and at what level of detail. Scope defines model boundaries, while the level of detail specifies how elements are represented, including attributes, state variables, and behaviours (Railsback and Grimm 2019; Robinson 2014).

Step 4: Agree on assumptions and potential simplifications to the hybrid model.

Finally, the modelling and stakeholder teams agree on assumptions and potential simplifications. Assumptions address uncertainties and knowledge gaps about the real system, while simplifications support model tractability (Robinson 2010). These should be explicitly agreed and documented, as they may arise throughout the conceptual modelling process.

5.7.5 Activity 5 - Discuss responsibility for data collection.

To effectively conduct an activity to discuss responsibility for data collection for a DES-ABS hybrid model, the workshop facilitator should first outline the specific data requirements for Discrete Event Simulation (DES) and Agent-Based Simulation (ABS). It includes explaining the need for detailed process flow data related to the facilities in the draw developed during activity 1, as well as individual agent data, such as behaviours and interactions for ABS. The

form Conceptual Modelling Tool HS4: HS Inputs Form (THS4) might be used to ensure that the outputs from workshop I are still valid after the second workshop. At this stage, it might be necessary to amend the Inputs Form (THS4) as some information collected for agents and facilities during Workshop I might not cover the discussions in Workshop II.

5.8 Substage 3a - Post Workshop

After Workshop II, the modelling team undertakes several follow-up tasks. First, it liaises with stakeholders to complete the performance measurement activity if it was not finalised during the workshop. The team then prepares a report summarising the outputs of Workshop II, including the conceptual model and associated data requirements (Tako and Kotiadis 2015). This report is shared with key stakeholders to confirm accuracy and allows them to review and validate the conceptual model outside the workshop setting (Tako, Kotiadis and Vasilakis 2010a).

5.9 Stage 4 - Develop a computer model.

Stage 4 is the last and contains the activities for transforming the conceptual model into a computer model. Unlike stages 2 and 3, this phase did not involve a structured workshop with active participation from stakeholders. Instead, it was primarily carried out by the modelling team, with the essential stakeholders providing support by validating the results of the computational model, as demonstrated in PartiSim (Tako and Kotiadis 2015).

For this stage, three activities were suggested: data collection, building a computer-based simulation model, and conducting preliminary tests. These activities are the same as those proposed in PartiSim (Tako and Kotiadis 2018a; Tako and Kotiadis 2015). This study relied on the three activities proposed in PartiSim to guide the hybrid simulation framework, as described in the following paragraphs.

5.9.1 Activity 1 - Data collection

The first activity is data collection, which involves gathering the numerical and qualitative information required for model development. This task is mainly led by the modelling team outside the workshops, with ongoing input from the project champion and key stakeholders. Stakeholder agreement is also sought on any amendments needed to progress the modelling.

Numerical data provide the quantitative basis for simulation, while qualitative information supports contextual understanding (Robinson 2014). Information gathered in earlier stages is compiled and reviewed to confirm that sufficient data are available to support the next steps in model development.

5.9.2 Activity 2 - Build a simulation model on the computer.

Coding the simulation model is the central task of this stage, involving the translation of the conceptual model into the selected software or using a programming language such as Python. Building on the PartiSim approach, this research adopts Robinson's (2014) best practices to guide this process.

Robinson recommends designing or drafting the model before coding. This design stage enables the modelling team to assess how the conceptual model will be implemented and to anticipate coding challenges, thereby reducing the risk of inefficient or unclear code.

For hybrid simulation, this research also recommends identifying interactions between modules, following Zulkepli and Eldabi (2015). This involves defining how information will flow between modules, using insights gained from activities 2 and 3 in stage 3. Modellers may draw on the guidance in Morgan, Howick and Belton (2017) when completing this task.

Once the structure is clear, the modelling team codes the model using the selected software, supported by relevant documentation and tutorials. Programming tools may also be used to

customise the model so that it represents system complexity accurately and meets the study objectives.

5.9.3 Activity 3 - Conduct preliminary tests (Model Verification and Validation).

After coding the model, the modelling team performs verification and validation to ensure that it functions correctly and produces credible results. This stage confirms that the conceptual model has been accurately translated into software and is sufficiently reliable for its intended purpose (Robinson 2014). In PartiSim (Tako and Kotiadis 2018b), stakeholders, particularly the project champion, check whether the computer model reflects workshop discussions. While their involvement remains important, this research proposes that, for hybrid models, each module should first be tested independently before any stakeholder validation takes place.

This study follows approaches used in hybrid simulation research (Nguyen, Howick and Megiddo 2024) and in DES-ABS modelling (Penny, Bayer and Brailsford 2023), which recommend model verification and black-box validation. Verification involves examining the model's internal logic, structure and components through inspections and code reviews, using the conceptual model as a reference (Robinson 2014). Black-box validation, in contrast, assesses the model's outputs and behaviour without reference to its internal workings (Robinson 1999).

5.10 Chapter Conclusion

In summary, this chapter presented a conceptual framework for facilitated hybrid simulation that supports the participatory development of hybrid models. The framework builds on and extends the PartiSim methodology (Tako and Kotiadis 2015; Tako and Kotiadis 2018b) by explicitly embedding stakeholder participation across all stages of model development, distinguishing it from existing hybrid simulation frameworks (Nguyen, Megiddo and Howick 2021; Zulkepli, Eldabi and Mustafee 2012; Chahal and Eldabi 2008). It retains the first four

stages of PartiSim—Initiate Study, Define Problem (Workshop), Define Conceptual Model (Workshop), and Model Coding—reflecting established simulation practice (Brailsford *et al.* 2019; Robinson 2014). The framework differentiates between stakeholder-led workshop activities and modelling tasks conducted between workshops, both of which are essential to managing the simulation process (Kotiadis and Tako 2021). A structured set of tools and supporting manuals underpins the framework, ensuring consistency, traceability, and systematic documentation. While preserving the overall structure of PartiSim, the framework introduces targeted adaptations to support hybrid simulation, including revised and new tools, as summarised in Figure 8.

Chapter 6 - Application of a Participatory Hybrid Simulation Framework to Brazilian Healthcare

6.1 Chapter Introduction

This chapter applies the participatory hybrid simulation framework introduced in Chapter 5 to the Brazilian healthcare context described in Chapter 3. It presents a detailed account of how each stage of the framework was implemented in practice. Sections 6.2 to 6.7 document the progression of activities undertaken during the development of Stages 1 to 3 of the framework, which are grounded in the theoretical basis discussed in Chapter 5. The outcomes of applying these stages, including the resulting conceptual model and its implications, are discussed in detail in Chapter 7. Full workshop outputs and supporting materials are documented in Appendix B.

6.2 Stage 1 - Initiate Study

The first stage of the project began a couple of months before the initial workshop, engaging stakeholders through online meetings. The goals were to understand the situation of interest, establish the feasibility and scope for a simulation study, and identify stakeholders and roles, as detailed in Section 5.3. Initially, the research aimed to study the network of services in São Paulo. However, discussions with three senior health experts highlighted the complexity and political challenges, prompting a focus on one administrative zone. As explored in Chapter 3, the southern area of São Paulo was considered, but political and ethical issues necessitated the involvement of a fourth stakeholder, the Director of Operations in Santo Amaro and Cidade Ademar (SACA).

The fourth stakeholder accepted the invitation to join the team. Two subsequent online meetings on Zoom focused on the healthcare system in Santo Amaro and Cidade Ademar. The first

meeting used the Initiate Study Tool HS1 - Bank of Questions to gather information about SACA's population and health services. The outputs from this tool are presented in Appendix B (Section B.1). The Director of Operations provided extensive details on primary, secondary, and tertiary care. The second meeting summarised the previous discussion and used slides to facilitate dialogue about healthcare facilities. It led to an agreement to focus the study on primary and secondary care in the two boroughs.

In the second meeting, the Director of Operations detailed numerous issues in SACA's healthcare system, including infrastructure, information, processes, and the impact of national politics. Audio recordings of the meetings helped to complete the Initiate Study Tool 1: Situation of Interest. Findings were recorded and shared with stakeholders for validation. This validated information helped establish the feasibility of the simulation study. Following the steps in the Initiate Study Tool HS2 - Feasibility of Hybrid Simulation Modelling, it was confirmed that Discrete Event Simulation (DES) and Agent-Based Simulation (ABS) would be used for this project. Following an assessment of the key application areas for each simulation method against the identified problems and potential improvements, as detailed in Appendix B (Section B.1), a decision was reached. The data obtained from the initial evaluation were analysed using the feasibility tool proposed in this study. The findings highlighted issues related to service capacity, staff availability, patients' social determinants of health, and health status, leading the research to focus on DES and ABS as the modelling methods for the identified problematic situation in SACA.

6.3 Substage 1a - Pre-workshop

This substage took place prior to the first workshop. It covered four main activities: (1) Identifying the modelling team and the stakeholder team roles, (2) deciding on the workshop

venue and time slot, (3) inviting stakeholders to the workshop, and (4) preparing materials for the workshop, as discussed in Section 5.4.

The first activity was to identify the stakeholders' team roles. Appendix B (Section B.4) lists the stakeholders and describes their role in this research. Fifteen stakeholders were selected to be part of the stakeholder team, and one was designated as the recorder, supporting the facilitator throughout the workshops. Each stakeholder was associated with a role considering its relevance to the study, according to the table of roles in PartiSim, cited in section 5.3.2.

The facilitated workshop was scheduled for 24 April 2022 and was planned to last 2.5 hours. Due to the COVID-19 restrictions in Brazil, all participants needed to wear masks and maintain a minimum distance between themselves. They also received the consent form and further information regarding the workshop's location.

The last activity in this substage was the production of the material for the workshop. Preliminary materials were prepared for the workshops (Figure 13), following similar practices to those adopted by Kotiadis, Tako and Vasilakis (2014). Two primary materials were prepared for the first workshop: a brief presentation and images for the rich picture. The presentation was used during the first few minutes of the workshop.

Figure 13 shows all the pictures downloaded from Google Images or open-access image repositories for the rich picture session. For instance, (1) indicates the image of doctors, (2) represents maintenance staff, and (3) illustrates habits such as smoking. Number 4 indicates the call centre department or staff, and (5) indicates the behaviours of patients or staff, such as disappointment or satisfaction with health services. The manual for conceptual modelling, which included tips for developing a rich picture, assisted the facilitator in preparing to lead the first session on drawing the rich picture. This manual was detailed in Appendix A (Section A.4).



Figure 13: Images selected to develop the rich picture.

6.4 Stage 2 - Define the problem (Workshop).

This stage was structured as a facilitated workshop. Stakeholders were invited to participate and share their opinions throughout the event, according to the activities and tools proposed in Stage 2 (Chapter 5, Section 5.5). While the stakeholder team had eight participants, the modelling team was represented by the researcher, who also served as the facilitator. Appendix B includes pictures taken during the first session (define the problem).

The first ten minutes were dedicated to introductions, using a brief presentation. Participants' roles in a facilitated workshop were explained, emphasising the importance of their contribution throughout the event. At this point, the purpose and format of the workshop were explained. The English word “workshop” is part of corporate vocabulary in Brazil, and it stands for

seminars or lectures on a specific topic. Stakeholders confirmed their understanding of the approach for this workshop.

After the introduction, I invited the group to discuss the problems caused by population ageing to the healthcare system in both boroughs, Santo Amaro and Cidade Ademar. The stakeholders sat at small tables arranged in a horseshoe-shaped layout, with Post-its and pens for each table, as shown in the images in Appendix B (Section B.5).

To start the discussion, the following question was posed to the group: “What are the major problems brought by population ageing to the health facilities in Santo Amaro and Cidade Ademar?”. To ensure the group did not focus solely on services, the facilitator quickly explained that they could think about problems in the whole system using an introductory slide. Most stakeholders participated with their opinions regarding the significant problems brought by population ageing to the health facilities in SACA. It was noticed that stakeholder 4, the most senior member, did not write down any issues on Post-it notes, only the other participants. Eleven answers were listed from this first brainstorm, as detailed in Appendix B (Section B.5).

After a few minutes of brainstorming, the facilitator prompted participants to prioritise one problem for the study. The group agreed on two main problems: (1) increased demand as people over 60 years are likely to have multiple comorbidities and require more time during the appointments, and (2) scarcity of infrastructure (current UBSs and URSI have limited physical space).

The next activity was a brief brainstorming of possible objectives for the study. The brief brainstorming session generated a range of aspirations that reflected the stakeholder group’s broad service objectives rather than the specific focus of the simulation study. These included improving access to healthcare through teleconsultation, increasing health promotion and disease prevention, enhancing cost-effectiveness, reducing the operating costs of health centres,

promoting digital inclusion, and introducing new technologies. Recognising that a simulation study cannot meaningfully address all these aims, the group identified “expanding access to healthcare” as the primary objective that could be investigated using hybrid modelling. This priority was subsequently refined in Workshop II to ensure it aligned with the study’s methodological capabilities, while the broader service ambitions were recorded for consideration in other initiatives.

Following this, the group was guided through the second session on the agenda - defining the “Transformation”. According to Checkland and Poulter (2006), several people consider it helpful and more accessible to start the discussion of CATWOE elements by Transformation (T) and Worldview (W) before moving on to the other elements. Hence, the process in this research started by defining first T and W, leaving the other elements in CATWOE to be discussed through the subsequent sessions planned for the workshop.

First, a brief explanation of transformation was provided, followed by an example of what “Transformation” would be in a fence-painting system (Checkland and Scholes 1999). After the group confirmed that they understood the meaning of Transformation, the stakeholder team was invited to brainstorm about the Transformation of the study system by posing the question: “What is the transformation that lies at the heart of the system?” (Checkland and Scholes 1999). Again, the group was instructed to use Post-it notes to record their opinion. The group reflected on the question before stakeholders 7 and 8 raised the two transformations, detailed in Appendix B (Section B.7).

To engage other stakeholders and encourage further contributions, the facilitator asked whether the group was happy with what Stakeholders 7 and 8 said. After a few minutes, stakeholder 4 expressed his opinion that the two transformations already registered on the Transformation flipchart covered the main processes requiring attention. The other participants expressed their

agreement with stakeholder 4. Thus, the group was asked to prioritise the transformation for this project. The group selected: “The need for improving health services for older people within SACA at both primary and secondary care levels to be met”.

Regarding the definition of the worldview, the facilitator recapped a statement made by Stakeholder 08, who emphasised equity and integrity when justifying the prioritisation of problems related to population ageing in the health system. Equity and integrity are values frequently highlighted in Brazilian policy documents and in discussions with professionals working in public healthcare. They are also identified as core values of the health system in São Paulo in the Municipal Plan 2022-2025. Stakeholder 04 noted that all actions taken by the SACA administration are aligned with this municipal plan and are intended to meet the healthcare needs of the local population. Building on this point, the facilitator asked about the wider impact of the transformation. Stakeholder 08 responded that ensuring older people receive the right care at the right time helps to reduce the losses associated with ageing, a view that was supported by the other participants.

Following the agenda, the group then moved on to building a rich picture. The facilitator used the Analyses One-Two-Three tool for hybrid simulation to lead this session (Section 5.5.3.1). The session began with an explanation of the concept of a rich picture before displaying the images on the table. After explaining the meaning of some of the pictures, stakeholders confirmed that they understood the tool and its dynamics. Appendix B (Section B.7) provides images from the workshop.

Next, the first picture, representing the primary care centre (UBS), was selected and placed on the flipchart sheet. By placing the first picture on the flipchart, the group felt encouraged to start choosing the images that would represent the elements of the system. The first question from the tool was then posed: “What are the other services or institutions in this system that we

should include in this diagram, considering the problematic situation?” The group immediately began selecting pictures to represent these services. After a few minutes, the group stopped selecting pictures for services. To confirm whether the group was satisfied with the rich picture up to that point, the facilitator asked, “Is this diagram complete?”.

The group confirmed that the diagram had all the services. The next part of this session started with a discussion about the people who are a part of the system. First, the group was led to identify the clients or beneficiaries in the system, followed by who works in the system and who would be the decision-makers or owners. At this point, the group seemed comfortable with the dynamic of developing a rich picture and continued building the representation of the system, considering the problematic situation.

After a short break, the group continued developing the rich picture, exploring the elements of the system (Analysis Two) - understanding the behaviour of each part of the system. The facilitator began by explaining behaviours and giving examples based on the script. Next, the group was prompted with the question, “What are the behaviours of interest of clients?”, followed by similar questions regarding decision-makers and those working in the system. It was observed that the discussion regarding clients’ or patients’ behaviours was more straightforward than that concerning interactions between agents and the environment, for instance. Initially, the group was silent until Stakeholder 6 began sharing her experience as a nutritionist and what she considered relevant behaviour in the system under study. Her contribution encouraged other members to express their opinions about each agent’s or individual’s behaviour within the system.

To complement the behaviour analysis, the group was asked about the decisions and actions of each agent in the system. Again, the group was quickly provided with information about decisions primarily related to the people who work in the system. After the workshop, all the

information collected during the development of the rich picture across the three levels of Analysis One, Two, and Three was transcribed from the audio recordings into the Conceptual Modelling Tool HS4: HS Inputs Form (THS4) and is available in Appendix C.

Overall, critical elements for ABS and DES were identified with the support of relevant questions. Analysis One covers the evaluation of agents and entities in the system. Agents were classified as customers or clients (C), actors or people who work in the system (A), and decision-makers or owners (O). On the other hand, entities represent all services or institutions in the system that are relevant to the problematic situation. For instance, stakeholders identified the population that lives or works in the area surrounding the 26 UBSs in Santo Amaro and Cidade Ademar as the clients or beneficiaries of the system. People who work in the system were identified as health professionals (e.g., nutritionists, psychologists, doctors, and nurses) employed in UBSs and URSI.

Analysis Two covered questions about the agent's and the environment's behaviour and attributes. This analysis (Chapter 5, Section 5.5.3.1) included nine questions that explore the relevant behaviour assumed by customers (C), decision-makers or owners (O), and actors (A) over time. Three questions were employed to describe the environmental factors and constraints, also known as element (E) in CATWOE, that might influence the problematic situation.

Finally, Analysis Three guided the discussions about the interactions between elements within the system and between elements and the environment. Interactions were identified between patients, community health agents (ACS), and between patients and health staff in URSI and UBS. Additionally, ACSs regularly interact with UBS staff, and the health staff in the primary care clinic periodically interact with the URSI (outpatient clinic for older people) team, mainly

verify the correctness of Workshop I outputs, and (3) preparing preliminary materials for use in Workshop II, following the theory proposed in Section 5.6 of this substage.

The first two activities are associated with Workshop I. Following the workshop, all outputs, from activities and tools, were organised in a report before being shared with the project champion. After the workshop, the notes were transcribed into a table, summarised in Table 34 (Appendix B, Section B.5). The project champion and sponsor received a report with the refined outputs from Workshop I for further comments. Both stakeholders provided feedback, and overall, both approved the report with minor corrections.

The period between workshops was also used to evaluate whether the outputs from Workshop I were sufficient to carry out the Workshop II activities. This analysis concluded that the outputs from Analysis Three, related to interactions between agents and between agents and the environment, were somewhat incomplete. Communication with the project champion and several key stakeholders reinforced the idea that this session would need further discussion. These stakeholders indicated that this part of the workshop was challenging because they had never previously considered the interactions between services and people within the health system, or how these interactions might cause changes in patients' behaviour, for example.

Upon reviewing the feedback from stakeholders, a decision was made to reassess Analysis Three, understanding the interactions between the components of the system, during the first minutes of Workshop II. Revisiting parts of the workshop content was therefore considered. This decision affected the planned time allocated to cover the activities from Stage 3. However, it was considered reasonable to revisit this content, especially after feedback from stakeholders who pointed out their difficulty in understanding what was expected from this part of the session. Therefore, the agenda for Workshop II included a review of Analysis Three.

Preliminary materials for Workshop II were prepared, and all the workshop arrangements (e.g., confirming the venue and sending invitations to stakeholders) were completed.

6.6 Stage 3 - Define the Conceptual Model (Workshop).

Like Stage 2, this step was conducted as a facilitated workshop, according to instructions in Section 5.7. The workshop took place two weeks after the first facilitated session, on 10 May 2022, and lasted two hours. All participants from the first workshop attended and were engaged in developing the conceptual simulation model. As in Workshop I, the modelling team was represented by me, and I also took on the role of facilitator. Similarly, this workshop was conducted in a participatory environment, with stakeholders sharing their points of view, occasionally disagreeing, and eventually reaching agreement on each section (Tako and Kotiadis 2015; Franco and Montibeller 2010).

This workshop was planned to cover four aspects: model representation, model contents and scope, performance, and behaviour measures, as well as a definition of objectives. However, as discussed in Section 6.5, before starting workshop II's agenda, the modelling team decided to revisit the last part of the first workshop. The group rediscussed the interaction between agents and the environment (third analysis in the tool Analysis One-Two-Three).

After revising Analysis Three, the group continued with the agenda for the second workshop, focusing on model representation. The stakeholder team was invited to stand around a table in the centre of the room. On the table, a blank flipchart, coloured pens, Post-it notes to identify and represent the services, and pre-printed rounded squares detailing the agents in the system according to UML notation were provided. Before starting the session, the facilitator briefly explained the notation and supported participants throughout the development of the model representation.

The group was introduced to the activity using an example from the UBS (primary care clinic) guidelines shared with the researcher during Stage 1. These guidelines included representations of the healthcare system in São Paulo using a simplified Business Process Model and Notation (BPMN), similar to the notation in (Rolón *et al.* 2015; Müller and Rogge-Solti 2011). Using this material as an example helped stakeholders quickly understand what was expected during the model development session. Additionally, two other factors contributed to making the session productive. First, most of the group were familiar with BPMN and business process modelling and had prior experience in process mapping projects for documenting or implementing new procedures. Second, using preliminary material based on SACA guidelines reduced the time spent recording the activities and elements in the model representation.

Appendix B (Section B.8) presents images of stakeholders working on the model during the workshop and the resulting representation. The group developed the model representation for four agents in the system: (1) patients, (2) health staff in primary care (nurses and doctors), (3) community health agents (ACS), and (4) staff at URSI (outpatient secondary care for older people). After defining the agents, the group described the interactions within and between agents using arrows. The final model representation developed during the workshop is provided in Appendix B (Section B.10).

The next part of the workshop focused on identifying performance indicators. Most healthcare services in São Paulo are regulated by key performance indicators (KPIs), following the São Paulo Municipal Health Department (SMS) guidelines. These guidelines were shared with the modelling team before the workshops. During the preparation of workshop II, the modelling team developed a preliminary list with KPIs, as shown in Appendix B, section B.9. These KPIs were discussed with the stakeholder team, who selected those suitable for measuring model performance. Three KPIs were selected, mainly due to data availability. The stakeholders explained that although several performance measures are included in the 2022-2025 Strategic

Plan, some KPIs have not been measured monthly. Instead, certain indicators have been incorporated into an action plan to ensure their implementation and feasibility by 2025.

Following the development of the initial DES and ABS model representations, stakeholders were asked to review and refine the study objectives defined in Workshop I. The discussion focused on identifying structural features of the healthcare system that directly affect patient pathways and capacity, and which therefore needed to be represented in the conceptual model. In particular, stakeholders highlighted the imbalance between primary and secondary care provision for older people in SACA. This issue was important for the conceptual model because it helped define the system boundary and justified the explicit inclusion of secondary care outpatient services (URSI) as capacity-constrained resources within the DES layer. The identification of two URIs within SACA informed key modelling assumptions regarding service availability, referral flows from primary care, and access delays for older patients. These elements were subsequently incorporated into the conceptual model to ensure that the simulation captured the interaction between demand growth and limited secondary care capacity.

Participants concluded that further investment in secondary care would be necessary to meet the 2022-2025 governance objectives. In other words, the group agreed that the priority should be increasing URSI capacity. At the time of Workshop II, stakeholders reported that 300 frail older individuals were awaiting care at URSI (April 2022), indicating a significant burden on the existing structure.

Stakeholder 2 added that this waiting list would be larger if the UBSs had applied the Multidimensional Assessment of Older People in Primary Care (AMPI-AB) to all older adults. AMPI-AB is an instrument used to evaluate the health status of older people, classifying individuals as independent, pre-frail, or frail (Saraiva *et al.* 2020). According to this stakeholder,

given the limited URSI capacity, the UBSs in SACA chose not to follow the guidelines strictly, applying AMPI-AB only to older adults who frequently visit health centres and whose health is in a critical condition.

However, the new administration (2022-2025) proposed updated targets for the number of older people assessed with AMPI-AB. At the time of the study, it was reported that UBSs would be monitored based on this number from 2022 onwards. Considering these new strategies and goals, the group concluded that examining the need to rebalance the capacity between primary and secondary care for older people would be the focus of this study. The stakeholder team identified two main objectives for the study, as shown in Table 16.

Table 16: Objectives of the study according to stakeholders.

The objective of the study
“Evaluate a future increase of X in access to URSI of older people with AMPI-AB above 11 points receive the care that will prevent the aggravation of ageing and maintain their autonomy”.
“Identify the operational impact of the progression of health statuses among older adults with different initial health conditions.”

Following the definition of the study objectives, participants took part in discussions on other key components of the conceptual model, including inputs, assumptions, and simplifications. These discussions concluded with a final session that focused on data collection strategies. While several elements were defined during the workshop, others required further clarification and were later revisited in a follow-up meeting with stakeholders. This post-workshop engagement allowed for the refinement and validation of the initial contributions, ensuring a shared understanding and agreement on the essential components of the conceptual model.

6.7 Substage 3a - Post-Workshop II

The substage following Workshop II comprised two main activities: (1) documenting the findings from Workshop II and (2) liaising with the stakeholder team to verify the correctness of the outputs from Workshop II.

Similar to Workshop I, a report containing all outputs from Workshop II was prepared and later shared with stakeholders. Audio recordings from the workshop were consulted to develop this report, and all relevant data for developing the computer model were collected and included in a report validated by the stakeholder team. In addition to the information from the workshop, the report included tables and statistics derived from spreadsheets sent by Stakeholder 7, the IT Manager, after the workshop. These spreadsheets mainly contained data from operations in primary and secondary care. Unfortunately, the current system does not record data regarding the population or states discussed during Workshop II. Hence, further discussions with the IT Manager were held to enable the Agent-Based Simulation (ABS) module to be used in the hybrid simulation model for SACA.

The participatory activities in Stages 1 to 3, along with complementary meetings in Substage 3a, informed the development of the conceptual model, discussed in the following chapter.

6.8 Chapter Conclusion

This chapter applied the participatory hybrid simulation framework to a Brazilian healthcare case study. It explained how the research was initiated, how facilitated workshops were used to explore the problem with stakeholders, and how both the conceptual and computational hybrid models were developed. Stakeholder engagement informed the definition of system boundaries, key entities, pathways and interactions, which were then captured in a conceptual model that

combined a discrete-event representation of the care pathway with agent-based state charts for patient health and decision making.

The participatory activities undertaken in Stages 1 to 3 resulted in a formal conceptual hybrid simulation model that synthesised stakeholder knowledge into an explicit representation of the system under study. This model articulated the referral criteria, waiting-list dynamics, treatment stages, patient state transitions, and the feedback loops linking primary and secondary care, thereby consolidating the shared understanding developed during the workshops into a coherent modelling structure. As such, the conceptual model constituted the principal output of Chapter 6 and served as a direct blueprint for computational development. Building on this foundation, Chapter 7 presents the conceptual hybrid model in detail and explains how it was systematically translated into a DES-ABS computer model implemented in Simul8.

Chapter 7 From Conceptual Hybrid Model to Computer Model

7.1 Chapter Introduction

This chapter presents the conceptual hybrid simulation model developed through the participatory process described in Chapter 6 and explains how this model was translated into a computer-based DES-ABS simulation implemented in Simul8. It begins by outlining the formal conceptual model that emerged from the facilitated workshops in Section 7.2. The chapter then describes the key conceptual modelling aspects, including assumptions (Section 7.2.1), data inputs (Section 7.2.2), and mechanisms used to operationalise interactions between the discrete-event and agent-based components. The implementation of the hybrid simulation in Simul8 is detailed in Section 7.2.4. Supplementary qualitative and quantitative information that supports the model development and implementation is provided in Appendix C. Model data, databases, and implementation details are provided in Appendices D and E.

7.2 Conceptual Hybrid Simulation Model for SACA

The conceptual hybrid model was developed to address the study's simulation objective: to assess whether the current configuration of primary and secondary care services for older adults in SACA can meet ageing-related demand, given existing capacity constraints.

Figure 15 shows the conceptual model representation for SACA. It is divided into two interconnected layers that represent the hybrid structure of the model. The upper panel is the discrete-event simulation (DES) layer, which traces the flow of an individual through the health-care system. It begins with the SACA population on the left, illustrated by round figures; one individual is singled out as the "patient". An arrow leads from this population to primary care, labelled "UBSs," where the patient has a consultation with a health specialist. This rectangular block abstracts all primary-care interactions into a single activity because, in

practice, clinicians, nurses and specialists can refer patients back and forth. Patients who are not referred to secondary care return home (indicated by the blue arrow looping back to SACA), with a follow-up appointment scheduled within three to twelve months.

From the primary care, a grey arrow marks the possibility that an older patient (aged ≥ 60) with an AMPI-AB score of ≥ 11 will be referred to secondary care, while those with lower scores are retained in primary care. Referred patients join a waiting list (WL) before being called for a welcome appointment at the URSI secondary-care service. Downstream of the welcome appointment, the stages in URSI care are: a first assessment by two professionals from the multidisciplinary team, a first appointment with a geriatrician, a group discussion in which the team reviews the case, and finally multidisciplinary treatment lasting twelve to eighteen months. Arrows loop back from treatment to primary care to indicate discharge at the end of treatment.

Two blue arrows illustrate circumstances in which patients may not progress through URSI: (1) “Interaction 1”, where a patient cannot attend URSI (for example, because of transport cost), leads directly back to primary care; and (2) “Interaction 2”, where the patient’s needs are not aligned with URSI’s service portfolio, also redirects them to primary care. While the initial interaction occurs during the welcome call, the subsequent interaction takes place within a multidisciplinary group discussion, during which each patient’s case is evaluated, and a determination is made as to whether it is suitable for treatment by URSI.

The lower rectangle is the agent-based simulation (ABS) layer, which provides behavioural detail for the entities represented in the DES layer. It contains three state-chart modules. The first module (on the left) tracks a patient’s health status over time. Individuals aged 57-59 are labelled “middle-aged”; at age 60, they are assessed using the AMPI-AB tool and categorised

as healthy, pre-frail, or frail. Arrows between these states show that health can deteriorate or improve, and all states have a transition to “deceased”, reflecting mortality risk.

The second module (bottom-right) represents the patient’s decision after the welcome appointment: they either move to “eligibility confirmed” if they accept treatment, or “unable to attend” if they decline because of social barriers. The third module (top-right) captures the outcome of the first geriatric and multidisciplinary assessments: patients are classified as having a moderate-to-high condition or a severe condition. Those with a severe condition may be recorded as non-aligned care (indicating that URSI cannot meet their needs and they must return to primary care), whereas those whose needs match URSI’s capacity move to aligned care for treatment.

Grey dashed arrows connect specific states in the ABS layer to the corresponding points in the DES pathway, illustrating how individual attributes influence system-level flows. The arrow from the “middle-aged” state to the primary-care consultation reflects that health-status assessment occurs at the primary-care visit when a patient reaches age 60. The link from the welcome appointment to the “eligibility confirmed/unable to attend” module shows that the decision to accept URSI care is triggered during this appointment. Subsequent dashed arrows from the geriatrician and multidisciplinary assessment boxes in the DES layer point to the moderate-to-high and severe condition states in the ABS layer, indicating that these health classifications are determined after the assessments.

Finally, arrows return from the treatment to the health-status module, signifying that a patient’s health may improve or deteriorate while in treatment and that completion of treatment feeds back into the broader population pool. Overall, the figure uses two layers and connecting arrows to link individual-level behaviours (health progression and decision-making) to the higher-level flow of patients through primary and secondary care, clarifying when and why agents transition

between states and how those transitions affect the wider care pathway. In the following sections, the remaining aspects of the conceptual model are discussed, beginning with the assumptions and simplifications.

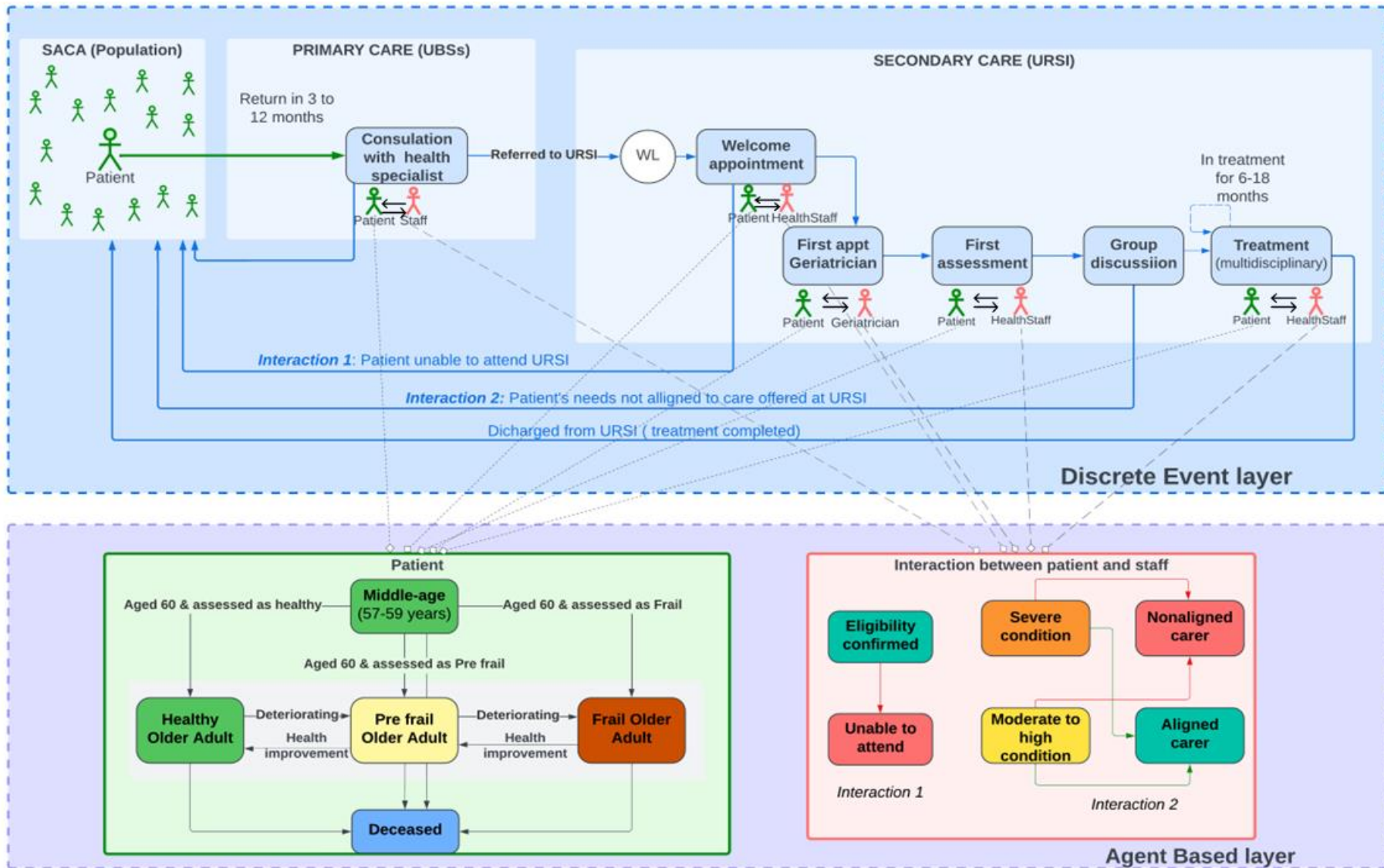


Figure 15: Conceptual model representation for SACA (author's own work)

7.2.1 Assumptions and Simplifications

Developing a DES-ABS model for SACA presented significant challenges due to the lack of available data, particularly for the ABS component. SACA has not yet implemented electronic medical records, meaning all patient records are in paper form, and patients may have multiple records. For instance, a patient referred to URSI will have a record at their registered UBS and another at URSI. Additionally, the AMPI-AB instrument, used exclusively in primary care, is not employed at URSI. As a result, no assessments are conducted when a patient is discharged from URSI, making it impossible to monitor the patient's health status progress after receiving care at URSI.

Due to the lack of data, several assumptions had to be made during the simulation model's development. The following list summarises the main assumptions incorporated into the hybrid simulation model for the ageing population in SACA. These assumptions were agreed upon with stakeholders and implemented in Simul8:

- The shortage of specialists in São Paulo, such as geriatricians, is not considered a restriction in this modelling.
- Only individuals aged 57 or above access the health facilities during the simulation run.
- The arrival rate to the model remains constant over the running period.
- Patients will have the same income range over the whole simulation run. Income is used as an attribute to link each individual to the population database estimated in this study.
- Only 5% of the older people who access secondary care have their AMPI-AB score reduced by 1 point.
- The model does not consider that people below 60 years may require care from secondary care facilities, such as AMA-E, or other services within the SACA service portfolio.

- The model does not consider that people below 60 years might require care from secondary care facilities, such as AMA-E or other services in the portfolio of services in SACA.
- Patients between 57 and 59 years assume the same states as older adults. However, AMPI-AB is an instrument that is excluded when assessing these individuals.
- Patients above 60 years follow the protocol of periodic visits to UBS. This model does not consider access to private healthcare services.
- Patients above 60 years visit UBS once per year.
- Initially, the model assumes that every person will undergo evaluation using AMPI-AB during the initial phase of the study.
- Eligibility for secondary care is based on social conditions, which consider determinants such as income, residence location, and living arrangements (e.g., living alone).
- All health professionals at UBSs are assumed to apply AMPI-AB to patients.
- The protocol of care at URSI is randomly assigned to an individual.
- The length of stay at URSI is randomly assigned to an individual.

Additionally, various simplifications have been made during the modelling process. The following list summarises the main simplifications adopted in the hybrid simulation.

- The model assumes the same operation and structure for primary care regardless of the patient's location. It does not distinguish primary care following the three types of UBSs described in Chapter 3.
- Among the four determinants of health (genetic/biological, environmental, healthcare access and social/behavioural), only healthcare access is considered a key factor for determining or changing the individual's health state, influencing the improvement of the health status.

- The 26 UBSs are grouped under one representation for primary care in the computer model, as the operation in primary care centres is restricted to the activity of “appointment”.
- Patients consider one behaviour - non-attendance to booked appointments, consequently not receiving care as booked.
- The AMPI-AB score is the only criterion for referring patients to secondary care. Chronic diseases or the existence of other illnesses were not considered as a criterion for referring patients to secondary care.
- The model did not include operations in AMA-E or secondary care for all residents in SACA, as it does not affect the patient pathway for URSI. Additionally, no details were provided for this operation.
- The operation of primary care was simplified to one activity named “Consultation with health specialist”.

All simplifications were necessary to develop a Simul8 model as operation in primary and secondary care involves several stages, and are highly influenced by the current staff member who has the authority to change the processes on a daily basis to attend to the increase on demand, for example, despite the guidelines and policies that setting how the operation in all health centres should be organised.

7.2.2 Model Input data

This section details all data input used to parameterise the model, outlining the data sources, equations, and rates. Main details of operational data are organised in the following sections, while a few tables and complementary data can be found in Appendix D.

7.2.2.1 Operational data - primary and secondary care

For modelling the operation of primary care centres, this research estimated parameters using operational data from 2019, shared by stakeholders and validated with the input of key stakeholders. One main parameter was calculated from this source - the average daily number of patients visiting the primary care centres. This parameter was used to control the daily number of work items processed through primary care.

Moreover, for secondary care, this model also considered additional information, such as opening hours, the number of resources available in each health centre, and staff schedule, to determine the daily staff availability. Table 17 summarises a few parameters used to model primary and secondary care operations.

Table 17: Input data for primary and secondary care.

Care Facility	Parameter	Value (baseline scenario)	Data sources
Primary care	Appointment	15 minutes on average.	UBS Guidelines
	Referral to secondary care	Aged 60 or above and AMPI-AB greater than 11	URSI Guidelines
	Number of patients (above 57 years) visiting healthcare centres	72 patients /day	Expert opinion
Secondary care	Online assessment	15 - 20 minutes on average.	URSI Guidelines
	Online assessment	20 patients contacted / day	Expert opinion
	First assessment with a multidisciplinary group	2 patients/day	URSI Guidelines
	First assessment with a geriatrician	1-3 patients/day	URSI Guidelines
	Duration - first assessment and appointment (All professionals)	60 minutes	URSI Guidelines
	Duration - treatment	365 to 540 days	Expert opinion
	Patients' daily bookings (geriatric doctor)	4-8 patients /day	URSI Guidelines

The URSI employs 2 geriatricians, 3 nurses, 1 nutritionist, 1 psychologist, 1 speech therapist, 1 pharmacist, 3 social workers, 2 physiotherapists, and 1 occupational therapist. Contracts are

typically for 20, 30, or 40 hours per week, and these hours are divided between appointment time, covering both initial and follow-up consultations, and administrative duties. Although URSI guidelines specify standard appointment durations, stakeholders noted that actual appointment lengths vary according to patient needs and daily workload. On busy days, for instance, staff may shorten consultations to ensure all patients are seen. In practice, appointments range from 30 to 60 minutes.

7.2.2.2 Patient absenteeism rates in primary care

During the workshops, two main patient behaviours were identified: absenteeism and preference for accessing primary care. Only absenteeism was incorporated into the model, as no reliable data were available to parameterise patient preferences for accessing primary care.

Absenteeism refers to the proportion of patients who have a booked appointment but do not attend. This rate varies across health centres and was estimated using Microsoft Excel spreadsheets containing operational data from 2019 shared by stakeholders. The estimates were validated by Stakeholder 7, the IT and Operations Manager in SACA, who confirmed the values reported in Appendix D (Table 39). For example, absenteeism rates range from 14% at UBS Guacuri to 44% at UBS Jardim Aeroporto. These values were used as parameters in the Simul8 model.

7.2.2.3 Secondary care staff - utilisation rate

Utilisation rates were estimated for each secondary care staff member. These rates were calculated from spreadsheets shared by stakeholders, containing data on consultations conducted in 2019. The data indicated the utilisation rate for each health professional is in Appendix D, Table 40. These rates were used to parameterise the probability of each staff member being assigned to a patient at URSI in Simul8 building blocks representing the staff in

the DES module. For example, geriatricians are allocated to 100% of patients, whereas nutritionists are included in the care protocol for only 50% of patients.

7.2.2.4 Database with health and demographic data for individuals in SACA.

For estimating the health status of individuals, a dataset was created with the support of data from a previous study of the ageing population titled ELSI-Brazil (Lima-Costa *et al.* 2023; Lima-Costa *et al.* 2018). The database creation process involved seven steps, detailed in Appendix D, Section D.2. The database includes several attributes: gender, age, AMPI-AB initial score, location (corresponding to the area of the UBS where the individual is registered), income (measured in minimum wages per month), whether the individual lives alone, and whether they have their transport.

7.2.2.5 Transition rates between patient health states

Individuals' health status can change over time, and in this model, three states are considered: healthy, pre-frail, and frail. As discussed in Section 7.2, the AMPI-AB score serves as the key attribute defining an individual's state throughout their life course. Transitions between states occur when health deteriorates or improves.

Several factors influence health status, including genetics, sex, ethnicity, and environmental conditions (Rudnicka *et al.* 2020). Although these factors are well recognised, there is limited research quantifying their effects on health trajectories over the life cycle (Paúl, Ribeiro and Teixeira 2012). Moreover, Brazil lacks longitudinal records that could support the estimation of ageing impacts on individual health. Consequently, this study relied on stakeholder expertise to estimate transition rates, as summarised in Table 18. Stakeholders provided annual probabilities based on their experience, which were then converted into daily rates.

In Table 18, percentages indicate improvement in health. This reflects the insights of health professionals involved in secondary care, who perceive that interactions between patients and the multidisciplinary team can positively influence outcomes. These interactions are considered a contributing factor to improvements observed in AMPI-AB assessments and, consequently, in patients’ overall health status.

Table 18: Transition rates between patients' states

Transition rates	Healthy to Pre-Frail	Pre-Frail to Frail	Frail to Pre-Frail	Pre-Frail to Healthy
Neutral (annual)	0.0003	0.0003	0.0005	0.0005

Figure 16 depicts the daily transition rates above in the conceptual patient state chart. Patients under 60 years of age are not assessed using the AMPI-AB instrument until they reach 60. However, they may already present health conditions that indicate the likely health state-healthy, pre-frail, or frail-they will assume in later life. Transitions between states, represented by arrows, reflect the conditions under which individuals move from middle-aged health status to the corresponding state at 60 years or older. The probabilities shown in Table 18 are incorporated into the state chart, governing transitions between health states. The final state for all individuals is deceased.

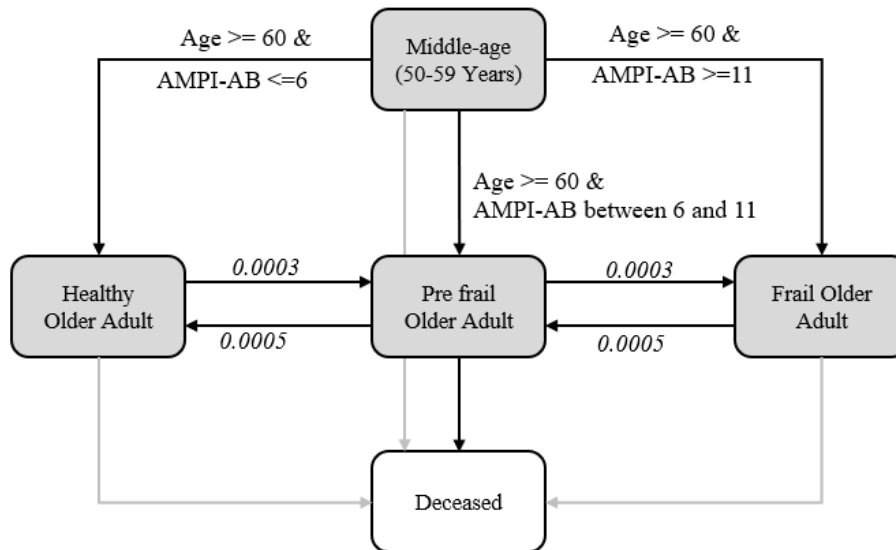


Figure 16: Daily transition between states.

7.2.2.6 Mortality rates

Age-specific mortality rates were parametrised in the model. This research adopted the mortality rates estimated by SEADE (2023) for people living in both boroughs in 2019. Annual rates were converted into daily rates. The probability rates were entered into Simul8 as transition rates between the different health states and the deceased state. The full mortality data table is available in Appendix D, Section D.1.

7.2.2.7 Transition rates and behavioural rules for interaction between patients and URSI staff.

The interaction between patients and staff might change the patient's route in the care pathway. As shown in Figure 15, two interactions were captured during the facilitated workshop. The first interaction occurs when the patient is contacted during the initial online assessment. At this stage, patients might decline treatment at URSI if one or more of the following four factors are valid attributes: (1) social restrictions, such as an income lower than three minimum wages; (2) limited public transport between their residence and the healthcare centre; (3) health status classified as frail; and (4) living alone.

The model relied on expert opinion as a data source. All individuals with an income equal to or lower than two minimum wages and living in the area covered by health centres 20, 21, or 22 (UBS Laranjeiras, UBS Mata Virgem, and UBS Jardim Aeroporto-Massaki Udihara) were assumed not to accept treatment in secondary care and to be referred to primary care. Other individuals with higher incomes living in the same area might accept treatment. According to stakeholders, approximately 80% of patients would agree to attend the first in-person assessment at URSI.

The other condition involves a combination of factors (3) and (4). Patients with a high degree of frailty (high AMPI-AB score) who live alone are unlikely to accept referral to URSI. In this case, they are referred to primary care and may be prioritised for home care. All the conditions described above were coded in the “Eligibility confirmed” state using the Visual Logic resource in Simul8. Appendix E provides artefacts of the Simul8 implementation to illustrate how the conceptual DES-ABS model was operationalised; it is not intended as a fully replicable software package.

The second interaction occurs when a multidisciplinary team evaluates the outcomes of the in-person assessment. According to stakeholders, around 30% of patients with severe conditions (e.g., dementia) are referred to primary care with an indication that their cases are eligible for home care or other services available in SACA, such as social care services. Patients with moderate to high conditions (or AMPI-AB scores above 15) might also be referred to another service. In this case, only 5% of patients in this category might not receive care at URSI. It is worth noting that the probabilities for this second interaction were also based on stakeholder opinion, as no data were available to calculate these rates.

The conditions for the second interaction were coded in the states “Severe condition” and “Moderate to high condition” in State Chart B, using the Visual Logic resource in Simul8. The full Simul8 model logic, sufficient for replication, is documented in Appendix E.

7.2.3 Hybrid Model Output

Table 19 summarises the outputs of the four modules in the SACA hybrid model. While the first column presents the modules that produce the output, the second column describes the output, and the last column informs the type of output - model simulation output and input for other modules (Onggo 2014).

Table 19: Outputs in the DES-ABS hybrid model

Module	Output description	Type of output
DES - UBS	Number of patients waiting for care at URSI	Model output
DES - URSI	Number of patients who completed their treatment at URSI	Model output
DES - URSI	Average Length of Treatment at URSI	Model output
ABS - Patient	Number of patients per health state and age range	Model output
DES - URSI	Patient health state (healthy, pre-frail or frail) after treatment	Input to module ABS Patient
ABS - Patient	Patient health state (healthy, pre-frail or frail) per age range	Input to the module DES
ABS - Interaction I Patient and Staff	Patient state: "unable to attend" = 1	Input to the module DES
ABS - Interaction II Patient and Staff	Patient state: "Non_aligned carer" = 1	Input to the module DES

Eight outputs were identified in this hybrid model. The first output comes from the DES-UBS module, which represents primary care. Patients are assessed using AMPI-AB in primary care and placed on a waiting list for secondary care. This output reflects the objective of increasing the number of older people who complete their first assessment and the average number of people eligible for secondary care who can complete treatment.

The second and third outputs come from Module 2 (DES-URSI), representing secondary care operations. The second output refers to the number of patients who complete treatment at a URSI. It provides insight into the operation of URSI, its capacity to offer treatment and monitor patients' health status. Patients with critical health conditions are likely to require longer care protocols, which demand more hours from health professionals and reduce their availability to attend to new patients. The third output complements the second, while the fourth presents statistics on the number of individuals in each of the six states (healthy, pre-frail, and frail for people below and above 60 years, and deceased). Collectively, these four outputs were considered model outputs or potential performance measures for analysis. They reflect both individual agent behaviours and event-driven system processes resulting from the DES-ABS hybrid model.

Four additional outputs were identified. One originates from the DES-URSI module and feeds into the ABS-Patient module. The other three are outputs from ABS modules that feed into the DES module. First, from the ABS-Patient module, the output represents the patient's state and age range. This serves as one of the inputs to the DES module and is used to determine whether an individual can be referred to secondary care. The last two outputs come from the module representing the interaction between patients and URSI staff. Based on these data, the DES-ABS module will again decide not to refer certain patients to secondary care.

It is worth noting that only the model outputs were identified and discussed during the workshop. The modelling team identified the remaining outputs before developing the model. Later, only the first three model outputs were used for analysis and model validation, as no data were available in SACA to validate the output ABS-Patient: Number of patients per health state and age range.

7.2.4 Run length

Prior to model execution, the Simul8 clock was configured to operate continuously, 24 hours a day and seven days a week. This configuration was necessary to support the agent-based components of the model, as the patient state chart relies on a continuous time representation to capture individual-level dynamics accurately. Individuals require a full 365-day cycle to age and to develop conditions or behaviours that may either deteriorate or improve their health status.

Although the simulation clock runs continuously, healthcare facilities operate according to predefined schedules. Accordingly, shift patterns were specified in Simul8 to reflect the actual opening hours of services. Primary care facilities were modelled to operate from Monday to Friday, between 7:00 a.m. and 7:00 p.m., while secondary care facilities operate from Monday to Friday, between 8:00 a.m. and 6:00 p.m.

With respect to temporal granularity, days were selected as the time unit for the simulation. This decision was informed both by the modelling horizon and by the constraints of Simul8, which offers four time-unit options: seconds, minutes, hours, and days. Given that the study adopts a one-year time horizon, the model was parameterised using the largest available time unit. Moreover, the agent-based patient module requires days as the minimum temporal resolution, as individuals must complete a 365-day cycle to age and potentially transition between health states.

7.3 Computer model

Building on the conceptual model outlined in Section 7.2 and the methodological choices detailed in Section 4.6, the hybrid simulation was implemented in SIMUL8 (v. 29.0, build 4377). The computer model has four modules: a deterministic discrete-event simulation (DES) representing the patient pathway through the 26 primary-care centres and the URSI secondary

facility, and three stochastic agent-based simulation (ABS) modules representing individual health trajectories and decisions.

The DES module directly operationalises the high-level flow described in the conceptual model (Figure 15): patients from the SACA population enter primary care, may be referred and queued for the URSI service, move through a series of assessments and treatment stages (from online triage to multidisciplinary review, geriatric consultation and therapy), and eventually return to primary care or exit the system. The visual layout of the URSI facility echoes the conceptual diagram, with objects representing its stages as in Figure 15.

Beneath this DES pathway sit the ABS modules. The first, or ‘patient’ module, mirrors the health-state chart in the conceptual model: individuals aged 57-59 transition into healthy, pre-frail or frail categories at age 60 based on their AMPI-AB scores and may improve or deteriorate over time, with an absorbing transition to death. The second module implements the decision node labelled “eligibility confirmed/unable to attend” in the conceptual model, modelling whether a referred patient accepts or declines URSI care at the welcome appointment.

The third module corresponds to the “aligned care/non-aligned care” decision: following the geriatric and multidisciplinary assessments, patients are classified as having a moderate-to-high or severe condition and either proceed to treatment or are returned to primary care if their needs fall outside URSI’s remit. These state charts are linked back to the DES objects via Visual Logic so that individual health status and decisions influence service flows at precisely the points indicated by the dashed arrows in the conceptual model.

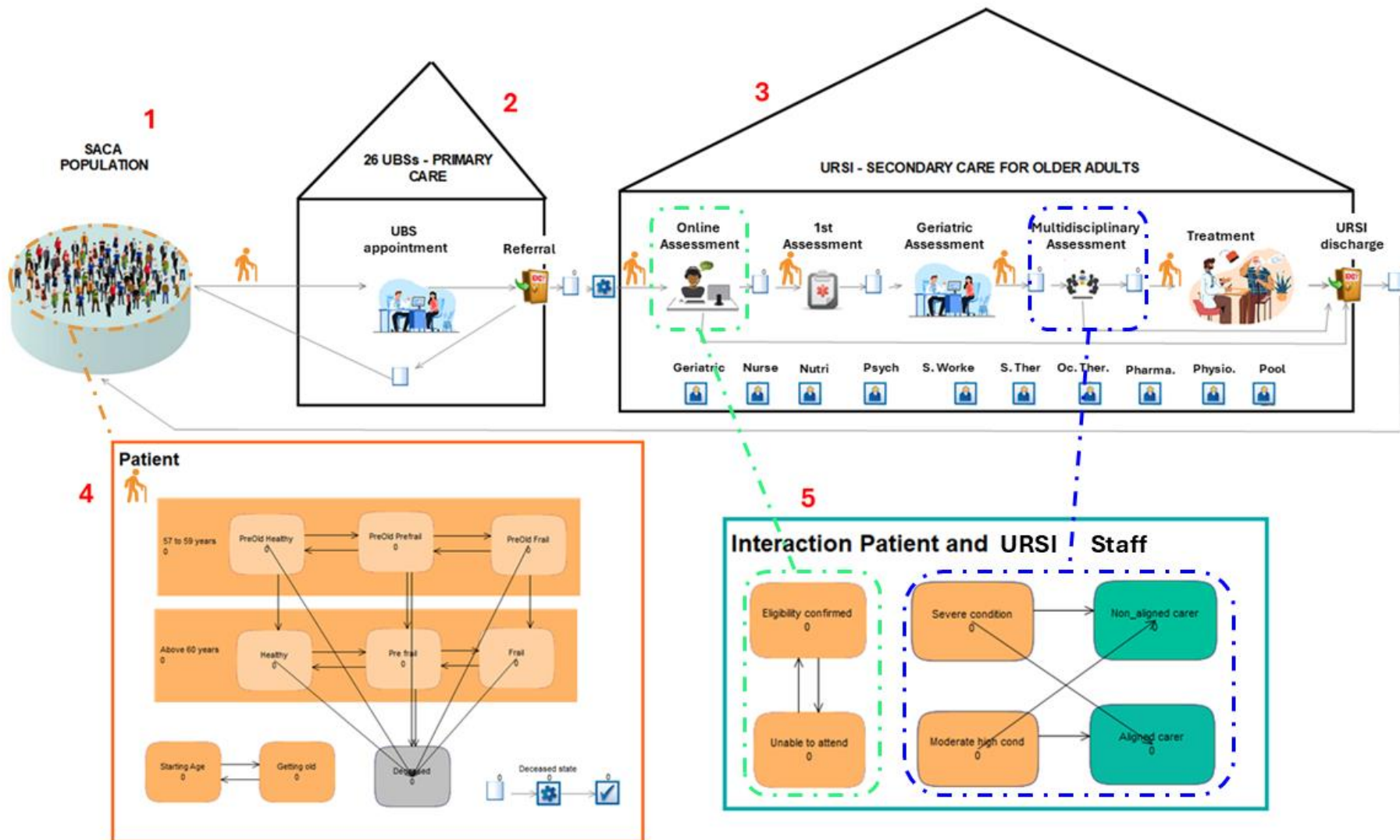


Figure 17: Computer model in Simul8

In line with the interaction-based hybridisation framework approach described in Chapter 2, the DES and ABS components remain visually distinct yet exchange data automatically through SIMUL8's Visual Logic. Hence, the model hybridisation can be classified as interaction model hybridisation (Brailsford *et al.* 2019). Further details on Visual Logic code and artefacts in the Simul8 model can be found in Appendix E. The following sections detail the warm-up period and model verification and validation.

7.3.1 Model Initialisation - defining the warm-up period

The first step in the simulation study was to determine an appropriate warm-up duration so that data collection would exclude the initialisation bias. To do this, the model was run for various lengths (up to 1400 days) with 30 independent replications each, and the output trajectories of key performance indicators (KPIs) were examined. Three KPIs were considered: (1) the number of patients completing treatment at URSI, (2) the number of patients waiting for treatment (number of patients waiting for treatment at URSI), and (3) the average length of treatment. However, KPI 1 (completed treatment) was not used to guide the warm-up period because it is an aggregate, system-level measure. Such measures can appear stable even when the underlying model behaviour has not yet reached a steady state, and therefore provide weaker evidence for identifying an appropriate warm-up period than metrics aligned with the model's internal dynamics (Wynants *et al.* 2020; Robinson 2005). Therefore, the warm-up analysis focused on KPI 2 and KPI 3, which reflect internal system state (queue length and treatment duration) and are more sensitive to initialisation effects.

Figure 18 shows the KPI 2, the average number of patients waiting for secondary care, over the simulation run lengths between 50 and 1400. In the initial approximately 100 days, the average queue remains quite low, typically under 1 patient. Subsequently, between roughly 150 and 250 days, the queue experiences rapid growth as referrals accumulate; by day 200, the mean queue size reaches around 76, and by day 250, it increases to approximately 118. After about 300 days,

the rate of queue growth decelerates and begins to approximate a linear trajectory. Beyond this juncture, the average queue length rises by approximately 3 patients every 50 days. By the time the system reaches around 700 to 900 days, the growth rate of the queue has evidently stabilised, suggesting that the system is nearing a steady-state increase. Indeed, after approximately 750 days, the incremental growth is about 0.06 patients per day (equivalent to about 3 patients every 50 days) and continues at this rate thereafter. This indicates that by the period of approximately 750 to 900 days, the impact of the initially empty system has diminished, and the queue is expanding in a consistent and reproducible manner. Consequently, a warm-up period of around 900 days would effectively eliminate most transient biases while still allowing for an extended duration for analysis.

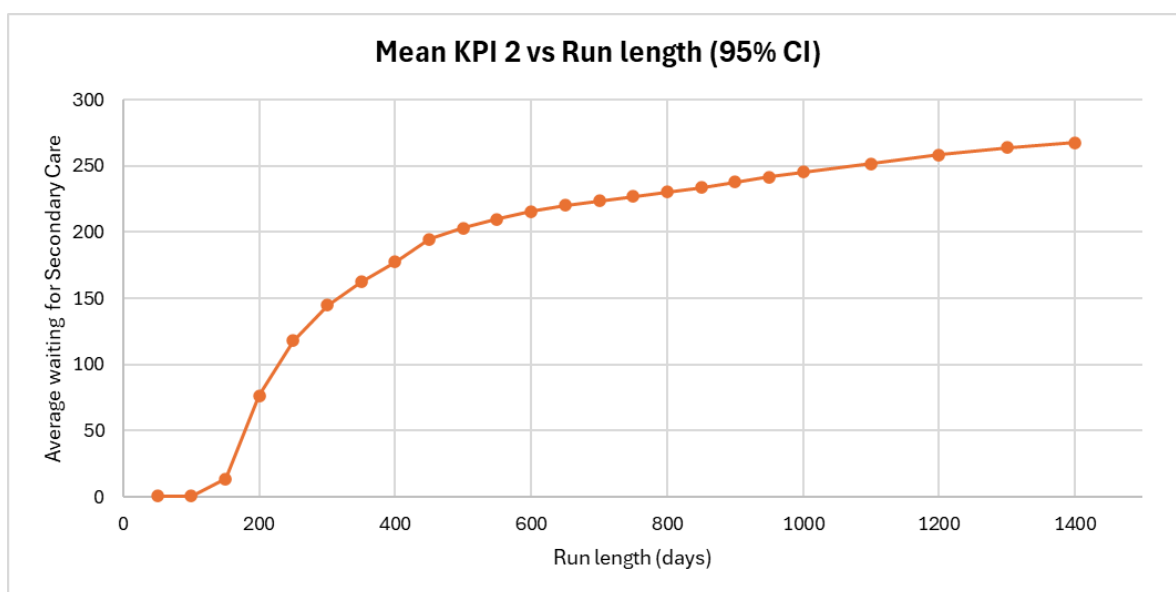


Figure 18: Warm-up period for KPI 2

To be cautious, a slightly higher threshold can be used (Sargent 2013). For instance, 950 days is the longest time observed for any replication to fully enter the linear regime. Using 950 days as the warm-up period ensures that all replications have reached steady linear growth in KPI 2 before data collection. In simulation studies, it is standard practice to base the warm-up period on the slowest-converging metric to avoid bias in steady-state estimates.

Figure 19 provides additional evidence for this decision by illustrating the daily incremental variations in the average queue length. Following the initial spike (100-300 days), during which this change is significant, the increment begins to decline and stabilises around 750-800 days. By roughly 900 days, the slope approaches zero (indicating no further decrease in the growth rate), thereby validating that a 950-day warm-up period adequately encompasses the conclusion of the transient phase for the queue length metric.

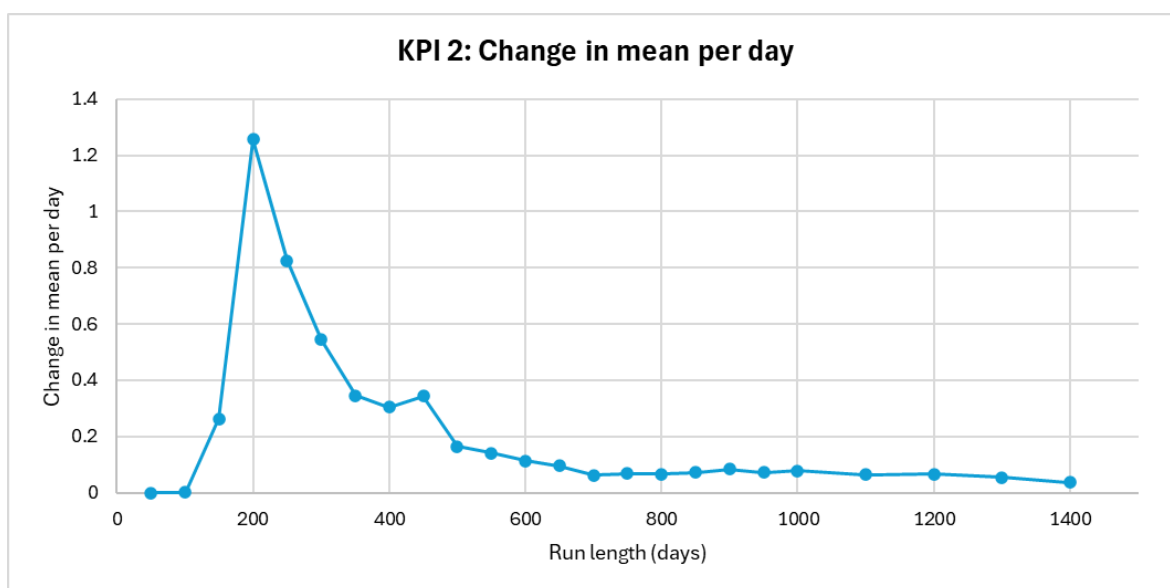


Figure 19: Change in the mean of KPI 2

Likewise, a similar analysis was applied to identify the appropriate warm-up period for KPI 3. As shown in Figure 20, at the beginning of the simulation, this metric is recorded as zero (since no patients have finished treatment within the initial several hundred days). Subsequently, it experiences a significant increase once the first groups complete their treatment: by day 400, the average treatment duration reaches approximately 369 days, and by day 600, it escalates to around 414 days. After approximately 600–700 days, the average treatment length fluctuates only marginally, around 415 days, suggesting it has reached a state of stability. Figure 20 illustrates that after the initial surge (approximately between 350 and 400 days), the average

treatment duration stabilises. By the time 700 days have elapsed, KPI 3 has effectively attained a consistent value (with only minor variations occurring thereafter).



Figure 20: Warm-up period for KPI 3

Figure 21 supports the observation that after 700 days, there is an insignificant trend in this metric (the average slope approaches zero around 650–700 days and remains within a very narrow range).

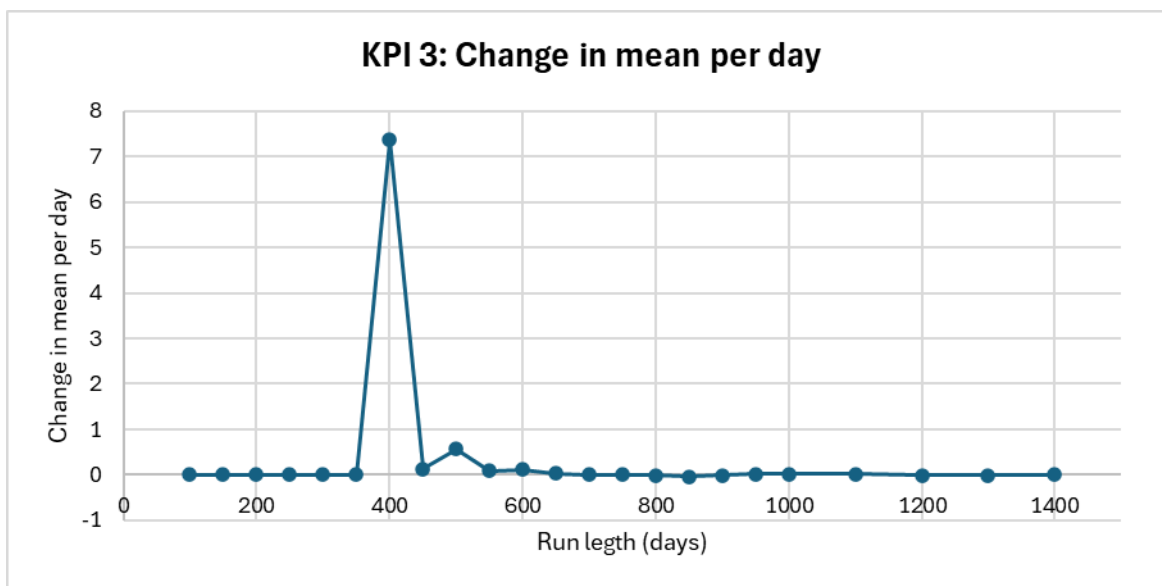


Figure 21: Change in the mean of KPI 3

To eliminate any start-up bias in both performance measures, the longer of the two convergence times was selected. It is evident that KPI 2 (queue length) requires a longer duration to stabilise compared to KPI 3 (treatment duration). Certain replications indicated that the transient phase of the queue length could extend to approximately 950 days before it fully transitions into a phase of linear growth. Conversely, the treatment duration reached stability around 750 days. Consequently, adopting 950 days as the warm-up period (the maximum limit of the queue's convergence range) ensures that any initialisation effects are removed for all KPIs. This cautious warm-up period still allows for a significant portion of each 1400-day simulation run to be utilised for gathering steady-state output data.

In conclusion, 950 days was established as the warm-up period for all future simulation runs, thereby guaranteeing an unbiased estimation of long-term performance beyond this timeframe. This methodology adheres to established best practices for determining warm-up periods, emphasising the slowest-converging indicator to maintain a conservative approach (Sargent 2013; Robinson 2007).

7.3.2 Model verification

Model verification aims to ensure that the model has been implemented correctly and behaves as intended (Sargent 2020; Robinson 2014). Verification of the hybrid model followed established guidance from Pidd (2004) and Robinson (2014), who argue that it should be conducted iteratively throughout development rather than as a single final step. The process combined systematic software checks, modular testing and independent review.

First, all simulation objects were verified using the Input Summary function within the Data and Rules tab in Simul8. This allowed a structured review of each object's name, assigned timing distributions, parameter values, routing-in and routing-out logic, and any associated Visual Logic code. This step ensured consistency between the conceptual model and its

software implementation and helped identify mis-specified distributions and incorrect routings at an early stage.

Second, all process flows were traced manually to confirm that queues, activities and routing rules were correctly connected. Each routing path was followed step by step to ensure that entities could not bypass activities unintentionally or become trapped in queues, and that all entry and exit points behaved as defined in the conceptual model.

Third, schedules linked to starting points were checked against the source data used in the study. Schedule values were stored externally in spreadsheets and cross-checked with the values implemented in the model to confirm accuracy and avoid transcription errors.

Fourth, probability distributions associated with activities and agent attributes were double-checked by comparing the implemented parameters with their data sources. Where assumptions had been made due to data limitations, these were verified for internal consistency and plausibility rather than empirical accuracy.

Fifth, all Visual Logic code (Appendix E) was reviewed line by line. Code was tested both before full model runs and during documentation development to confirm that conditional statements, counters and state changes behaved as intended. Intermediate outputs were monitored during test runs to ensure that code execution matched expected behaviour.

Sixth, the hybrid model was developed using a modular approach. Each DES and ABS module was first built and tested in isolation within a separate testing environment. This allowed verification of each module's internal logic before incremental integration into the full hybrid model, reducing the risk of compounding errors.

Seventh, the completed model was reviewed by Simul8 experts, who independently examined the simulation objects and Visual Logic code. Feedback from this review led to minor

corrections in object routing and parameter specification, providing additional confidence in the model's correctness.

Finally, extensive test runs were conducted using extreme-value and stress-testing scenarios. Model outputs were examined for unexpected behaviour, such as negative queues, implausible waiting times or unstable system dynamics. Only after these checks were completed was the final model version accepted for validation, discussed in the next section.

7.3.3 Model validation

This study adopts a black box validation approach to assess whether the simulation model, treated as an input-output system, produces results that are consistent with observed data, following the principles outlined by Sargent (2013). Black box validation was applied to evaluate the accuracy of the hybrid simulation model developed in Simul8.

Validation relied on data from both the real system and the simulation model. Data for the first and third KPIs were primarily based on stakeholder opinion, while the second KPI was supported by monthly operational measurements collected in 2019. The simulation model was run for thirty replications in Simul8 to capture stochastic variation in model behaviour.

For each KPI, Table 20 summarises descriptive statistics comparing the real system and the simulation model across three key performance indicators (KPIs). These descriptive comparisons provide initial insight into the alignment between simulated and observed performance and motivate the need for formal statistical validation. For KPI 1 (patients completing treatment), the model produces a lower mean than the real system but shows reasonable variability. For KPI 2 (referrals waiting), the model underestimates the mean relative to the real system and exhibits higher variability, as reflected by the coefficient of variation. For KPI 3 (average length of treatment), the model-generated mean lies within the expert-reported real-system range, with relatively low variability. Overall, the descriptive statistics indicate that

the model captures the general magnitude and variability of system performance, while some discrepancies remain, particularly for referral waiting volumes.

Table 20: Descriptive Statistics - Real System vs. Model outputs

Descriptive Statistics	KPI 1: Number of patients that completed its treatment at URSI		KPI 2: Number of referrals waiting for URSI		KPI 3: Average Length of treatment at URSI (days)	
	Real System	Model	Real System	Model	Real System	Model
Mean \pm SD	221	171.87 \pm 11.69	166.08 \pm 59.65	75.88 \pm 35.69	365–540**	419.88 \pm 24.84
Minimum	-	151	85	5.8	-	366.02
Maximum	-	194	280	138.5	-	438.02
Median	221	170.5	164	76.3	-	431.02
Range	1	30	12	30	1	171
Coefficient of Variation (CV%)	-	6.80%	36%	47.03%	-	5.9%

Note: *KPI1 real SD not available; only an average \sim 221 is known;

** KPI3 real data given as an expert range, 365–540 days, with no precise mean/SD

Due to differences in sample size, distributional form, and data availability across the KPIs, validation was conducted using the two-sample Mann-Whitney U test (Sargent 2020; Sornette *et al.* 2007). The Mann-Whitney U test was used to compare the outputs of the model with the real system. This non-parametric test was selected because it does not require the assumption of normality and is suitable for comparing independent samples with unequal sizes. The analysis was conducted as a two-tailed test with a significance level of 0.05. The null hypothesis stated that there is no difference between the distributions of the model and the real system, while the alternative hypothesis stated that the model and the real system are different. All observations, including outliers, were retained in the analysis.

For KPI 1, the test produced a Mann-Whitney U statistic of 0.00 and a two-tailed p-value of 0.104. As the p-value exceeded the chosen significance level, the null hypothesis was not rejected. This indicates that there is insufficient statistical evidence to conclude that the model output differs from the real system. However, this result should be interpreted with caution, as the real system is represented by a single observation, which substantially limits the statistical power of the test.

Despite the lack of statistical significance, the effect size, measured using the rank-biserial correlation, was equal to 1.00, indicating a very large practical difference. The real system value was greater than all model observations and lay far in the upper tail of the model's distribution. This suggests a meaningful discrepancy between the model and the real system in practical terms, even though this difference could not be confirmed statistically. Therefore, the findings should be considered exploratory, and further real system data are required to support robust inferential conclusions.

Figure 22 shows the combined histogram for KPI 1, which provides visual support for the statistical results by illustrating the distributional difference between the model and the real system. This visual separation demonstrates a substantial practical difference between the model and the real system, even though the Mann-Whitney U test did not detect a statistically significant difference at the 5% level due to the real system being represented by only one observation.

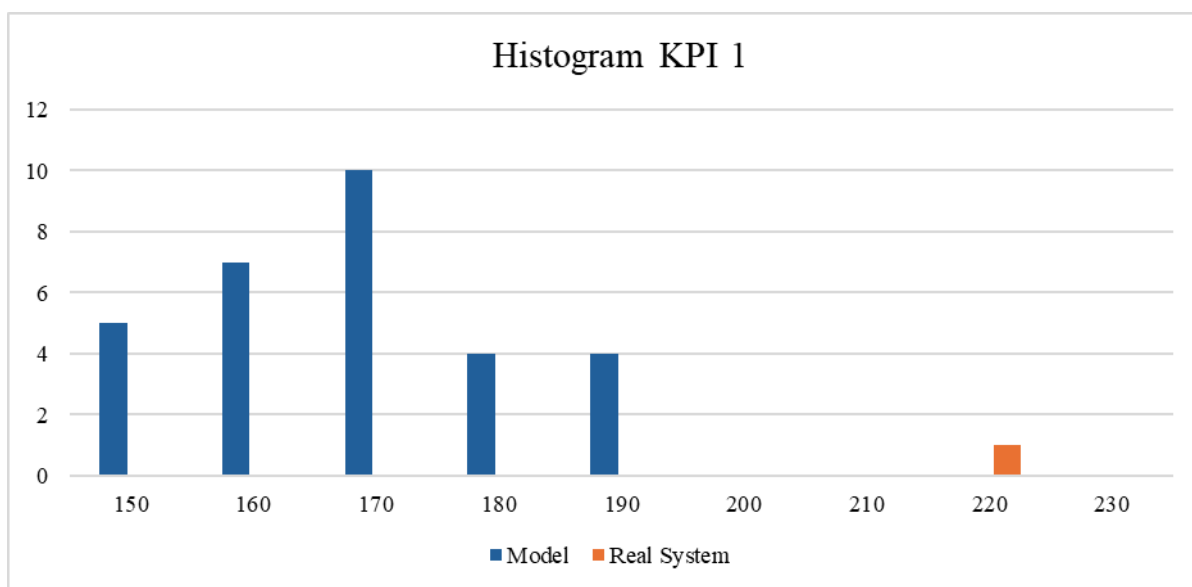


Figure 22: Histogram KPI 1

Consequently, the histogram confirms that the lack of statistical significance might be driven by limited real-system data rather than alignment between the model and real system and suggests that the model systematically underestimates KPI 1.

For KPI 2, a two-tailed Mann-Whitney U test was conducted to compare the model outputs ($n = 30$) with the real system data ($n = 12$). This non-parametric test was selected due to the unequal sample sizes and the presence of outliers, and because it does not require the assumption of normality. The analysis was performed at a significance level of 0.05. The null hypothesis stated that there is no difference between the distributions of the model and the real system, while the alternative hypothesis stated that the two distributions are different.

The Mann-Whitney U test produced a U statistic of 26.0 and a two-tailed p-value < 0.001 . As the p-value is below the significance threshold, the null hypothesis was rejected. This indicates a statistically significant difference between the model outputs and the real system values for KPI2. Therefore, the results suggest that the model does not accurately reproduce the real system behaviour for this performance indicator.

The effect size, measured using the rank-biserial correlation, was 0.86, which represents a large effect. This indicates a substantial practical difference between the model and the real system distributions. The real system data include several high values that extend beyond the upper range of most model outputs, contributing to the observed discrepancy. These findings suggest that, for KPI2, the model systematically underestimates the real system, and further model refinement or calibration may be required.

Figure 23 depicts the combined histogram for KPI 2, which further supports the statistical findings by illustrating the distributional differences between the model outputs and the real system data. Although there is some overlap between the two distributions in the mid-range, the real system shows a pronounced right tail that is largely absent from the model outputs. This visual evidence is consistent with the Mann-Whitney U test results, which indicated a statistically significant difference between the model and the real system for KPI 2, and it

reinforces the conclusion that the model underestimates higher KPI 2 values observed in the real system.

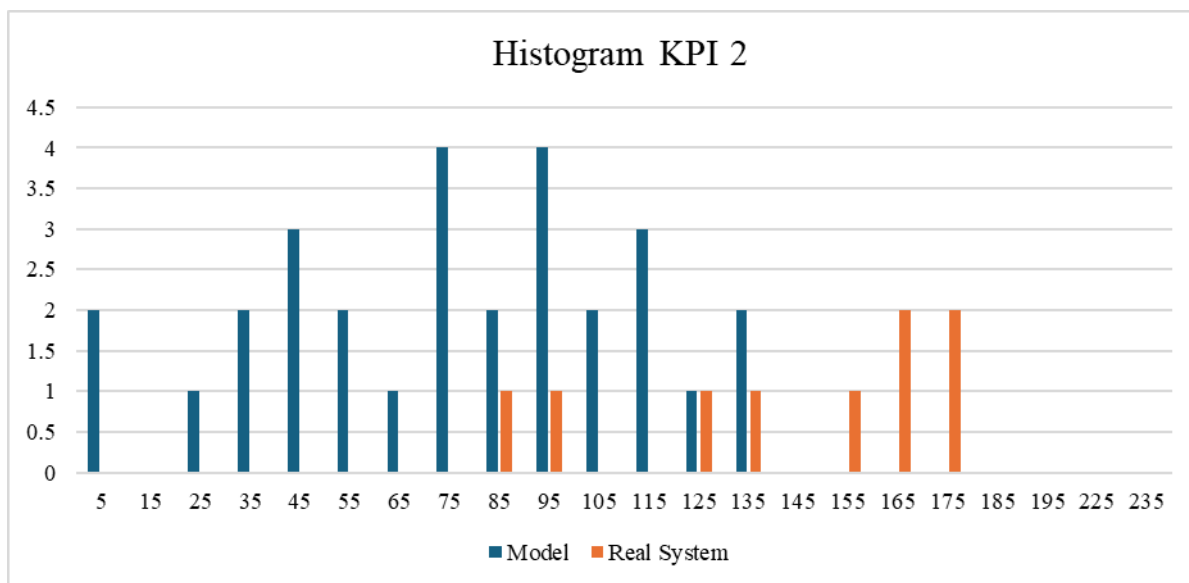


Figure 23: Histogram KPI 2

For KPI 3, a two-tailed Mann-Whitney U test was conducted to compare the model outputs ($n = 131$) with the real system, which was represented by a single average value of 452.5. The test was selected due to the non-normal nature of the data, the inclusion of outliers, and the unequal sample sizes. The significance level was set at 0.05. The null hypothesis stated that there is no difference between the distributions of the model and the real system, while the alternative hypothesis stated that the two distributions are different.

The Mann-Whitney U test produced a U statistic of 0.00 and a two-tailed p-value of 0.086. As the p-value exceeded the chosen significance level, the null hypothesis was not rejected. This indicates that there is insufficient statistical evidence to conclude that the model output differs significantly from the real system for KPI3. However, this result must be interpreted with caution, as the real system is represented by a single average value, which severely limits the statistical power of the test.

Despite the lack of statistical significance, the effect size, measured using the rank-biserial correlation, was equal to 1.00, indicating a very large practical difference. The real system value was higher than all model observations, suggesting that the model consistently underestimates the real system for KPI3. This discrepancy is further supported by the reported real-system range (365-540), which extends beyond the upper range of the model outputs. Consequently, the findings should be considered exploratory, and the collection of additional real-system data is required to enable robust statistical validation.

As shown in Figure 24, the simulated treatment durations are concentrated within a relatively narrow range, while the real system presents an average for the range between 365 and 540 days reported by stakeholders.

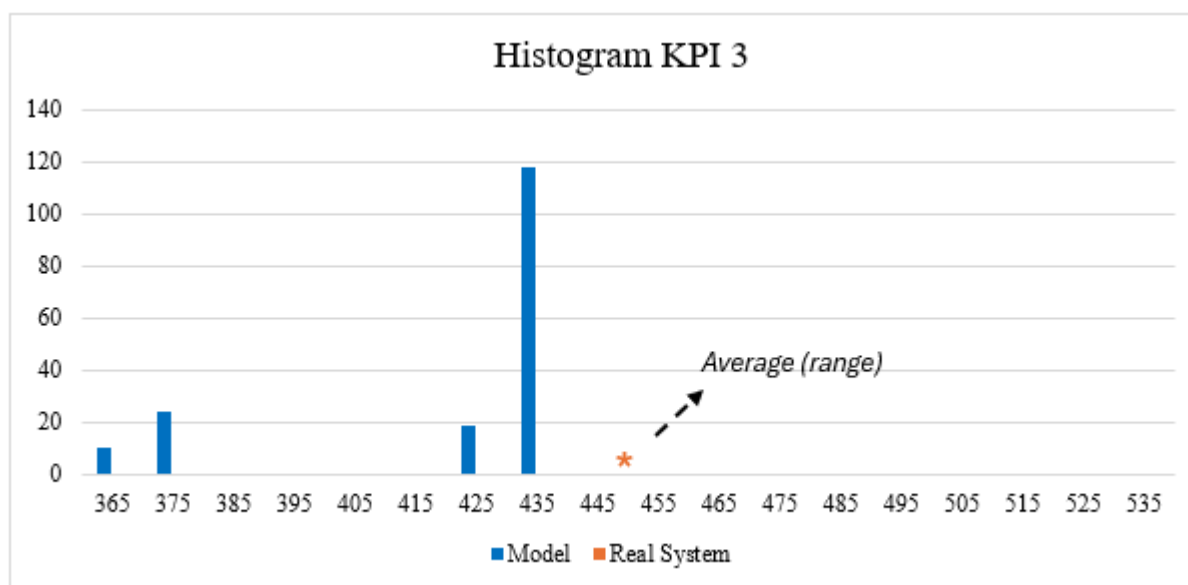


Figure 24: Histogram KPI 3

Overall, the validation results for KPI 1 and KPI 2 indicate mixed model performance. For KPI 1, although the Mann-Whitney U test did not identify a statistically significant difference, both the effect size and the histogram showed that the real system value lies well above the model distribution, suggesting a clear practical discrepancy that could not be confirmed statistically due to limited real-system data. In contrast, for KPI 2, both the statistical test and the visual

analysis demonstrated a significant difference between the model and the real system, with the model consistently underestimating higher real-system values. Taken together, these findings suggest that while the model captures general trends, it does not fully reproduce real-system behaviour for key performance indicators, and further calibration and validation using additional real-system data are required to improve model reliability.

Despite the results from model validation, this study moved forward with the use of the model for simulating the real system. It is worth mentioning that the model is not validated for accurate point estimates of KPI levels, but it remains useful as an experimental tool to explore relative system behaviour under controlled scenario changes.

7.3.4 Model experimentation (preliminary *what-if* analysis)

Despite model experimentation being part of Stage 5 in PartiSim, this study proposed a preliminary analysis of the KPIs under changes in resources currently available in URSI. The aim is to understand how capacity could potentially be changed in order to meet the increase in demand. Three possible changes to resources were proposed.

Three resource configurations were considered: the current setup (baseline), Plan 1, and Plan 2, involving different allocations of specialist staff for initial assessments and treatment. Table 21 summarises the hours per specialist dedicated to the first appointment, treatment per day, as well as the number of staff members per scenario: current, plan 1 and 2.

As noted in Chapter 6, initial assessments involve two staff members from different specialities. Currently, each professional is devoted one hour per day to initial appointments, yielding a total of eight hours with the 15 current staff. Plan 1 adds one geriatrician and reallocates nurse hours away from initial appointments while increasing social worker capacity from one to four hours. Plan 2, which adds another geriatrician, eliminates nurse hours for initial appointments and increases hours for social workers and several other specialities. Across these adjustments, total

initial appointment capacity rises from eight hours in the baseline to nine hours in Scenario 3 and returns to eight hours in Plan 2 due to further redistribution.

Table 21: Changes in daily hours dedicated to appointments through 2 potential scenarios

Professional group	First Appointment (hours/day)			Treatment (hours/day)			Number of staff members per scenario		
	Current	Plan 1	Plan 2	Current	Plan 1	Plan 2	Current	Plan 1	Plan 2
Scenario									
Geriatricians	1	1	1	4	4	4	2	3	4
Nurse	1	1	0	4	4	5	3	3	3.5
Nutritionists	1	0	0	6	7	7	1	1	1.5
Psychologists	1	1	1	6	6	6	1	1	1
Speech therapists	1	0	0	5	6	7	1	1	1.5
Pharmacists	1	1	1	6	6	6	1	1.5	2
Social workers	1	4	4	3	2	2	3	3	3
Physiotherapists	1	0	0	4	7	7	2	2	2.5
Occupational therapists	1	1	1	4	4	6	1	1	1

First analysis confirmed that geriatricians are the main bottleneck in the URSI due to limited staffing and full allocation to secondary care patients. Increasing the number of geriatricians by one raises overall capacity but shifts the bottleneck to pharmacists. To address this, the plan includes hiring an additional pharmacist with 50% of the current full-time allocation. For other professional groups, no new staff are added; instead, their working hours are reallocated across activities. Hours assigned to first appointments are reduced, and nutritionists, speech therapists, and physiotherapists no longer undertake first appointments. As indicated in Table 21, these adjustments rebalance capacity across roles and reflect changes agreed as feasible during the stakeholder workshops, considerably increasing the capacity as shown in Figure 25. Assuming a 12-month treatment cycle for all patients, the current system allows 191-287 patients to complete treatment per year.

For Plan 2, this work assumes the addition of another geriatrician. As in Plan 1, changes to working hours and reallocation across activities are required, together with new hires across several specialities, as shown in Table 21. Only psychologists and occupational therapists retain

the same number of staff. These changes ensure a further increase in capacity, as illustrated in Figure 25.

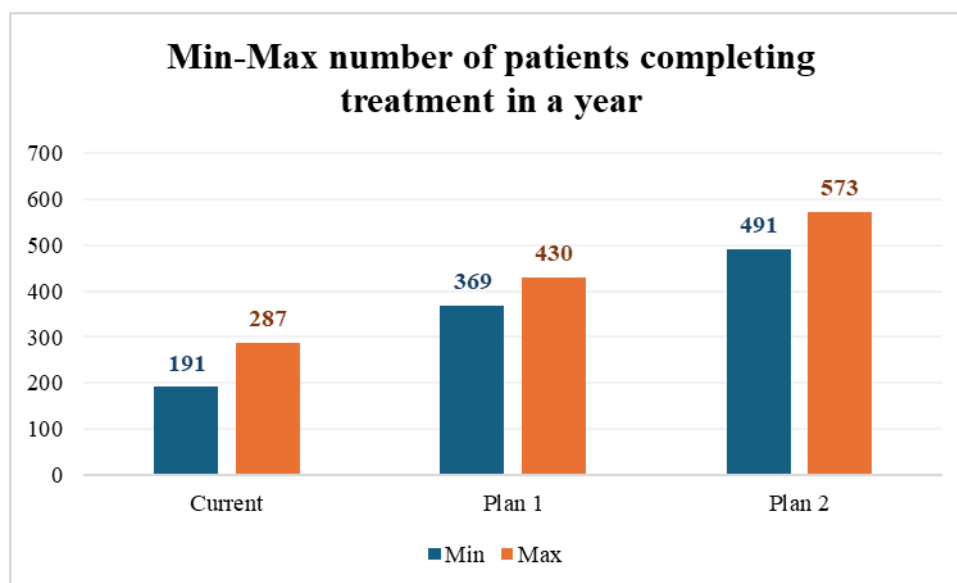


Figure 25: Minimum and Maximum number of patients completing treatment.

Table 22 summarises the variables and key performance indicators (KPIs) used across the three simulated scenarios and reports the corresponding model outputs. It compares the baseline scenario, reflecting URSI operations in 2019, with two alternative configurations.

Table 22: Simul8 preliminary scenarios outputs

	Variables in each scenario		KPI 1	KPI 2	KPI 3
	URSI Operation	Patient health status	<i>Number of patients that completed its treatment at URSI</i>	<i>Number of referrals waiting for URSI</i>	<i>Average Length of treatment at URSI (days)</i>
Baseline	Same operation in 2019	Frail patients	171.87 ± 11.69	75.88 ± 35.69	419.88 ± 4.84
Scenario 1	Same operation in 2019	Pre-frail and Frail patients*	171.57 ± 6.65	356.56 ± 1.02	435.27 ± 16.98
Scenario 2	Double capacity operation in 2019	Pre-frail and Frail patients*	357.13 ± 24.41	159.80 ± 12.4	438.65 ± 23.41

* Following SP Government plan to have older people with AMPI-AB greater than 5 attending URSI

Scenario 1 expands the patient group to include both pre-frail and frail individuals while maintaining 2019 operational capacity. In contrast, Scenario 2 retains this expanded eligibility but doubles service capacity to assess the impact of increased resources on system performance.

The table presents mean KPI values across simulation replications, with the associated standard deviations capturing the extent of stochastic variability inherent in the DES-ABS model. The remaining columns show the model outputs for three KPIs: KPI 1, the number of patients who completed treatment at URSI; KPI 2, the number of referrals waiting for URSI; and KPI 3, the average length of treatment at URSI (in days). The table compares the baseline scenario (based on 2019 operations) with two alternative scenarios. Scenario 1 expands the patient group to include both pre-frail and frail individuals while maintaining the same operational capacity as 2019, whereas Scenario 2 doubles URSI's service capacity under the same patient conditions to assess the potential effects of increased resources on system performance.

For KPI 1, the baseline and Scenario 1 exhibit almost identical mean values, indicating comparable throughput under unchanged capacity, while Scenario 2 demonstrates a substantial increase in completed treatments. In terms of KPI 2, Scenario 1 shows a pronounced rise in waiting referrals relative to the baseline, whereas Scenario 2 markedly reduces the waiting list compared to Scenario 1, although it remains above baseline levels. KPI 3 displays a moderate increase in average treatment length in both alternative scenarios, alongside greater variability when capacity and patient mix are altered.

Under the baseline configuration, the model produces a mean of approximately 172 completed treatments, a relatively modest waiting list, and an average treatment duration of around 420 days. Figure 26 depicts the boxplot for KPI across the baseline and 2 scenarios. It shows a narrow interquartile range across all three KPIs, indicating stable system performance with limited variability. Scenario 1 maintains a very similar distribution for KPI 1, with overlapping

medians and interquartile ranges compared to the baseline, confirming that throughput remains unchanged.

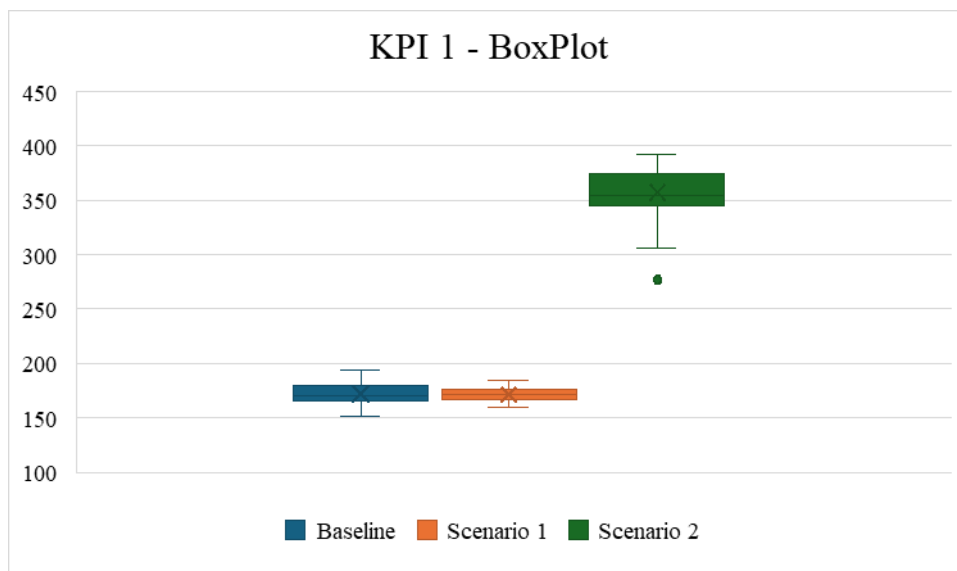


Figure 26: KPI1: Box Plot of 3 Scenarios

In contrast, Figure 27 depicts the KPI 2 box plot. It displays a pronounced upward shift and greater dispersion, highlighting a substantial and systematic increase in waiting referrals.

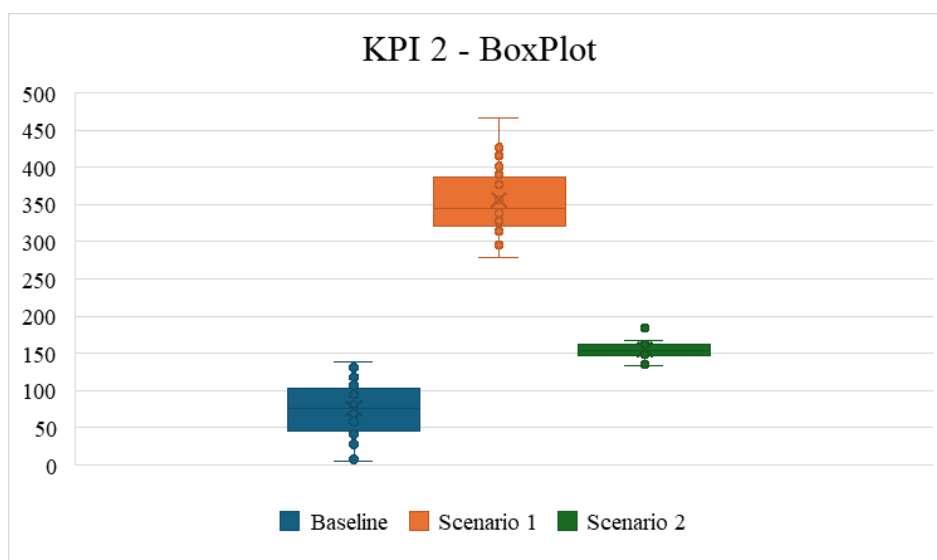


Figure 27: KPI2: Box Plot of 3 Scenarios

This suggests that expanding eligibility without increasing capacity generates excess demand that accumulates in the queue rather than translating into higher throughput. The broader spread observed is consistent with demand-driven congestion rather than random variation.

Scenario 2 demonstrates a clear structural change across all KPIs. The box plot for KPI 1 shows a marked upward shift in the median and distribution, with minimal overlap with the other scenarios, indicating a significant increase in completed treatments driven by the doubled capacity. For KPI 2, the distribution shifts downward relative to Scenario 1 and becomes more compact, suggesting that increased capacity effectively alleviates waiting list pressures while also reducing variability.

The KPI 3 box plot, in Figure 28, shows a moderate increase in median treatment duration and a wider spread, implying that higher throughput may allow more complex cases to progress through the system or introduce mild congestion effects at higher utilisation levels.

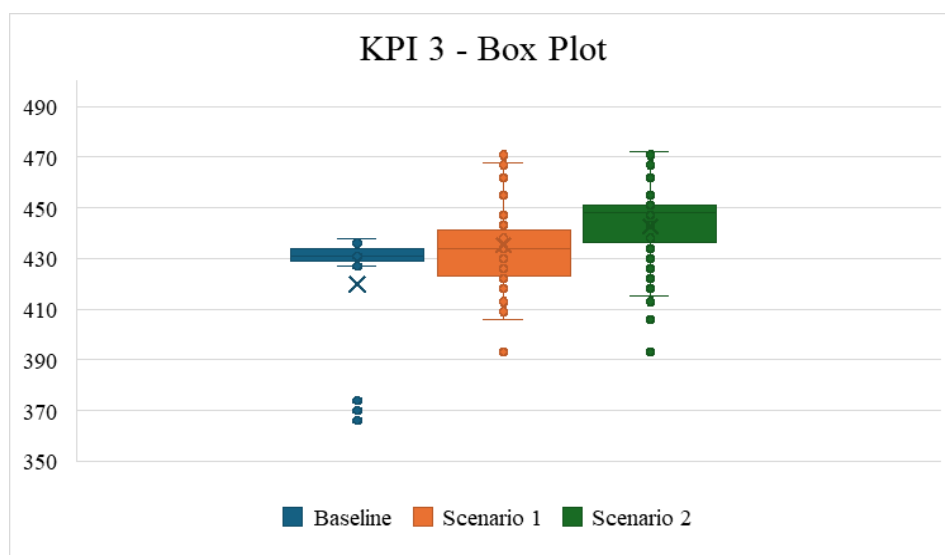


Figure 28: KPI3: Box Plot of 3 Scenarios

Overall, the box plots reinforce the numerical results by illustrating that differences between the baseline and Scenario 1 are marginal for throughput and largely stochastic, whereas Scenario 2 exhibits clear, non-overlapping shifts indicative of statistically and practically

meaningful improvements. These findings confirm that system performance is primarily capacity-constrained and underscore the importance of aligning service resources with anticipated increases in demand.

7.3.5 Chapter conclusion

This chapter presented the development and initial exploration of a hybrid simulation model applied to the context of population ageing in the SACA case study. A combined DES-ABS approach was used to represent interactions between service capacity and the healthcare needs of older people. The model development was informed by structured stakeholder engagement and followed the stages of the PartiSim framework.

Two illustrative scenarios were implemented as a what-if analysis to explore issues identified during earlier stakeholder workshops. The baseline scenario represented the current system, reflecting existing referral criteria and service capacity. Scenario 1 examined the effects of extending referral eligibility to a broader group of older people, while Scenario 2 considered an increase in capacity through the introduction of an additional URSI.

The following chapter reflects on the application of the participatory framework in practice, focusing on methodological insights, as well as the strengths and limitations identified through the Brazilian case study.

Chapter 8 - Reflection and design of the Participative HS Conceptual Modelling Framework.

8.1 Chapter Introduction

This chapter introduces reflections on the development process and presents the final version of the participative hybrid simulation framework. The starting point was an initial participative hybrid simulation framework adapted from the PartiSim methodology (Chapter 5), which was stage-by-stage tested in a Brazilian case study, which is detailed in Chapter 6 and 7.

This application provided an opportunity to examine the feasibility of the adapted design in practice and highlighted several methodological and contextual aspects that informed further adjustments and design of the final framework version (Section 8.7). Drawing on these insights, the framework proposed in this research was gradually refined to combine participatory elements with a hybrid DES-ABS simulation model in a way that supports the modelling team in their task of engaging stakeholders in developing a hybrid model.

The chapter starts by bringing the research reflections on each of the four stages (Section 8.2 to 8.6), followed by the discussion of the final participative HS framework (Section 8.7).

8.2 Reflections on Stage 1 and Substage 1a

Reflecting on the initial stage of developing the participative hybrid conceptual framework, it becomes clear that this phase extended beyond a procedural adaptation of PartiSim (Tako and Kotiadis 2018a); it was a formative process that highlighted both the opportunities and the constraints of facilitated approaches when applied to hybrid simulation. Stage 1 was primarily intended to familiarise the modelling team with the problematic situation in Brazil and to examine whether hybrid simulation might be a suitable methodology. At the same time, it

exposed layers of complexity, uncertainty, and gaps in existing literature that influenced the direction of the study.

One important reflection from this stage relates to the adaptation of PartiSim's initial activities. PartiSim's focus on structured engagement and problem exploration offered a useful starting point, but its DES-centred orientation did not provide sufficient guidance for the development of a hybrid model. This gap led to the introduction of new tools and the revision of existing ones, most notably the expanded bank of questions and the feasibility tool (THS2). The lesson here is twofold: first, that current facilitated frameworks, while useful, are not designed to meet the conceptual requirements of facilitated hybrid modelling; and second, that in situations marked by methodological uncertainty, modellers may need to create and adapt tools rather than rely solely on existing ones.

The revised bank of questions illustrates this point. Extending the scope from three to six thematic areas supported a more comprehensive exploration of the healthcare system, incorporating both operational issues and broader political and regulatory dimensions. At the time, this was a practical decision, since narrowing the scope would have limited the ability to capture the overlapping features of DES, SD, and ABS. In retrospect, however, the process highlighted the challenge of balancing completeness with manageability. While stakeholders valued the structured approach, the quantity of information risked overwhelming both novice modellers and the later facilitation process. This suggests that tool adaptation should be guided not only by a desire for thoroughness but also by consideration of what can realistically be analysed and applied in subsequent workshops.

Another reflection concerns the reliance on secondary sources and online meetings during COVID-19 restrictions. The absence of on-site visits meant that the "situation of interest" had to be understood through documents, guidelines, and short conversations rather than direct

observation. Although this limited the richness of contextual insight, it also drew attention to the importance of transparency and validation. Tools such as the PartiSim Initiate Study Tool 1 (Tako and Kotiadis 2018c) allowed for iterative checking with stakeholders, which helped build a shared understanding of the problematic situation despite the lack of first-hand engagement, as suggested by PartiSim (Tako and Kotiadis 2018b). The insight here is that constraints, while restrictive, can also encourage more deliberate practices of validation.

Uncertainty was also evident in assessing the feasibility of hybrid simulation. The literature at the time offered little beyond DES-SD combinations, leaving the researcher to explore ways of including ABS. For a novice modeller, this was challenging, particularly in reconciling different levels of abstraction and methodological assumptions within a facilitated process. The reflection from this experience is that conceptual development carries a degree of risk of designing tools that may not be effective, of placing additional demands on stakeholders, and of diverging from established practices. However, such experimentation is often necessary to address methodological gaps, such as in a hybrid simulation arena.

Scope management presented another challenge. The Brazilian healthcare system is complex and politically embedded, and early discussions made it clear that representing the entire system within one model was not possible. Although initially frustrating, this realisation helped focus attention on primary and secondary care within SACA. This narrowing of scope was not only a pragmatic decision but also a methodological requirement, as hybrid simulation benefits from a bounded system where different methods can be meaningfully integrated. From this perspective, scope definition should be seen as a step that supports conceptual clarity and stakeholder engagement.

Occupying the dual role of simulation modeller and workshop facilitator influenced the experience. At the outset, heavy reliance on tools, scripts and manuals provided methodological

support and confidence but also introduced rigidity into the facilitation process. Observations from this phase suggest that novice facilitators benefit from mentoring and structured support, and that modellers who assume facilitation duties can feel overwhelmed without such guidance. The complexity inherent in hybrid simulation appears to amplify these challenges, underscoring the need for frameworks and mentoring to support novices, whether they are facilitators, modellers or both.

In summary, Stage 1 and Substage 1a were marked less by smooth progress and more by continuous arranging between methodological aspirations (Sections 5.3 and 5.4), and practical constraints as described in Sections 6.2 and 6.3. The reflections from this phase highlight the importance of adapting tools, the potential value of working within constraints, the inevitability of uncertainty, the role of scope definition, and the significance of novice support. Although the stage revealed challenges, it also provided the conceptual and practical base for the facilitated workshops that followed, grounding the move towards hybrid simulation in Brazil in both methodological development and contextual awareness.

8.3 Reflections on Stage 2 and Substage 2a

The first facilitated workshop (Stage 2) offered important insights into the practical application of a participative hybrid conceptual framework. In theory, this stage was intended to identify problems, boundaries, and broad objectives through structured stakeholder engagement. In practice, it revealed the complex social dynamics that can both support and constrain participative modelling.

One key reflection concerns power imbalance within the stakeholder group. Although brainstorming initially generated a range of perspectives, the presence of a senior stakeholder (Stakeholder 4) quickly influenced the group dynamic. Deference and implicit validation-seeking became apparent, with participants less willing to express divergent views. The

facilitator was placed in a challenging position of respecting hierarchy while also trying to promote inclusivity. While this behaviour may reflect Brazilian professional hierarchies, its effect on the workshop was considerable. The experience suggests that methodological tools alone cannot address established social hierarchies. Facilitators may need to anticipate such dynamics in advance, for example, by profiling participants or structuring activities that protect the contributions of less dominant voices.

The introduction of Conceptual Modelling Tool HS3 (Analysis One, Two, Three) was another point of learning. The tool, designed to support the identification of CATWOE elements and the development of a rich picture, acted as both a methodological aid and a scaffold for the novice facilitator. Dividing system exploration into three levels gave stakeholders a gradual entry point into increasingly complex discussions. However, a paradox emerged: while Analysis One (actors and entities) was straightforward and engaging, Analyses Two and Three (interactions and environmental factors) proved more difficult, despite stakeholders' direct experience of the system. Their hesitation and silence suggested the challenge of turning tacit knowledge into explicit representations. This indicates that hybrid simulation not only combines methods but also requires techniques to make implicit, experiential knowledge visible and discussable.

Time management also presented difficulties. PartiSim recommends a two-hour minimum for initial workshops, but this was insufficient for hybrid simulation. Activities that involve multiple perspectives and abstraction levels require more time than DES-based projects. As a result, important tasks in Stage 2 were shortened, and objectives were defined at a surface level rather than through deeper discussion. This suggests that hybrid simulation frameworks need to adjust time expectations, recognising that integrative modelling requires longer engagement.

Future workshops should plan for at least three hours, or consider multiple sessions, to avoid the compromises observed here.

Substage 2a, the post-workshop reflection, further emphasised the importance of validation. Stakeholders valued the use of flipcharts and visual tools, which maintained engagement despite the workshop's challenges. They also openly noted the difficulty of discussing interactions and environmental influences, confirming the facilitator's own observations. This shows that acknowledging difficulty can be constructive: it highlights areas for methodological refinement and strengthens the credibility of the process through transparent feedback.

8.4 Reflections on Stage 3 and Substage 3a

The second facilitated workshop (Stage 3) was designed to move from problem identification towards the development of a conceptual hybrid model. Reflection on this stage highlights the tension between technical ambition and human limitations.

One key methodological decision was to replace the traditional process flow diagram with UML notation, allowing for both DES and ABS representations. While this choice reflected an intention to broaden methodological scope, its application revealed the cognitive demands it placed on stakeholders. Participants were confident when mapping processes but less certain when describing patient states or agent behaviours. Their surprise at the idea of "defining a patient on paper" illustrated the novelty of simulation thinking for those more familiar with business process modelling. The lesson here is that tools in hybrid simulation must remain accessible without careful adaptation into formats that stakeholders can readily use; conceptual rigour risks reducing participative engagement.

Stakeholder fatigue also emerged as a challenge. By the time objectives were to be defined, participants had lost momentum, and discussion defaulted to agreement around a single

suggestion rather than deeper deliberation. This points to a broader issue in participative hybrid modelling: stakeholder attention is limited, and the cognitive demands of engaging with multi-method representations accelerate its depletion. Effective facilitation, therefore, requires not only sufficient time but also active management of energy levels through breaks, varied activities, and clear communication of progress.

Activity 4, which focused on module interfaces and information flows, proved more successful. This was likely because it required less abstraction and was closely linked to participants' operational expertise. From a reflective perspective, this suggests that hybrid simulation frameworks could benefit from sequencing activities so that more abstract tasks are interspersed with concrete ones, balancing difficulty to sustain engagement.

The post-workshop substages confirmed the consequences of earlier challenges. Additional meetings were needed to address unfinished activities and clarify uncertainties, extending the process and increasing demands on stakeholders. This highlights the cost of limited facilitation resources. Relying on only a facilitator and recorder was not sufficient; in retrospect, a larger modelling team, with clear roles for facilitation, observation, and technical support, would have reduced the burden and improved responsiveness during the workshop.

8.5 Reflections on Stage 4

Stage 4 of the participative hybrid simulation framework involved translating the conceptual model into a computer-based hybrid simulation. This stage marked the shift from participatory and conceptual development to the technical construction and testing of the model. It was a key moment in the research, as the ideas, structures, and relationships developed in earlier workshops were formalised within a computational environment. Although the conceptual model provided a coherent representation of the healthcare system in Santo Amaro and Cidade

Ademar (SACA), developing, verifying, and validating the hybrid model exposed several practical challenges, particularly related to data availability and quality.

Building the hybrid model highlighted the complexity of operationalising the conceptual framework in a real healthcare setting. The model combined Discrete Event Simulation and Agent-Based Simulation to capture both process flows and behavioural dynamics within SACA's healthcare network. While this integration reflected the main dynamics identified during the participatory stages, it was constrained by limited reliable data for parameterisation and validation. Data from municipal and regional health authorities were often incomplete, fragmented, or outdated. Operational information on patient flows, referral rates, appointment durations, and staff utilisation was inconsistently recorded across care levels, and many datasets were available only in aggregated form, restricting their use for simulation inputs.

As a result, several model parameters had to be estimated through secondary literature and expert consultation rather than being drawn directly from administrative records. This ensured model functionality but introduced uncertainty into the calibration process. Behavioural data for the agent-based component were especially difficult to obtain, as no systematic records existed on patient decision-making, health-seeking patterns, or provider-level variation. These parameters, therefore, relied on stakeholder input and professional judgement. Although validated through discussion with local stakeholders, such assumptions inevitably simplified complex real-world behaviours.

Data limitations also directly shaped the validation process. Validation assessed the extent to which the model reproduced observed system patterns through two approaches: structural validation, where stakeholders judged whether the model logic matched their experience, and quantitative validation, where model outputs were compared with available performance indicators. Stakeholders confirmed that the model's logic was credible and aligned with their

understanding of service delivery. However, quantitative validation was weakened by inconsistent and incomplete datasets. Comparisons with indicators such as patient throughput, waiting times, and staff workload could be made only at aggregated levels. While model outputs fell within plausible ranges, the absence of detailed reference data prevented more rigorous validation.

These constraints also affected the preliminary experimentation conducted during stage 4. The aim was to test how different configurations of primary and secondary care capacity might respond to rising demand driven by population ageing. Scenarios examined interventions such as expanding primary care capacity and improving coordination across services. However, uncertainty around key parameters—such as patient arrival rates, referral probabilities, and service times—meant that results required cautious interpretation. Parameter ranges were based largely on expert opinion rather than empirical evidence. Thus, although the direction of change (e.g., reduced waiting times following service expansion) aligned with stakeholder expectations and theoretical reasoning, the magnitude of effects cannot be treated as precise estimates.

The absence of comprehensive datasets had broader implications for interpreting the model's findings. The results offer insights into system structure and behaviour in SACA and highlight potential areas for improvement, but they should be viewed as indicative rather than predictive. The model demonstrated how population ageing might influence demand and how different interventions could alleviate bottlenecks, yet it cannot provide exact forecasts due to data limitations. Instead, it should be regarded as a decision-support tool that offers a structured representation of the system and a platform for exploring policy alternatives.

Data constraints also limited the external validity of the model. Although the conceptual framework has wider applicability, the simulation itself was tailored to the specific conditions of the SACA boroughs. Applying the model elsewhere would require further data collection

and local calibration. Strengthening access to consistent, disaggregated health data would therefore be essential for future implementations.

Despite these constraints, the participative nature of the modelling process mitigated some negative effects. Stakeholders contributed to validating the model's logic, providing contextual knowledge, and interpreting results. Their understanding of healthcare delivery helped verify assumptions and maintain realism. This collaborative process enhanced model credibility and strengthened the conclusions drawn, even in the context of incomplete quantitative data.

Reflecting on Stage 4, it is evident that data limitations accumulate throughout the modelling process, influencing model design, validation, and interpretation. Although stakeholder validation is essential for establishing conceptual and contextual credibility, it cannot replace the need for a minimum level of representative empirical data. In its absence, model validity and the robustness of outputs are weakened, conclusions become more restrictive and less reliable, and the potential benefits of integrating ABS with DES are significantly reduced.

Overall, Stage 4 showed that the hybrid model remains a valuable tool for understanding the healthcare challenges associated with population ageing in SACA. However, its insights are exploratory rather than definitive. The limitations encountered emphasise the importance of strengthening health information systems and incorporating real-time and longitudinal data in future modelling efforts. Although data constraints reduced the precision of the outputs, the participatory process and structured conceptual approach ensured that the results remained meaningful for policy reflection and system learning. This stage contributes to a deeper understanding of the relationship between data quality, model reliability, and decision-making in hybrid simulation and offers lessons for studies in similar contexts.

8.6 Final Reflections on Stages 1 to 4:

Looking across Stages 1 to 4, several broader reflections can be drawn. First, participative hybrid conceptual modelling is as much a social process as a methodological one. Issues such as hierarchy, fatigue, and group dynamics repeatedly influenced outcomes, at times more strongly than technical decisions. Second, methodological development was shaped by the researcher's novice position. Inexperience was not only a constraint but also a driver for creating new tools and processes that may be useful for other novices. Third, shortages of resources, time, and data, particularly information on patients' health status, were recurring challenges. Each gap required adaptations which, while sometimes productive, also limited depth and rigour.

The Brazilian case study, therefore, shows that hybrid simulation is not only a technical exercise in combining methods but also a participative effort to work through uncertainty, resource constraints, and social dynamics. These reflections highlight both the vulnerabilities and the opportunities of facilitated hybrid approaches: they can expose hidden knowledge, encourage dialogue around complex issues, and contribute to the ongoing development of simulation methodology.

Taken together, the reflections from Stages 1 to 4 and the cross-cutting insights provide both lessons and constructive directions for practice. They show that participative hybrid conceptual modelling requires ongoing adaptations between methodological ambition, social dynamics, and resource constraints. At the same time, they point towards opportunities for adapting tools, sequencing activities, and supporting facilitation. Building on these lessons, the following section presents the development of a Participative Hybrid Conceptual Modelling Framework, which consolidates the experiential learning from the Brazilian case study into a structured

approach intended to guide future applications. These insights collectively inform the revised conceptual framework presented in the following section.

8.7 Towards a Participative Hybrid Conceptual Modelling Framework

PartiSim provided the foundation for developing the Participative Hybrid Conceptual Modelling Framework. Initially, it was assumed that adapting PartiSim for hybrid simulation would require only modifications to the toolset, while the stages and activities (Tako and Kotiadis, 2015) could remain largely unchanged. However, the research process, particularly the fieldwork in Brazil, revealed that significant adjustments to the workflow of activities were also necessary. Consequently, both activities and tools were refined to create a framework more suitable for hybrid simulation.

Applying this revised framework to study the impact of population ageing in SACA proved valuable, as it offered a comprehensive and structured approach. The Brazilian case study engaged multiple stakeholders, ensuring that diverse perspectives and knowledge sources were integrated into the development of a hybrid simulation for assessing healthcare facility scenarios designed to meet the needs of older adults. This application also confirmed the practical relevance of the concepts introduced in Chapter 4.

As illustrated in Figure 29, the framework evolved through three stages: the original PartiSim methodology, the initial pre-test HS version (second column, detailed in Chapter 4), and the post-test HS version (first column). Activities adapted to the specific requirements of hybrid simulation are highlighted in red and pink in the first and second columns, respectively, while those representing broader improvements to PartiSim are shaded in yellow.

For instance, in Stage 1, Activity 3 “Evaluate data availability” was introduced in the post-test version (column 1) to anticipate difficulties arising from absent or limited data. By contrast, the activity “Identify stakeholder team” in Stage 1 was moved from the second to the final position.

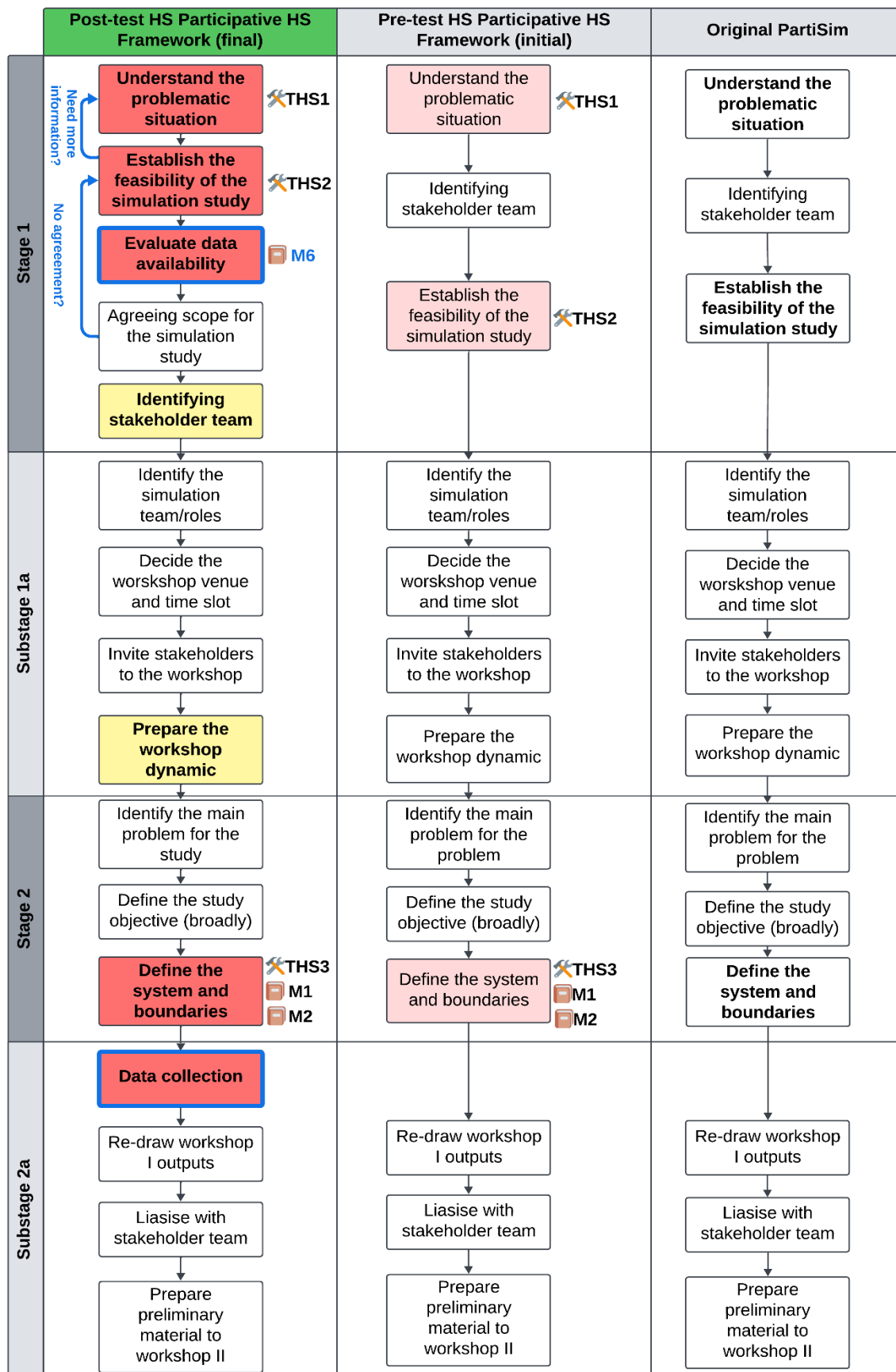


Figure 29: Proposed HS Framework vs. Initial HS Framework applied in Brazil and PartiSim (author’s own work)

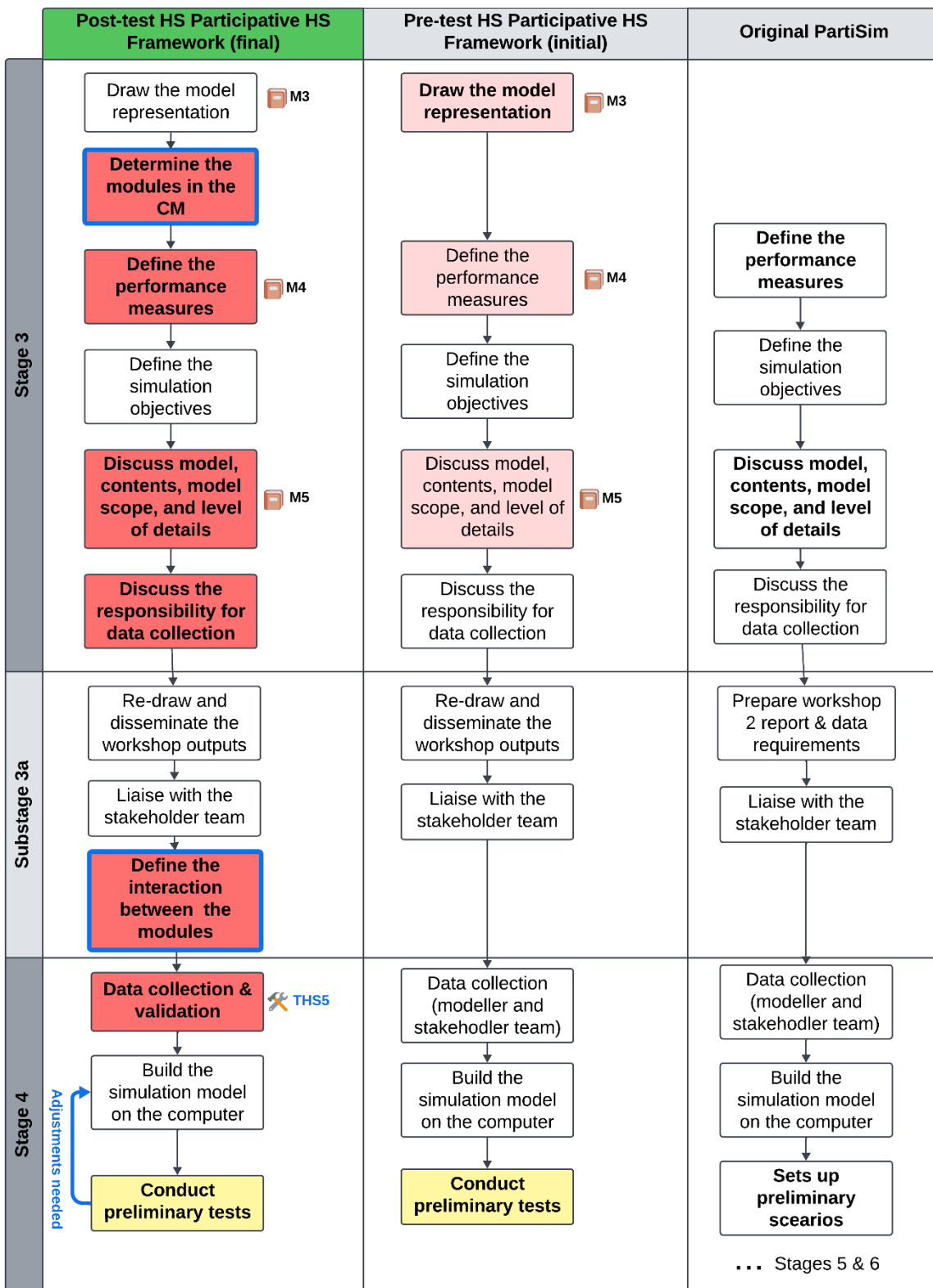


Figure 29 (continued)

It represents a minor refinement in the sequencing of activities. A similar adjustment was applied to “Prepare the workshop dynamics” in Substage 1a, relocated to the end of its

sequence. New tools and manuals were also added, such as Tool M6 (Manual for Conceptual Modelling: Data Availability Assessment), which supports Activity 3. In total, twelve activities were subject to varying levels of adjustment.

Several tools and manuals introduced prior to the Brazilian study were retained, including Tool THS1 (Initiate Study Tool HS1: Bank of Questions) and Tool THS2 (Feasibility of Hybrid Simulation Modelling and Scope of the Model for the First Workshop) in Stage 1, and Tool THS3 (Analysis One, Two, and Three for Hybrid Simulation) in Stage 2, along with associated manuals M1 (Employing Tool HS3: Analysis One, Two, and Three for Hybrid Simulation) and M2 (Tips for Developing a Rich Picture). In Stage 3, Manuals M3 (Drawing a Communicative Model with UML Notation), M4 (Identifying Measurement in an HS Model), and M5 (Discussing Elements in a Hybrid Conceptual Model) were also preserved. A new addition, Tool THS5 (List of Data that Might Be Needed in a DES-ABS Hybrid Model), was included in Stage 4.

Comparing the post-test HS framework with the original PartiSim (columns 1 and 3 in Figure 20) shows that changes extended well beyond initial toolset revisions. Substage 1a underwent only minor sequencing edits, whereas other stages were amended more substantially to meet hybrid simulation requirements, introducing not only new tools but also new activities (see red highlights in Figure 20, column 1).

Stage 1 and Stage 3 underwent substantial changes during the revision process. In Stage 1, the activity “Identify stakeholder team” was repositioned, all existing activities were scrutinised, and two new tasks were introduced: “Evaluate data availability” and “Agree scope for the simulation study.” These additions enable the design of a hybrid simulation to anticipate data limitations and set clear boundaries from the outset. Stage 3 also saw significant revisions,

which are discussed in detail later in the report. The following sections examine these modifications stage by stage, drawing on the reflections presented in Sections 8.2 to 8.6.

8.7.1 Stage 1 - Initiate study

The first stage aims to establish initial contact between the modelling team and selected stakeholders. In addition to enhancing the team's understanding of the problem situation and system, it also serves to assess the feasibility of applying hybrid simulation. As shown in Figure 29, a few adjustments were made to the activities and tools in this stage.

A new activity, evaluate data availability (highlighted in blue), was also introduced, alongside minor refinements to improve the overall flow of activities, as outlined in the following paragraph.

Activity 1 - Understand the problematic situation.

As discussed in Chapter 4, this activity establishes the first contact between the modelling team and stakeholders to gather information about the problem situation and the system. No major changes were proposed to this activity following the SACA case study.

Three tools were associated with this step: two from the original PartiSim methodology and one adapted for hybrid simulation during this research. These include the Initiate Study Tool HS1: Bank of Questions (THS1), PartiSim Toolset 1 Initiate Study Tool 4: List of Reading Materials, and PartiSim Toolset 1 Initiate Study Tool 1: Situation of Interest (see Chapter 4). Together, these tools support the task of understanding the problem situation by broadening knowledge beyond healthcare services to include system rules, strategies, people, and the consequences of their interactions.

A further refinement was the inclusion of PartiSim Toolset 1 Initiate Study Tool 2: Recording Observations, designed to capture insights from on-site visits. Although on-site observations

could not be conducted in this research due to COVID-19 restrictions, the tool remains valuable for future studies as a structured means of documenting observations and supporting a deeper understanding of the system (Tako and Kotiadis 2018c).

Activity 2 - Establish the feasibility of the study.

The second activity in Stage 1, Establishing the feasibility and scope of the study, was significantly revised after the SACA case study. Originally placed as the final task in Stage 1, it was moved to follow directly after Activity 1, reflecting its importance for subsequent decisions and its close connection to the first activity.

In the pre-test form, this activity combined several tasks under the heading of the feasibility of the study. The SACA case study, however, showed that merging diverse tasks created unnecessary complexity and risked confusion. As a result, the activity was redefined to focus only on assessing whether hybrid simulation was suitable for the problem. The task of defining the study scope was separated and added as a new fourth activity in Stage 1. To support feasibility analysis, this research introduced the Initiate Study Tool HS2: Feasibility of Hybrid Simulation Modelling and Scope of the Model (THS2).

Inputs for feasibility assessment were drawn from Activity 1 and documented in PartiSim Initiate Study Tool 1: Situation of Interest. Using this information with the tool proposed in Section 4.3.3.1, the researcher concluded that the SACA case involved patient flow, waiting times, and resource allocation, typical applications for Discrete Event Simulation (DES). In addition, aspects such as patient behaviour, decision-making, social determinants of health, and chronic disease management indicated the value of incorporating Agent-Based Simulation (ABS).

A further adjustment was the introduction of iteration between Activities 1 and 2 (Figure 29). This potential loop ensures a more robust assessment by allowing modellers to revisit earlier

steps before deciding on the most appropriate simulation approach. Once the hybrid model configuration is defined, the team can then proceed to assess data availability.

Activity 3 - Evaluate data availability.

This activity was introduced after the SACA study to evaluate whether sufficient data were available to build a hybrid model. Data availability refers to the accessibility, completeness, and quality of information needed to represent a system accurately and support analysis and decision-making. It requires mapping data sources from stakeholders and confirming that they are adequate for the objectives of the simulation.

At this stage, the team may use Tool M6 (Manual for Conceptual Modelling: Data Availability Assessment) to verify the availability of data for the simulation methods identified in Activity 3. Depending on the outcome, the approach may be limited to a single method, or the modelling team may collaborate with stakeholders to generate datasets for model development and validation. As noted by Nguyen, Howick and Megiddo (2024), early planning for black-box validation reduces the need for extensive assumptions later in the process. The manual proposed in this research was designed to guide modellers in this task, drawing on data management literature (Márquez and Pedro 2017; Fan and Geerts 2012) and insights from the SACA, as discussed in the following paragraphs.

Manual for Conceptual Modelling: Data Availability Assessment (M6)

This manual supports the data availability assessment, which ensures that the requirements of a hybrid simulation are met through accessible, accurate, and reliable data. Table 23 presents a checklist of key topics to guide discussions with stakeholders and the critical review of information collected.

The checklist can be applied in three steps:

Step 1: Engage stakeholders to obtain insights about data availability. Use the checklist to structure questions and ensure that all essential aspects are covered.

Step 2: Critically review the data collected so far, comparing it against the checklist to identify gaps or inconsistencies.

Step 3: Confirm that the available data are suitable for representing the problem situation, support the chosen methods, and accurately reflect the system's dynamics.

Table 23: Checklist for data availability assessment.

Aspects to understand	Potential items to be covered during the assessment
Data Identification and Requirements	List specific data required for each module in the hybrid simulation. <ol style="list-style-type: none"> 1. Confirm the availability of individual agent data (patient, staff) 2. Confirm whether interactions can be studied using logs or datasets. 3. Verify that interactions, decision rules, and environmental factors are monitored and data stored. 4. Ensure the availability of time-series data and feedback loops.
	Determine the source of each data type (internal or external data)
	Determine the role and interaction of each data type in the hybrid model.
Data Sources and Access	Internal sources: databases, logs, transaction records, expert opinion.
	External sources: previous research, third-party datasets, and public repositories.
	Access Permissions: Check for any legal or regulatory restrictions on data access.
Data Quality and Integrity	Accuracy: confirm data has been verified or cross-checked where possible
	Timeliness: Confirm that data is up-to-date and relevant.
	Consistency: Ensure data is consistent across different sources.
Data Format and Volume	Data format: Confirm that the data format (e.g., CSV, XML) is suitable for simulation.
	Volume: Assess the size of the dataset and confirm that data is available to represent all components in the hybrid simulation.
	Data calibration: confirm datasets for validation purposes are complete and reliable

The checklist does not attempt to capture every possible consideration. Instead, it outlines fundamental elements that modellers should review when assessing data availability. It draws on best practices in data management (Márquez and Pedro 2017; Fan and Geerts 2012) and should be treated as a starting point, to be adapted and extended according to the specific needs of each hybrid simulation study.

Activity 4 - Agree on the scope of the hybrid simulation study.

No further changes were made to the scope of this task. It was only repositioned within the Stage 1 workflow. Originally part of Activity 2, defining the scope of a hybrid simulation study was separated into a distinct activity following the SACA case study. This change aimed to ensure clear communication between the modelling team and stakeholders, establishing project boundaries and objectives. Scope definition involves summarising insights from informal meetings and preparing recommendations for the initial facilitated workshop, promoting a shared understanding of the project's direction.

Acting as a roadmap, this activity guides project execution and decision-making, and identifies the team responsible for stakeholder engagement. It reduces the risk of the modelling team being unprepared during workshops and enhances overall outcomes. The research proposed four key topics for the simulation project scope: a summary of stakeholder discussions, an assessment of the current healthcare system, a description of geographical coverage and relevant decision-makers, and suggestions for involved stakeholder groups. Additionally, potential data limitations or required actions should be noted if data collection and validation are planned.

Activity 5 - Identify the stakeholder team.

The identification of stakeholders remained unchanged following the SACA case study, with the only modification being its repositioning from the second to the fifth activity in Stage 1.

This adjustment makes it the final activity in the stage, enhancing practicality and streamlining the workflow. Initially, the modelling team should focus on understanding the problem and identifying potential methods for integration into the hybrid model. The outcomes of preceding activities can provide valuable input for selecting stakeholders.

A further consideration is the identification of personal traits. In the SACA case study, the researcher focused on individuals and their roles but did not fully assess whether candidates possessed the personal qualities required for each role. Ensuring the right fit is crucial for effective workshop dynamics. Therefore, the researcher recommends using the Manual for Initiate Study Tool 3: Stakeholders' Contact Details (Tako and Kotiadis 2010), particularly Table 1, and consulting Brailsford *et al.* (2009) to support stakeholder selection. The modelling team should allocate time to analyse participants' traits and use this information to prepare the first workshop.

In summary, although Stage 1 retained its primary objective of establishing initial contact between the modelling team and stakeholders, it underwent substantial modifications following the SACA case study. New activities and tools were introduced to better support modellers in exploring hybrid simulation for complex healthcare challenges, while some original PartiSim tools were found to remain suitable for this purpose. A comprehensive overview of the activities and tools in the post-test Hybrid Simulation framework compared with the original PartiSim methodology is presented in Table 24, highlighting both retained elements and newly added elements (highlighted in blue).

Table 24: Comparing the Post-test HS Framework and Original PartiSim (Stage 1)

Stage	Activities in the post-test HS framework	Tools proposed	PartiSim activities	PartiSim Tools
Stage 1 -	Understand the problematic situation.	Initiate Study Tool HS1: Bank of questions (THS1)	Understand the problematic situation.	PartiSim Toolset 1 Initiate Study Script 2: Bank of questions

Stage	Activities in the post-test HS framework	Tools proposed	PartiSim activities	PartiSim Tools
Initiate Study		PartiSim Toolset 1 Initiate Study Tool 4: List of reading materials		PartiSim Toolset 1 Initiate Study Tool 4: List of reading materials
		PartiSim Toolset 1 Initiate Study Tool 1: Situation of Interest		PartiSim Toolset 1 Initiate Study Tool 1: Situation of Interest
		PartiSim Toolset 1 Initiate Study Tool 2: Recording Observations		PartiSim Toolset 1 Initiate Study Tool 2: Recording Observations
	Establish the feasibility of the simulation study.	Initiation Study Tool HS2 - Feasibility of hybrid simulation modelling and scope of the model for the first workshop. (THS2)	Establish the feasibility and the scope of the simulation study	PartiSim Toolset 1 Initiation Study Script 1: Feasibility of simulation modelling and its use
	Evaluate data availability	Manual for Conceptual Modelling: Data Availability Assessment (M6)		
	Agreeing on the scope of the simulation study			
	Identifying stakeholder team	PartiSim Toolset 1 Manual for Initiate Study Tool 3: Stakeholders' Contact details, especially Table 1 (stakeholders, roles and personal traits).	Identifying stakeholder team	PartiSim Toolset 1 Manual for Initiate Study Tool 3: Stakeholders' Contact details

8.7.2 Substage 1a - Pre-workshop

Activities in Stage 1a, pre-workshop, underwent only minor changes, as depicted in Figure 29. The first three activities remained unchanged before and after the São Paulo case study. Only the fourth activity, Preparing the workshop dynamics, was adjusted in scope. In PartiSim, this task is largely administrative, focused on running the facilitated workshop.

Since PartiSim uses only Discrete Event Simulation (DES) (Tako and Kotiadis, 2015), its toolset is ready for immediate use. In a hybrid simulation, however, the modelling team may need to adapt the workshop dynamics to explore combinations beyond the one applied in the

SACA case study. The team should be equipped with tools to guide discussions on identifying system elements during the initial workshop. While this research proposes a new tool for developing DES-ABS models, modellers may need to make minor adjustments to ensure smooth facilitation when other simulation methods are involved.

8.7.3 Stage 2 - Define the problem (workshop)

Figure 29 shows the before and after of stage 2, defining the problem workshop. This research preserved the activities and tools proposed in this stage and only proposed minor adjustments to Activity 2 regarding the activity dynamic and time allotment. The following paragraphs recap the aim of each activity in this stage and discuss improvements implemented.

Activity 1 - Identifying the main problem for the study.

This activity aims to identify the main problem for the study and serves as the first task in the guided workshop. It also functions as an icebreaker, helping to create a welcoming and cooperative environment among participants. Individual brainstorming engages the group in discussion and begins with a broad question, followed by probing prompts from the Initiate Study Tool HS1: Bank of Questions (THS1), which supports exploration of multiple perspectives within the system.

Given that participants may be unfamiliar with guided workshops, it is recommended to allocate more time to this activity than in the SACA study. Rather than 15 minutes, a 30-minute session is suggested as the optimal duration for conducting a brainstorming, as outlined in the reflections in section 8.3.

Activity 2 - Defining the study objectives (broadly).

This activity aims to define the study objectives in a general manner. As discussed in Chapter 5, it is not intended to establish the final research goals but to engage participants in an initial

discussion of potential outcomes for the hybrid simulation study. No further changes were made to this activity following the SACA case study, as the guidelines in Chapter 5 and PartiSim Toolset 1 remain sufficient for defining objectives in a hybrid model.

Activity 3 - Defining the system and boundaries.

Compared to PartiSim, this activity was fully redesigned to meet the requirements of hybrid simulation. A new tool, Analysis One, Two, and Three for Hybrid Simulation, guides participants through three levels of analysis to identify elements for the DES-ABS model.

The SACA case study demonstrated that this tool is essential for helping stakeholders capture the problematic situation and represent it in a rich picture. The toolset includes: (1) Conceptual Modelling Tool HS3: Analysis One, Two, and Three for Hybrid Simulation, (2) Manual for Employing Tool HS3: Analysis One, Two, and Three, and (3) Manual for Employing Tool HS3: Tips for Developing a Rich Picture. Together, these resources support the modelling team in defining the system and boundaries within a hybrid simulation. Minor adjustments to the tool's application are recommended.

Given the tool's extensive content, additional time is required to complete this activity effectively. It may be beneficial to split it into two workshops. Workshop I would cover Activity 1 and Analyses One and Two, while Workshop II would begin by reviewing the rich picture developed previously. This approach reinforces earlier discussions, allows participants to refine the visual representation, and then proceeds to Analysis Three using the Conceptual Modelling Tool HS3.

In conclusion, the primary aim of Stage 2 remained consistent with PartiSim, focusing on establishing initial contact between the modelling team and stakeholders. However, as depicted in Table 25, the post-test HS Participative Framework introduced new tools to better support hybrid simulation. Notably, THS3 (Conceptual Modelling Tool HS3: Analysis One, Two, and

Three for Hybrid Simulation) became the core tool used during Workshop I, enabling stakeholders to contribute effectively to the development of a DES-ABS hybrid model and allowing the modelling team to gather relevant information. Additionally, two PartiSim tools—the PartiSim User Guide and PartiSim Toolset 3 - Stakeholder Form 1: Brainstorm Study Objectives, were retained and incorporated into the final HS Participative Framework. Table 25 provides a detailed comparison of all activities and tools, highlighting both the retained elements and the modifications introduced in the post-test framework.

Table 25: Comparing the Post-test HS Framework and Original PartiSim (Stage 2)

Stage	Activities in the post-test HS framework	Tools proposed	PartiSim activities	PartiSim Tools
Stage 2 - Define the Problem Workshop	Identify the main problem for the study	Refer to the PartiSim User Guide	Identify the main problem for the study	Refer to the PartiSim User Guide
	Define the study objectives (broadly)	PartiSim Toolset 3 - Stakeholder Form 1: Brainstorm study objectives	Define the study objectives (broadly)	PartiSim Toolset 3 - Stakeholder Form 1: Brainstorm study objectives
	Define the system and boundaries.	Conceptual Modelling Tool HS3: Analysis One, Two, and Three for Hybrid Simulation (THS3)	Define the system and boundaries.	Manual for Conceptual Modelling Tool 1: Conceptual Modelling Tool 1: Define the System
		Manual for employing the Tool HS3: Analysis One, Two, and Three for hybrid simulation. (M1)		
	Manual for employing the Tool HS3: Tips for Developing a Rich Picture (M2)			

8.7.4 Substage 2a - Post-workshop

Minor changes were made to Substage 2a following the SACA case study, as depicted in Figure 29. A fourth activity, Data Collection, was added as the first task in this stage, while the other three activities were retained. The final activity, Preparing Preliminary Materials for Workshop II, was also reviewed.

The new Data Collection activity was introduced to create a smoother workflow. Previously, data collection was part of the first activity, Re-draw Workshop I Output. At this stage, the modelling team works with extensive information gathered in Stage 2, particularly from the Conceptual Modelling Tool HS3: Analysis One, Two, and Three for Hybrid Simulation (THS3). In the SACA case study, responses from THS3 were represented in a rich picture. At this point, the team needed to convert this information into the Conceptual Modelling Tool HS4: HS Inputs Form (THS4) and assess whether sufficient data had been collected to support subsequent stages. THS4 is therefore used to record data from Workshop II and during Activity 1 (Data Collection).

A minor adjustment was also made to Preparing Preliminary Materials for Workshop II. While it remains the final activity in Substage 2a, its scope is expanded to include identifying potential modules in the system representation. The modelling team conducts a preliminary analysis of the rich picture to identify modules that will facilitate discussion of the conceptual model during Workshop II.

In the SACA case study, five modules were initially identified using the approach described by Zulkepli, Eldabi and Mustafee (2012). Two DES modules for primary and secondary care, and three ABS modules-one for patients and two for interactions between URSI staff and patients. Subsequent discussions revealed that the DES modules could be merged, as primary and secondary care workflows are integrated within the same patient pathways, a consolidation explained further in Chapter 6.

8.7.5 Stage 3 - Define Conceptual Model (workshop)

Figure 29 shows that the initial five activities in Stage 3 remained largely unchanged. Following the SACA case study, an additional activity was added after Activity 1 (Drawing the Model Representation).

Another adjustment concerns the minimum duration of the workshop. While the activities themselves were adequate, the SACA experience indicated that workshops should last at least three hours, rather than the original two, to allow stakeholders sufficient time to understand the dynamics and fully engage in all tasks. Additional time should be allocated to Activities 2 and 4 to ensure complete development of the PMM and a thorough discussion of elements in the conceptual model (Activity 4). Extending the workshop in this way reduces the need for follow-up meetings, which often involve only a subset of stakeholders and risk losing valuable input from the entire group. The following paragraphs summarise the six activities proposed for Stage 3 after the SACA study.

Activity 1 - Draw the model representation.

The new tool introduced in Activity 1, Draw the Model Representation, provided guidance and graphical elements for depicting the DES-ABS hybrid model. No additional changes were required for this activity following the SACA study. The final model representation employed the notation outlined in the Manual for Conceptual Modelling: Drawing a Communicative Model with UML Notation (M3). These graphical conventions effectively conveyed a multi-layered DES-ABS model, which stakeholders validated, demonstrating clear understanding and agreement, and readily linking it to the workshop drawings.

Activity 2 - Determine the modules in the conceptual model.

As outlined in Figure 29, this activity was added to Stage 3 following the SACA study. It begins with the conceptual model developed during the workshop, which is then divided into modules. The modelling team should also follow the guidance provided in Step 1 of the Manual for Conceptual Modelling: Discussing Elements in the Hybrid Conceptual Model at this stage, as detailed in Chapter 5, section 5.7.4.1 Manual for Conceptual Modelling: Discussing elements in the Hybrid Conceptual Model (M5).

Activity 3 - Define performance measures.

In Chapter 5, the focus was on identifying performance indicators for the system under study. This was facilitated using the Manual for Conceptual Modelling: Identifying the Performance Measurement in the HS Model, an extension of the Manual for Conceptual Modelling Tool 3: Drawing the Performance Measurement Model in PartiSim (Tako and Kotiadis, 2010), incorporating guidance on defining behaviour measurements.

Workshop discussions explored both performance and behaviour measures, confirming the manual's effectiveness in identifying measurements for a DES-ABS model. No additional changes were proposed to this activity after the study in SACA, as shown in Figure 29. However, the original 15-minute allocation was insufficient to fully develop the PMM as recommended by the manual and PartiSim. The researcher therefore proposes extending the duration to a minimum of 30 minutes.

Activity 4 - Define the simulation model objectives

This activity focuses on discussing the study's objectives, using the same tools as in the SACA case study. Stakeholders engage in a brainstorming session, guided by key questions from the facilitator, to link previous workshop discussions to the current session. Examples from other simulation studies may be provided for clarity, and the broad objectives established in Workshop I are revisited, allowing stakeholders to retain or adjust them.

Two PartiSim tools are recommended for this stage: (1) PartiSim Toolset 3 - Stakeholder Form 1: Brainstorm Study Objectives, and (2) PartiSim Toolset 3 - Conceptual Modelling Tool 4: Study Objectives - Item 2. The first tool captures participants' input on objectives, while the second guides the formal declaration of the study objectives, supporting both discussion and documentation.

Activity 5 - Discuss model contents, model scope and level of detail.

As discussed in Chapter 5, the elements of a hybrid conceptual model must be determined for each module. To assist modellers, the researcher expanded Robinson's (2008) framework to include the hybrid model perspective, where the inputs of one module may serve as outputs for another, and vice versa. Applying this revised framework supports the modelling team in identifying the elements of a hybrid conceptual model. Following its application in the SACA study, no further changes were deemed necessary. The only recommendation is that modellers review the framework prior to the workshop to become familiar with its approach for hybrid simulation.

Activity 6 - Discuss responsibility for data collection.

This activity builds on the PartiSim approach and the conceptual framework applied in SACA, with the primary goal of identifying individuals responsible for supporting the modelling team in data collection. Since data availability was addressed in Stage 1, this activity also reviews the progress of data collection and the development of required datasets. A minor adjustment includes discussions on data availability to confirm the team's success in gathering data since Stage 1.

If the team identifies a lack of data or insufficient progress in securing the necessary information, they may need to make critical decisions regarding the conceptual model's scope. This could involve developing a stand-alone simulation model or introducing assumptions and simplifications. Any assumptions must be clearly documented, and consensus must be reached between stakeholders and the modelling team before translating the conceptual model into a computer model. In the SACA case study, for instance, a database was created from scratch using a prior longitudinal study of older adults in Brazil (Lima-Costa *et al.* 2023), together with a set of assumptions and simplifications as detailed in Chapter 5, Section 5.7.5.

In essence, Stage 3 underwent the most substantial changes following the study in Brazil. Table 26 summarises the activities discussed in this section and consolidates all tools identified as essential for supporting the modelling team in developing a conceptual model during the workshop, with the main changes highlighted in blue, as detailed in the preceding paragraphs, in comparison to the original PartiSim.

Table 26: Comparing the Post-test HS Framework and Original PartiSim (Stage 3)

Stages	Activities in the proposed framework	Tools proposed for each stage	PartiSim activities	PartiSim Tools
Stage 3 - Define Conceptual Model Workshop	Draw the model representation.	Manual for Conceptual Modelling: Drawing a Communicative Model with UML notation. (M3)		
	Determine the modules in the conceptual model.	Refer to step 1 in Manual for Conceptual Modelling: Discussing elements in Hybrid Conceptual Model (M5)		
	Define performance measures	Manual for Conceptual Modelling: Identifying the Measurement in HS Model (M4)	Put forward and agree on performance measures to address the problem identified in the workshop I	PartiSim Toolset 3 Manual for Conceptual Modelling Tool 3: Drawing the Performance Measurement Model
		PartiSim Toolset 3 Manual for Conceptual Modelling Tool 3: Drawing the Performance Measurement Model		PartiSim Toolset 3 Stakeholder Form for Conceptual Modelling Tool 3 (optional)
	Define simulation model objectives.	Manual for Conceptual Modelling Tool 4: Conceptual Modelling Tool 4: Study Objectives	Define simulation model objectives	Manual for Conceptual Modelling Tool 4: Conceptual Modelling Tool 4: Study Objectives
	Discuss model contents, model scope and level of detail	Manual for Conceptual Modelling: Discussing elements in Hybrid Conceptual Model (M5)	Discuss model contents, model scope and level of detail	
	Discuss responsibility for data collection.		Discuss responsibility for data collection.	

8.7.6 Substage 3a - Post workshop II

Minor changes were proposed to Substage 3a, as shown in Figure 29. In the initial design, the activities from PartiSim were assumed sufficient to cover the tasks between completing the second facilitated workshop and beginning model coding. However, hybrid simulation introduces additional complexity beyond the choice of simulation methods. Combining two or more methods may require different linkages and interactions (Morgan, Howick and Belton 2017). The following paragraphs briefly review the two activities originally included in the conceptual framework and the third activity added to this substage following the SACA case study.

Activity 1 - Re-draw and disseminate workshop outputs.

This activity aims to produce a report summarising the results of the second workshop. The scope defined for this task in both PartiSim and the conceptual framework applied in the SACA case study was deemed satisfactory; therefore, no modifications were required.

Activity 2 - Liaise with the stakeholder team.

Ensuring the accuracy of findings from the facilitated workshop through stakeholder engagement is essential, particularly given the additional activities in this stage. The modelling team must have a clear understanding of the workshop outputs and confirm that all critical elements for developing the computer model have been addressed. A shared understanding between the stakeholders and modelling teams is crucial for the conceptual model developed during the workshop.

Activity 3 - Define the interaction between modules.

Originally part of the activity Build a Simulation Model on the Computer in Stage 4, this task was moved to an earlier stage before data collection to ensure a seamless workflow. This

adjustment reflects the fact that decisions made during model-building can influence subsequent data collection. In this activity, the modelling team identifies how modules interact, determines which information flows between elements, and defines rules for this information exchange. To support this process, the researcher recommends using the toolset proposed by Morgan, Howick and Belton (2017). While initially designed for DES-SD combinations, this tool has proven effective in identifying interaction patterns between modules, a position corroborated by Brailsford *et al.* (2019).

8.7.7 Stage 4 - Develop a computer model.

As shown in Figure 29, stage 4 underwent minor modifications. Two adjustments were proposed: first, the dynamics of the initial activity, involving data collection and validation, were refined based on insights from the SACA study; second, an interaction between Activities 2 and 3 was introduced into the framework. The following paragraphs provide a concise overview of the four activities in Stage 4.

Activity 1 - Data collection and validation:

This activity was originally based on PartiSim. Initially, it was assumed that the PartiSim guidelines would be sufficient to complete the task. However, during the SACA case study, the modelling team encountered difficulties in tracking all the data required for a hybrid model. Consequently, a new checklist was proposed to support data collection, as described in the following paragraphs.

List of data that might be needed in a DES-ABS hybrid model (THS5)

This tool is designed to support modellers during the data collection activity for developing a DES-ABS hybrid model. The data collected will depend on the specific context and objectives of the hybrid model. Table 27 summarises the essential data the modelling team should gather prior to building the computer model. A general list of the required data includes:

Table 27: Checklist of potential data to be collected for a DES-ABS model.

Simulation method	Data
Discrete Event Simulation (DES)	<ol style="list-style-type: none"> 1. Event data: Types of events (e.g., arrival, departure, service start, service end); Event triggers and conditions; Event frequencies and distributions. 2. Queue data: Queue length, capacity and queue discipline. 3. Resource data: types and quantities of resources (e.g., servers, machines), Resource availability schedules, Resource allocation rules and priorities 4. Service process data: Service time distributions, processing times, setup times
Agent-Based Simulation (ABS)	<p>Validate data in Conceptual Modelling Tool HS4: HS Inputs Form (THS4) such as:</p> <ol style="list-style-type: none"> 1. The agent itself: who are the agents (Analysis One in Conceptual Modelling Tool HS3: Analysis One, Two, and Three for Hybrid Simulation) (e.g., patients, doctors, health centre managers) 2. Agents attribute: demographic information, behavioural rules (Analysis Two in Conceptual Modelling Tool HS3: Analysis One, Two, and Three for Hybrid Simulation) 3. Agents' behaviour: preferences, decision-making process, routines and habits (Analysis Two in Conceptual Modelling Tool HS3: Analysis One, Two, and Three for Hybrid Simulation) 4. Interaction rules: how agents interact with each other; how agents interact with their environment (Analysis Three in Conceptual Modelling Tool HS3: Analysis One, Two, and Three for Hybrid Simulation)

Activity 2 - Build a simulation model on the computer.

No adjustments were made to this activity. Modellers retain the freedom to select the commercial programming software or programming language for coding the conceptual model developed in Stage 3. Accordingly, this research does not provide manuals or step-by-step guidelines for this task but recommends that modellers consult tutorials or support communities as needed.

Activity 3 - Conduct preliminary tests.

A key amendment involves the interaction between Activity 3, conducting preliminary tests, and Activity 2, building the simulation model. Verification and validation should be performed

iteratively, allowing individual model modules to be tested as they are developed rather than waiting for the entire model to be completed. This approach aligns with best practices in simulation model development (Sargent 2020; Brailsford *et al.* 2019). The Manual for Conducting Hybrid Model Verification & Validation, developed for the SACA case study, proved essential in guiding novice modellers to test the model and ensure its accuracy.

Ultimately, different from the previous stage, the final stage, model coding, was reviewed with minor adjustments to the first activity, as outlined in Table 28. In this case, a new tool, the List of data that might be needed in a DES-ABS hybrid model (THS5), was introduced to support the data collection task before the model coding.

Table 28: Comparing the Post-test HS Framework and Original PartiSim (Stage 4)

Stages	Activities in the proposed framework	Tools proposed for each stage	PartiSim activities	PartiSim Tools
Stage 4 - Develop a computer model	Data collection and validation	List of data that might be needed in a DES-ABS hybrid model (THS5)	Data collection (modeller and stakeholder team)	
	Build a simulation model on the computer.		Build a simulation model on the computer.	
	Conduct preliminary tests		Liaises with the project champion over the correctness of the model and its results (verification and validation)	

8.8 Chapter Conclusion

Chapter 8 presented the final proposed framework for hybrid simulation, developed after applying the initial conceptual framework outlined in Chapter 5. This framework was refined through multiple adjustments informed by the experience of conducting a hybrid simulation study within the Brazilian healthcare system. Following its application, the researcher critically evaluated the outcomes of each stage and implemented modifications to create a conceptual

framework suitable for future researchers, regardless of their prior experience. Building on the insights gained from implementing the framework in SACA, this study introduces the Participative Hybrid Conceptual Modelling approach, which guides the development of hybrid simulations while actively engaging stakeholders. The chapter also demonstrates how the framework evolved from the original PartiSim methodology to the post-test HS framework, highlighting the key adjustments and additions made throughout the process.

Chapter 9 - Discussion and Conclusions

9.1 Introduction

This chapter summarises the key findings of the study and discusses what they mean for both theory and practice. It begins by discussing how the research addressed gaps identified in the literature through the development of the participative hybrid conceptual modelling framework (Section 9.2), before examining challenges encountered during its application.

Particular attention is given to the experience of the researcher as a novice modeller in Section 9.2.2, while the implications of methodological choices and simplifications, and challenges on hybrid model validation are in Sections 9.2.3 and 9.2.4, respectively. The potential value of involving an additional observer with expertise in specific simulation approaches is discussed in Section 9.2.5. Section 9.3 outlines the contributions of the study to the field of hybrid simulation in healthcare, and the chapter then revisits the research aims and objectives to assess how far they have been achieved in Section 9.4. Finally, the chapter concludes with a proposed agenda for future research (Section 9.5).

9.2 Discussion of Research Findings

This section discusses the key findings that emerged throughout the research, integrating insights from the literature review in Chapter 2, the Brazilian healthcare context outlined in Chapter 3, and the methodological design presented in Chapter 4. It reflects on how the participatory hybrid simulation framework was developed in Chapter 5 and subsequently applied in Chapter 6. Chapter 7 addressed the conceptual and practical challenges identified earlier in the thesis. Drawing on the reflections and refinements discussed in Chapter 8, this section synthesises how the study's contributions advance understanding of both participatory modelling practice and the implications of population ageing for healthcare systems.

9.2.1 From Literature Gaps to Framework Design

Developing a conceptual model is recognised as an important stage in constructing a simulation model (Robinson 2015). A conceptual model serves as a bridge between the initial problem statement and the computational model that will later be implemented to deliver value. It sets out assumptions, identifies boundaries and clarifies the model's intended purpose (Kotiadis and Robinson 2008). The quality of this stage often determines the overall value of the work, because weak conceptualisation can undermine even technically advanced computational models (Gabriel *et al.* 2022). This challenge is amplified in hybrid simulation, where more than one paradigm must be integrated in a coherent and systematic way (Tako *et al.* 2019). In such contexts, the modeller team has to be ready to explore different facets of the same problem (Mustafee *et al.* 2015). Hence, the role of conceptual modelling is not only technical but also communicative, since it provides a shared platform for supporting understanding of how different paradigms contribute to the representation of a complex problem.

Despite this importance, the review conducted for this research revealed a persistent gap. Although conceptual modelling is often acknowledged in principle, in practice it receives limited attention (Tako *et al.* 2019). Many studies either bypass the stage altogether or limit it with model representation. In such cases, the computational model is presented as the primary outcome, with little reference to the conceptual decisions that shaped it. This practice reduces transparency, limits the possibility of replication, and obscures the rationale behind key modelling choices (Gabriel *et al.* 2022; Robinson 2008). A minority of studies provide more explicit accounts by reporting the purpose of the model, its assumptions, or its boundaries, yet these remain exceptions rather than the rule, as discussed in Chapter 2, Section 2.4. Particularly within hybrid simulation, conceptual models were rarely published in a structured format. As a result, the reasoning process that leads from problem identification to simulation implementation often remains hidden, which restricts opportunities for learning across studies.

Another key gap concerns the role of stakeholders in the conceptual modelling process. The literature shows that most hybrid simulation studies pay only limited attention to stakeholder engagement (Dos Santos, Kotiadis and Scaparra 2020). Even when engagement is reported, it is often confined to consultation rather than genuine participation. Stakeholders may be asked to provide information or validate outputs; however, they are seldom involved in shaping assumptions or exploring alternative perspectives. This stands in contrast with developments in facilitated modelling, where the modeller acts as a facilitator rather than an analyst (Franco and Montibeller 2010). In traditional modelling approaches, the modeller takes responsibility for defining the problem, constructing the model, and proposing solutions, with little involvement from others. The focus is often on achieving technically optimal solutions, which can result in models that are mathematically sound but socially distant from the concerns of those who will use them.

Facilitated modelling offers an alternative. Here, the modeller works with stakeholders from the outset to co-define the problem, shape the assumptions, and test possible solutions. This approach values shared understanding and transparency, recognising that models in applied settings must be both technically credible and socially acceptable (Tako 2025; Lamé and Simmons 2020; Kotiadis and Tako 2018). While the solutions produced through facilitated modelling may not always be optimal in a strict mathematical sense, they often carry legitimacy and ownership among stakeholders, which increases the likelihood that they will be used in practice. Yet, in hybrid simulation literature, facilitated approaches remain underdeveloped (Jones *et al.* 2022; Tako *et al.* 2019). Stakeholder involvement is often marginal, and the complexity of integrating different paradigms is typically treated as a technical (e.g. matching data structures, harmonising algorithms, resolving formal modelling incompatibilities) rather than a social challenge (e.g. differences in values, priorities, assumptions, professional cultures, or communication styles) between stakeholder groups.

The Brazilian study conducted for this research highlighted the practical implications of this gap. During the preparation of workshops, it was initially difficult to identify which activities were necessary to capture the components of the health system and to translate them into a hybrid conceptual model, considering both technical (e.g., data issues) and social challenges (e.g. different views on Brazilian health care structure and communication style). The literature confirms that stakeholder involvement is demanding even when a single simulation method is used, and this difficulty increases when paradigms are combined (Anagnostou *et al.* 2024). In the Brazilian case, stakeholders brought diverse perspectives, local knowledge, and different expectations. These contributions were essential to building a credible conceptual model, but they also introduced complexity that required careful facilitation. The experience demonstrated the need for a structured participatory framework to support hybrid conceptual modelling. Without such support, modellers risk either oversimplifying stakeholder engagement or being overwhelmed by the complexity of combining multiple paradigms and viewpoints (Nguyen, Howick and Megiddo 2024; Jones *et al.* 2022; Chahal, Eldabi and Young 2013).

This research also revealed that existing studies concentrate mainly on DES-SD combinations. These have received more attention than DES-ABS or other hybrid forms that incorporate agent-based modelling. Even in DES-SD contexts, stakeholder engagement across the modelling stages is rare (Dos Santos, Kotiadis and Scaparra 2020). Frameworks are often expert-driven, with the modeller determining the scope and structure of the model. While this may produce efficient computational results, it overlooks the social dimension of modelling and limits the legitimacy of outcomes in practical settings. To address these gaps, this research designed and tested a structured conceptual framework specifically aimed at supporting stakeholder involvement in hybrid simulation.

The framework was developed through an action research strategy. This approach emphasises iterative cycles of intervention and reflection, allowing both theoretical insights and practical

experiences to inform the outcome (Coughlan and Coughlan 2002; Chiasson, Germonprez and Mathiassen 2009). The PartiSim methodology was selected as a starting point. PartiSim had been developed for discrete-event simulation and was designed to support participatory modelling processes (Tako and Kotiadis 2015). However, because it was tailored for DES, its tools and activities did not fully address the requirements of hybrid simulation. At the beginning, only minor adjustments were made to extend PartiSim to DES-ABS combinations, a conservative approach, given the challenges surrounding hybrid simulation. As the Brazilian case study progressed, it became clear that more extensive modifications were needed. The final framework, therefore, synthesises theoretical understanding with empirical lessons from the case study. It represents not only the application of an existing method but also the development of new tools and activities designed for hybrid contexts.

One of the most acute challenges was the absence of facilitated methods when applied directly to hybrid simulation (Jones *et al.* 2022). PartiSim provides a valuable structure for DES, but hybrid models require additional tools to manage the complexity of combining paradigms (Anagnostou *et al.* 2024; Tako *et al.* 2019). For example, in early stages, it was necessary to assess feasibility across paradigms and to evaluate the availability of data for each. This led to the design of the Initiation Study Tool HS2, which provides a systematic way to evaluate hybrid feasibility. At later stages, additional manuals were developed, such as communicative models based on UML and hybrid conceptual model elements. These supported structured discussions with stakeholders and enabled clearer documentation of decisions. By formalising these processes, the framework addresses calls in the literature for greater guidance on hybrid conceptual modelling and extends existing approaches into new territory.

Formalising conceptual modelling also has wider implications. It elevates conceptualisation from a background activity to a central and deliberate practice. In doing so, it underscores that hybrid simulation is not simply a computational exercise but a process of conceptual

integration. This integration requires active participation from stakeholders, not only for legitimacy but also for accuracy. In the Brazilian case, stakeholders were able to identify critical aspects of the health system that might otherwise have been overlooked. Their input was particularly important when balancing the process orientation of DES with the individual-level heterogeneity of ABS. Without structured facilitation, these insights might not have been captured, and the resulting model would have been less representative of the system under study.

The framework also emphasises continuous participation rather than one-off involvement. Iterative engagement at multiple stages enabled stakeholders to refine assumptions, provide feedback, and build confidence in the model (Jones *et al.* 2022; Eldabi *et al.* 2019). Artefacts such as workshop outputs and verification checklists were used to capture these inputs and ensure that they informed the evolving model (Tako *et al.* 2019; Kotiadis and Tako 2018). These mechanisms served not only as methodological innovations but also as safeguards. They helped to prevent the construction of technically sophisticated models that lack credibility among those who will ultimately use them.

The SACA study provided a practical test of the framework under real-world conditions. These conditions included incomplete data, conflicting priorities among stakeholders, and broader socio-economic inequalities that shaped health service provision. Workshops were essential for eliciting tacit knowledge that could not be captured through formal data sources alone. Boundary-setting activities also played a vital role in managing expectations and ensuring that the model remained both feasible and relevant. These experiences illustrate the dual contribution of the framework. On one hand, it strengthens methodological rigour in hybrid simulation by offering structured tools for conceptualisation and participation. On the other hand, it demonstrates practical feasibility in resource-constrained settings, where data and time are often limited.

Beyond the immediate case, the framework contributes to broader debates in operational research. By integrating DES and ABS in a pluralistic manner, it aligns with principles of action research, which emphasise collaboration, reflection, and adaptability. The framework also addresses the social dimensions of modelling in healthcare, recognising that models are not only technical artefacts but also instruments that influence policy, practice, and service delivery. By embedding participation as a methodological principle rather than treating it as an optional addition, the framework offers a way of reconciling technical robustness with social credibility. This contribution is particularly significant in healthcare contexts, where demographic change, resource pressures, and complex service integration create urgent challenges. Hybrid simulation offers technical potential to address such challenges, but without a participatory conceptual framework, its impact is likely to remain limited. The framework developed through this research, therefore, has value not only in advancing academic debates but also in offering practical guidance for healthcare systems globally. Its combination of structured conceptualisation, stakeholder engagement, and methodological flexibility provides a transferable model that can support health planners and decision-makers in diverse settings.

9.2.2 Challenges of Being a Novice Modeller in Hybrid Simulation

One of the reflections from this study concerns the researcher's position as a novice modeller. Hybrid simulation requires combining distinct paradigms, each with its own assumptions, data requirements, and modelling practices. As the literature review highlighted (Chapter 2), DES, ABS, and SD are traditionally applied independently, and each demands a considerable level of technical and methodological expertise (Mustafee *et al.* 2017b; Macal and North 2014; Ahmed, Robinson and Tako 2014). Bringing them together within a single framework intensifies this challenge. From the perspective of a novice modeller, the learning curve was

steep, not only in terms of technical coding but also in developing the judgement needed to decide which paradigm best represented aspects of the healthcare system.

The reflections from practice confirmed that in the early stages, the modeller's limited experience created concerns about confidence in representing the system correctly (Singh, Cascini and McComb 2021; Wang and Brooks 2007). For example, when developing the ABS layer of the hybrid model, questions arose around how much behavioural detail should be included and how to avoid unnecessary complexity. The literature suggests that these are common difficulties even for experienced modellers (Badham *et al.* 2019; Eldabi *et al.* 2018). In this research, the presence of structured tools in the participative framework reduced some of the uncertainty by guiding both the modeller and the stakeholders through the steps of conceptualisation. However, this experience also highlighted that future adoption of the framework may require additional support materials, training, or collaboration with more experienced modellers, especially for those at the beginning of their careers.

9.2.3 Implications of the Chosen Methodology and the Impact of Simplifications

An important point emerging from this study concerns the implications of methodological choices and the simplifications introduced during model building. The decision to combine Discrete Event Simulation (DES) and Agent-Based Simulation (ABS) was guided by both the literature and the modeller's understanding of stakeholder needs. DES was well-suited to representing patient flows and resource allocation, while ABS enabled the representation of heterogeneity and interactions between individuals. Nevertheless, as discussed in Chapter 2, every simulation involves decisions about the level of detail and scope of representation, as it is impossible to model the full system (Brailsford *et al.* 2019; Eldabi *et al.* 2018; Robinson 2014).

These simplifications influence the interpretation of the results. Erdemir *et al.* (2020) note that excluding components or simplifying model structures and using data from one context for another will inevitably limit what can be represented and influence what the model can and cannot predict. In this study, using non-local data and grouping behaviours reduced the ability to capture heterogeneity in older adults' health-care use; consequently, estimates of resource utilisation and patient outcomes may not generalise to the specific population of SACA. Simplifying treatment pathways and omitting exogenous factors (e.g., access to nutritious food and physical-activity opportunities, living and built environment) means that the model attributes change in health status entirely to health-care interactions, potentially overestimating the effectiveness of interventions. The reliance on aggregated data also limited opportunities for rigorous verification and validation, and the absence of implementation data in the literature meant that findings about potential system improvements could not be tested against real-world outcomes (Brailsford *et al.* 2019; Mustafee *et al.* 2015).

Stakeholder participation helped manage these simplifications by identifying what details were essential. Their involvement ensured that omissions reflected shared priorities rather than modeller bias, but did not reduce the risks of subjectivity and bias. Stakeholder views are inherently subjective and can be influenced by personal experience, organisational culture, or political interests (Ackermann *et al.* 2011). If such views are not cross-checked with data, the model risks reproducing biases or misconceptions. Franco and Montibeller (2010) argue that participatory modelling processes are vulnerable to cognitive and motivational biases, which can distort assumptions about causal relationships, priorities, or magnitudes of effects. As a result, the model may reflect stakeholder narratives rather than the underlying system behaviour.

Another key limitation concerned the lack of detailed behavioural data. In hybrid models with ABS elements, detailed data are needed to define agent rules, behaviours, and interactions. In

many low- and middle-income countries (LMIC) contexts, such data are incomplete or inconsistent (Bagherian and Sattari 2022). When behavioural data are limited, the credibility and realism of the ABS component tend to decrease. Research on hybrid simulation underscores these issues. Mustafee *et al.* (2017a) observe that hybrid models often evolve in an ad hoc manner, with limited guidance on how to integrate methods or maintain data consistency. Without a reliable data foundation, such models can become less transparent and difficult to validate. When behavioural data are missing, modellers or stakeholders, as in this research, make assumptions about decision rules and interactions, introducing uncertainty that can reduce confidence in the results. Furthermore, greater model complexity may create a misleading sense of precision when it is based on uncertain data.

At the conceptual modelling stage, it is therefore important to decide whether to include an ABS component when data are limited, or to focus on a single, well-supported method. Mustafee *et al.* (2017a) recommend using hybrid models only when their added complexity provides clear value. If robust data exist for a DES model but not for agent behaviour, a high-quality, stand-alone DES may be preferable, as it is easier to validate, more transparent, and more credible.

In this study's healthcare setting, data on older adults' behaviours were limited, making these points particularly relevant. While hybrid DES-ABS models can capture complexity, their value depends on data quality. A narrower DES model can still produce reliable insights with fewer assumptions and simpler validation, helping to maintain stakeholder trust. As data improves, the model can evolve into a hybrid version. This stepwise approach keeps complexity in line with evidence and balances ambition with feasibility.

9.2.4 Challenges in Hybrid Model Validation

The validation exercise highlighted several limitations related to the availability and nature of data provided by stakeholders. For some key performance indicators, particularly KPI1 and KPI3, the real system was represented only by aggregated measures or single average values, while for KPI2, the available data were limited and highly variable. These conditions constrained the application of formal statistical validation techniques and reduced the strength of inferential conclusions (Sargent 2013). Such data-related challenges are common in healthcare modelling, where information is often incomplete, fragmented, or collected for administrative rather than analytical purposes (Katsaliaki and Mustafee 2011; Günal and Pidd 2010; Brailsford and Hilton 2001). As a result, discrepancies between model outputs and real-system observations cannot be interpreted solely as model failure; however, they might be understood in the context of data scarcity and measurement limitations.

In addition to data constraints, the use of a hybrid simulation approach introduces further challenges for model validation. Hybrid models combine different simulation paradigms, each of which represents the system at a different level of abstraction and relies on various assumptions (Brailsford *et al.* 2019). Consequently, validation in hybrid simulation is not a single, uniform activity, but a combination of multiple validation processes. Operational components, such as those modelled using discrete-event simulation, may be assessed using statistical comparisons, while behavioural components, such as those represented through agent-based simulation, often rely on qualitative judgement, expert opinion, and face validation (Macal and North 2010b; Ormerod and Rosewell 2006). This multiplicity of validation requirements increases the overall difficulty of achieving full empirical validation and may lead to situations where some model components appear valid while others do not.

Within this context, it is not possible to infer with certainty whether the observed lack of validation for some KPIs is attributable to the overall model structure or to specific components of the hybrid model, including the agent-based layer. The ABS component was designed to represent human behaviour, decision-making, and interactions that are inherently difficult to observe and quantify in the real system (Macal and North 2005). Behavioural rules were therefore informed largely by stakeholder knowledge and expert judgement rather than by direct empirical measurement. While this approach enhances realism and relevance, it also limits the extent to which ABS behaviour can be statistically validated. Small differences in behavioural assumptions, decision timing, or interaction rules can produce emergent system-level effects that influence KPIs, particularly those sensitive to delays, queues, or resource contention (Macal and North 2009; Epstein 1999). Consequently, the role of the ABS component in contributing to validation discrepancies cannot be isolated or ruled out and should be interpreted as a plausible but unquantifiable source of deviation.

Despite these limitations, the model remains valuable as an exploratory tool for examining alternative scenarios rather than as a mechanism for producing precise predictions of real-world performance. Its main contribution lies in enabling comparative “what-if” analyses and in supporting understanding of how changes in capacity, policy choices, or behavioural assumptions may shape system behaviour. Importantly, this modelling effort would not have been possible without active stakeholder engagement. Stakeholders provided critical contextual knowledge, helped define system boundaries and performance measures, and supported the interpretation of results in situations where quantitative data were limited or unavailable (Robinson *et al.* 2010). In this data-constrained context, the participative process effectively compensated for gaps in empirical evidence and enabled the development of a meaningful and credible representation of the healthcare system (Zimmerman *et al.* 2016; Freebairn *et al.* 2016; Kotiadis, Tako and Vasilakis 2014).

9.2.5 Value of Having an Additional Observer or Researcher with a Specialised Background

A further reflection concerns the potential value of involving an additional researcher or observer, particularly one with expertise in ABS or SD. As noted in Chapter 2, each simulation paradigm has its own technical depth. DES has a strong tradition of operational modelling in healthcare (Arisha and Rashwan 2016), while ABS are less frequently applied and often demand specialised expertise to implement effectively (Abdelghany and Eltawil 2017; Macal and North 2010a). For a single modeller, particularly one still developing their skills, covering all paradigms to the same standard is difficult.

Having another researcher with a background in ABS, or alternatively SD, could have added several benefits. First, it would have provided additional assurance regarding the technical validity of the model, particularly in defining agent behaviours and interactions. Second, an additional perspective could have helped challenge assumptions during the workshops and offered alternative ways of representing complex dynamics. This aligns with Franco and Montibeller's argument that facilitated modelling benefits from diverse expertise and reflective practice (Franco and Montibeller 2010). Third, an observer not directly responsible for coding could have focused on group dynamics, ensuring that stakeholder contributions were fully captured and translated into the model.

Although the study demonstrated that a single novice modeller can implement the framework, the reflections suggest that collaborative modelling teams may strengthen both the technical quality and the participative process. This is consistent with the literature on multi-methodology research, which notes that hybrid approaches often require collaboration across disciplinary boundaries (Eldabi *et al.* 2018). For future applications of the framework, the inclusion of an

additional modeller or observer with expertise in specific paradigms would therefore represent a valuable enhancement.

9.3 Contributions of this research

9.3.1 A Comprehensive Review of Hybrid Simulation in Healthcare: Gaps, Challenges, and Insights on Conceptual Modelling.

The systematic review in Chapter 3 contributed to determining the extent to which existing studies have explored hybrid simulation in healthcare. It presented an in-depth analysis of hybrid simulation literature, categorising it into three groups: (1) survey and purely methodological papers, (2) framework papers, and (3) case studies, as discussed in the previous section.

For the first group, the research summarised the aims and main findings of the papers, highlighting the evolution of commercial packages, challenges in model coding, and the critical features of combining single simulation methods, particularly DES-SD (Section 2.3.1). Despite recognising the benefits and challenges of hybrid simulation (HS) in healthcare, the field lacks comprehensive guidance for seamlessly developing HS models, unlike the well-established methods for single simulations like DES (Robinson *et al.* 2014; Tako and Kotiadis 2018b), SD (Vennix 1996a), and ABS (Macal and North 2010b). These conclusions were reinforced by the second group of papers, which proposed HS conceptual frameworks.

The second group examined studies that proposed conceptual frameworks in hybrid simulation, comparing them to Robinson's (2014) four-stage simulation lifecycle (Section 2.4). A few papers have been dedicated to this topic, confirming the findings discussed in the previous paragraph about the lack of guidance in developing an HS model. This comparison led to four main findings. First, HS papers have focused on the stages from conceptual modelling to model experimentation compared to the four-phase simulation lifecycle. None of the works have

included the fourth phase, model implementation, as a stage in their proposed HS lifecycle. Second, none of the works have included activities assessing whether hybrid simulation is the ideal method for the problematic situation. Instead, all works developed the conceptual framework for a specific hybrid model, such as DES-SD, going against the argument that *“the aim should not be to simply build a hybrid model ... Before embarking on building a hybrid model, analysts are reminded to consider whether the added complexity [hybrid simulation] is worthwhile.”* (Tako *et al.* 2019, page 1270)

Third, previous studies have not considered the engagement of stakeholders at any point in the modelling cycle. Despite adding activities to each stage, the participation of stakeholders in the activity is not included in their framework. These findings were also confirmed in the review of the third group, the case studies in hybrid simulation. As discussed in Chapter 2, this study examines soft OR methods for stakeholder involvement, which have proven helpful in standalone simulation studies (Tako and Kotiadis 2018). While some of the studies we reviewed mention using interviews or workshops to understand the problematic situation, the mere inclusion of these qualitative methods does not suffice to conclude that soft OR methods were integral to their approach. Fourth, studies focused on briefly describing the activities in each stage. No included tools, such as manuals, scripts or forms, are signed as part of their approach.

This research also reviewed the application of hybrid models in healthcare, exploring the four hybrid model types. The extensive literature review contributed to a holistic understanding of hybrid simulation methods from two perspectives - the hybrid model (Section 2.3) and the conceptual modelling stage (Section 2.4).

The first perspective adopted the areas of variability in Dos Santos, Kotiadis and Scaparra (2020). It examined the management lens (strategic or operational) category of the problem explored (Disease Management, Hospital Management, Healthcare System). It analysed how

hybrid models were conducted, detailing how the different methods were combined, how data were incorporated into the models, and how implementation and validation were carried out. Findings from this analysis showed a shift in the type of model preference. In Dos Santos, Kotiadis and Scaparra (2020), DES-SD was the most popular, and SD-ABS applications were nonexistent. However, this research showed that DES-ABS has become the most popular hybrid model. SD-ABS has also been applied in healthcare, especially in the past four years. Despite the hybrid model combination, implementation has still not been reported in case studies. When reported, it is said to be a potential but not a real study. Another area of opportunity is model validation and verification which has not been reported by the case studies or only restricted to a statistical approach. This research also confirmed that not much progress was made towards stakeholder engagement in HS. A few studies have reported the participation of stakeholders; however, it was restricted to data validation or model validation. None has reported the active involvement of stakeholders throughout the model development.

Additionally, the research examined conceptual models in case studies, focusing on how the elements were reported. While all studies included conceptual models, an in-depth analysis revealed that most did not clearly describe all elements. According to Robinson's (2008) framework, which includes objectives, inputs, outputs, content, assumptions, and simplifications, objectives were the most reported element in case studies. Other elements were only partially reported or omitted entirely. Furthermore, model representation remains an area needing improvement. Studies often used screenshots of the coded model or separate illustrations of single methods, indicating opportunities for further research. Some of the consequences of not including a proper model representation in simulation studies are that it reduces clarity, making it difficult for readers to understand the model's structure and logic; it hampers reproducibility, as other researchers cannot replicate the study accurately; and it impairs communication among stakeholders, limiting the practical application of the findings.

This comprehensive examination significantly contributed by highlighting the practices in conceptual modelling, addressing a notable gap in the literature. The findings also provided insights into how to report conceptual models. They corroborated the need for further research in conceptual modelling in hybrid simulation (Tako *et al.* 2019; Eldabi *et al.* 2019; Eldabi *et al.* 2018).

9.3.2 Enhancing Stakeholder Engagement in Hybrid Simulation

As outlined in Chapter 2 and Section 2.4, the current HS literature showed that conceptual models for hybrid simulation are still unable to cope with stakeholders' involvement throughout its stages (Jones *et al.* 2022; Dos Santos, Kotiadis and Scaparra 2020). In response to these limitations, this research proposed using PartiSim as the foundation for developing a facilitated approach to hybrid simulation, resulting in the Participative Hybrid Conceptual Modelling Framework. As far as the researcher is aware, this represents one of the first attempts in the HS literature to establish a structured method for involving stakeholders explicitly in the conceptual modelling stage of a hybrid simulation study.

The researcher found that the staged structure of PartiSim offered a practical and intuitive way to engage stakeholders throughout the development of a hybrid simulation model. From the modeller's perspective, the overall process appeared straightforward, largely due to PartiSim's clear facilitation logic and supportive set of tools. As emphasised by Tako and Kotiadis (2015), a key strength of PartiSim lies in its ability to allow modellers to move flexibly between hard and soft OR paradigms as needed. The experience gained in this study confirms this observation: PartiSim enabled productive discussions about the problem situation and model boundaries without requiring stakeholders to understand hybrid simulation concepts. Through these facilitated interactions, participants became active contributors to the conceptual

foundations of the hybrid model, which were subsequently translated into the DES-ABS computer model presented in Chapter 6.

Developing and conducting the conceptual framework was not without difficulty, largely due to two factors: the researcher's inexperience and the wider lack of guidance on conceptual modelling for hybrid simulation. As a novice modeller and facilitator with a background primarily in DES, considerable effort was required to build competence in Soft OR, hybrid modelling, and ABS. This aligns with findings by Tako and Kotiadis (2015), who note that transitioning to new paradigms is particularly challenging for inexperienced modellers, who often gravitate toward modelling activities rather than stakeholder engagement. The scarcity of methodological resources for facilitated conceptual modelling in HS further compounded this challenge.

Despite these difficulties, PartiSim played an important role in supporting stakeholder involvement in this study. Its structured stages facilitated communication within a multidisciplinary group, helping build shared understanding and supporting collaborative model development. Stakeholder feedback during the workshops reinforced the value of using a facilitated approach.

Additionally, this study also contributes to growing evidence of PartiSim's flexibility. Recent work has shown that PartiSim can be adapted beyond traditional DES settings, including for optimisation-oriented modelling (Noorain 2024; Noorain, Kotiadis and Scaparra 2019). The successful application of PartiSim to the first four stages of a hybrid DES-ABS simulation in this research provides further confirmation of its adaptability and suggests strong potential for its extension to other forms of hybrid simulation.

Lessons learned from this experience have not only informed the refinement of the conceptual framework but have also contributed to the researcher's development as a facilitator. These

insights will undoubtedly support future participatory hybrid simulation studies, where structured stakeholder engagement continues to be both essential and challenging.

9.3.3 Exploring Population Ageing in Brazil through a Participative Hybrid Conceptual Modelling Framework

The findings from applying the conceptual framework in Santo Amaro and Cidade Ademar, Brazil, are detailed in Chapter 8. This framework, developed by a multidisciplinary group with expertise in Brazilian healthcare practices, involved four stages. Including individuals from diverse backgrounds enabled thorough discussions on the challenges and issues arising from population ageing in Brazil. The discussions revealed these challenges' multifaceted nature, including healthcare, social security, and economic implications.

Stakeholder involvement extended beyond creating a hybrid simulation model, fostering discourse on an underexplored but significant issue in Brazil. Participants highlighted the increasing importance of discussions about population ageing amid significant demographic shifts. Despite this, current actions and investments prioritise immediate issues, especially concerning communicable diseases, rather than focusing on non-communicable diseases (NCDs) and long-term population trends. Experts and policymakers now prioritise these complex challenges and opportunities, though such forums remain rare.

The research provided a unique platform for discussing the impacts of population ageing, involving stakeholders directly engaged in daily healthcare operations. By bringing frontline health experts together, the study facilitated valuable exchanges of insights and experiences, highlighting practical challenges and needs associated with an ageing population. Workshops ensured that the perspectives of those actively caring for older people were included, leading to a deeper understanding of the issues. Consequently, the research not only advanced academic knowledge but also fostered dialogue among diverse stakeholders from across the system,

laying the groundwork for practical solutions and policies to address the real-world consequences of population ageing.

9.4 Aims and Objectives Revisited

As outlined in Chapter 1, this study set out to introduce a participatory conceptual hybrid simulation framework and to explore its usefulness through a real-world healthcare case study in Brazil. Two main aims guided the research. The first aim was to develop a methodology that supports modellers in involving stakeholders during the conceptual modelling and development of facilitated hybrid simulation studies. The second aim was to examine how population ageing affects healthcare services for older adults in São Paulo by applying the facilitated hybrid simulation approach. Across the thesis, all aims and research questions have been addressed.

The structure of the dissertation reflects the sequence of activities needed to achieve these aims. Chapter 2 provided a review of the simulation literature, covering stand-alone and hybrid simulation methods. By examining methodological papers, frameworks, and case studies, this chapter established the need for a structured participatory approach to hybrid simulation and therefore contributed directly to Research Questions 1 to 3 and Aim 1.

Chapter 3 presented the Brazilian healthcare context, focusing on population ageing and its impact on regional health services. This chapter confirmed that the pressures associated with ageing populations, well documented in the international literature, are also visible in Brazil. It showed that the healthcare system faces growing demand but limited preparation for the demographic transition. These findings supported the relevance of Aim 2 and guided the development of the case study.

Chapters 5 to 7 addressed the development and practical application of the conceptual framework. Chapter 5 introduced the initial version of the participatory hybrid simulation framework, describing the activities and tools adapted from PartiSim for hybrid use. Chapter 6

applied the framework in the Santo Amaro and Cidade Ademar (SACA) case study and presented the outputs from the participatory workshops, the resulting conceptual model, and the hybrid DES-ABS computer model in Chapter 7. Together, these chapters directly answered Research Questions 1 to 3 by demonstrating how stakeholder engagement was embedded, how PartiSim was modified, and which activities and tools were essential for participatory hybrid modelling.

Chapter 8 reflected on the experience of applying the framework in practice and evaluated its strengths and limitations. Based on insights from the case study, several adjustments were proposed, resulting in the post-test version of the Participatory Hybrid Simulation Conceptual Modelling Framework. This revised version responds to methodological challenges identified in the Brazilian context and completes the work for Aim 1.

Finally, Chapter 9 discussed the contributions of the research and revisited the aims and research questions. It explained how the hybrid model helped examine ageing-related pressures in SACA and how the simulation supported understanding of patient flows, resource constraints, and coordination challenges. This chapter, therefore, addressed Aim 2 by showing that the conceptual framework can be translated into a hybrid model that offers insights into the impact of population ageing on healthcare services.

In summary, the thesis demonstrates that the proposed participatory conceptual framework was successfully developed, applied, and refined. Through the combination of literature analysis, framework design, empirical testing, and reflection, all research aims and questions stated in Chapter 1 have been fully addressed.

9.5 Future Research

The established conceptual framework can be used as a guide to developing a DES-ABS for complex healthcare problematic situations. Although this research has made a few contributions

to the field, bringing valuable insights towards consolidating hybrid simulation as the avenue for tackling real and complex problems, there are still gaps in the hybrid simulation domain that require attention from future work. Hence, the following paragraphs enumerate a few opportunities for future work.

Future Work 1: Expanding the proposed framework, including the post-coding stages.

Although PartiSim is a comprehensive methodology that covers all stages of the modelling lifecycle, including post-coding validation and implementation, this study focused primarily on the conceptual modelling phase, as described in Chapter 5. Future research could expand the proposed framework to encompass all four phases of the simulation lifecycle (Robinson 2014), ensuring continuity from problem structuring through to experimentation, implementation, and model deployment. Such work would build on the reflections presented in Chapter 8, where several opportunities for enhancing later stages of the process were identified.

Future Work 2: Expanding the framework to other hybrid models.

Although tools in Stage 1 of the framework support identifying an appropriate hybridisation approach, this study applied the framework specifically to the development of a DES-ABS model, as detailed in Sections 7.2 and 7.2.2. The tools introduced in Stage 2 were tailored to this hybrid structure, meaning that the applicability of the framework to other hybrid configurations (e.g., SD-DES, SD-ABS) remains untested. Further studies should investigate whether the framework is sufficiently flexible to support the development of alternative hybrid simulation architectures or whether additional modifications are required. It is worth noting that PartiSim has already been adapted for other modelling contexts, such as optimisation (Noorain 2024; Noorain, Kotiadis and Scaparra 2019), which demonstrates its flexibility and potential for further methodological extensions.

Future Work 3: Applying the proposed framework in other fields beyond healthcare.

This research deliberately focused on healthcare, from the literature foundation established in Chapter 2 to the case study in Chapters 3 and 6. Although the conceptual modelling challenges identified here align with gaps reported in other fields, the analysis remained healthcare-specific. A broader systematic literature review extending beyond healthcare would enable scholars to assess whether the methodological issues reported in Section 2.4 are equally prevalent in other sectors. Such work could help evaluate the generalisability of the proposed framework and identify opportunities for domain-specific adaptation.

Future Work 4: Empirical Studies to assess the effectiveness of the proposed framework for non-experienced modellers.

The conceptual framework was developed by a novice modeller, as acknowledged in Section 9.2.2, who found the stages intuitive and supportive of participatory hybrid modelling. Future empirical work should examine the extent to which the framework is similarly accessible to other novice or early-career modellers. Capturing their experiences would help refine the sequence of activities, confirm the clarity of the tools and guidance provided, and strengthen the framework's value as a pedagogical and practical resource.

Future Work 5 - Repeat the simulation using appropriate data collection.

As discussed in Sections 7.2.1 to 7.2.2, the current hybrid model relied on a limited dataset, which constrained the parameterisation and validation of the DES-ABS components. A valuable direction for future work would be to repeat the simulation using a richer and more granular dataset collected directly from the SACA healthcare system. Improved access to operational, behavioural, and disaggregated flow data would support more rigorous validation and enable

researchers to assess whether the current hybrid design accurately represents system dynamics or whether alternative modelling approaches or software platforms may be more suitable.

Appendix A - Participative Hybrid Simulation Tools and Supporting Materials

This appendix presents the set of tools that underpin the Participative Hybrid Simulation Conceptual Modelling Framework described in Chapter 5. The tools operationalise the framework by providing structured templates, question sets, and guidance for engaging stakeholders and recording modelling decisions. To improve the clarity and focus of the main text, detailed descriptions and formats of the tools are presented in this appendix.

A.1. Initiate Study Tool HS1: Bank of questions.

The bank of questions is the main tool proposed in Stage 1, Activity 1. As shown in Table 29, new questions address system structure, societal influences and rules, and expanded prompts on behaviours and interactions. Most original PartiSim questions were retained, especially those concerning the problem situation and potential improvements.

In addition to revising the Bank of Questions, this study proposes an ideal sequence for using each group of questions. Early interactions often involve a small number of key stakeholders who may hold strong views about the problem. Beginning with problem-focused questions could therefore bias the modelling team’s initial understanding. To protect the exploratory nature of this stage, the order in which the questions from Table 29 are used is important.

Initial informal meetings should concentrate on the system itself, using the first three groups of questions in Table 29. Questions about the problematic situation and potential improvements should be left until later. This approach helps modellers form an overarching view of the system, from macro to micro levels, before examining specific issues.

Table 29: Initiate Study Tool HS1: Bank of questions.

Aspects to understand	A sample of potential questions
System structure	What are the services or institutions that compound the system? How many types of services are provided?

Aspects to understand	A sample of potential questions
(network of services)	<p>What are the interactions (links) between those services?</p> <p>What are the impacts of those interactions in operation?</p>
Operational	<p>Does this network of services work well?</p> <p>Which operation plays an essential role in the system?</p> <p>On a typical day, what is the progression of activities followed?</p> <p>Whom does the system serve?</p> <p>Who is involved in the provision of service?</p> <p>Who is affected?</p> <p>Who makes decisions?</p>
People and roles	<p>Who would object to change?</p> <p>Can you identify any people who would not be happy with changes?</p> <p>What decisions do the people make?</p> <p>What actions are being taken by the people served by the services?</p> <p>Do people served by the system change their behaviour due to their experience?</p>
Society and rules	<p>What are the rules or norms in the system?</p> <p>What external factors or forces impact the system?</p> <p>How do the norms and rules impact the problematic situation?</p> <p>What are the known problems in the system?</p> <p>What is the purpose of the current system?</p> <p>Are there any specific targets that need to be reached?</p>
Problem situation	<p>On a typical day, what is the progression of activities followed?</p> <p>Are there any bottlenecks?</p> <p>What do you think is the cause (of the bottlenecks)?</p> <p>How did the problematic situation originate?</p> <p>What are the specific questions the model (project) should answer?</p> <p>Is there room for improvement?</p>
Improvement	<p>Have improvements been proposed/explored so far? What are they?</p> <p>What was the goal of these improvements?</p> <p>Who proposed those improvements?</p> <p>What do you think could potentially improve the situation?</p> <p>Has a change been implemented in the past? What results did it have?</p>

A.2. Initiation Study Tool HS2 - Feasibility of hybrid simulation modelling and scope of the model for the first workshop.

This tool guides the modelling team in assessing the appropriateness of hybrid simulation methods to the problematic situation. The tool was structured as a table, displayed in Table 30, where key applications for each single simulation method are listed. In this table, key applications for each simulation method are listed. A previous study is provided in the third column as an illustrative example for each key application. It is worth mentioning that Table 30 is not an exhaustive list. Instead, it presents a known application discussed in the simulation literature, and it aims to be a first attempt to support modellers in identifying the simulation methods or methods to be used in the simulation project. In this tool, some recommended steps to use Table 30 are provided as follows:

Step 1: Analyse the information collected during Activity 1

For this task, the modelling team used the two tools to capture information in activity 1 - Initiate Study Tool 1: Situation of Interest, and the answers registered the questions in the Initiate Study Tool HS1: Bank of questions (THS1).

The first tool records preliminary problems and potential improvements or changes. In the system, according to the stakeholders' view. At this stage, preliminary problems do not refer to the main problem in the simulation study. Instead, it refers to potential problems listed by stakeholders after exploring the questions in the "Problem situation" aspect of the bank of questions.

Step 2: Evaluate each problem and potential changes identified in Activity 1

For each preliminary problem, the modelling team should use Table 30 to confirm the appropriate simulation method or methods to represent it. Using the key applications in Table 30, the modelling team should find similarities between the potential problems and changes for the problematic situation and those listed in Table 30.

Table 30 summarises the topics commonly explored by each simulation method in healthcare. More than one topic should be considered within each simulation method and across the three methods. Like in PartiSim, this research also suggests complementing the analysis with Table 12 with information about the study's stakeholder expectations, resources, and time availability.

Step 3: Discuss the findings with the whole modelling group.

Discussing findings about the most appropriate simulation method for each potential problem with the entire group is essential for several reasons. It ensures a comprehensive understanding of the complexities and nuances of each problem, as different team members may have unique insights and expertise. This collaborative approach fosters diverse perspectives. Additionally, it enhances transparency and buy-in, as the whole modelling team is involved in the decision-making process, ensuring that the chosen simulation methods are well-understood and supported by the whole team. This collective evaluation also helps identify any potential issues or limitations early on, allowing for adjustments and refinements to be made before implementation, ultimately improving the quality and success of the simulation project.

Table 30: Key applications of each simulation method in healthcare.

Method	Some of the key applications include	Examples (for reference)
DES	Patient Flow and Wait Times: DES helps analyse patient flow through various departments, identify bottlenecks, and suggest changes to reduce patient wait times and improve service delivery.	(Hossain, Debusk and Hasan 2017)
	Resource Allocation: By simulating different scenarios, ensuring that resources are used efficiently, reducing costs, and improving patient care.	(Bedoya-Valencia and Kirac 2016)
	Operational Efficiency: DES models can evaluate the impact of changes in operational procedures, such as new admission processes or scheduling, on overall hospital efficiency.	(Troncoso-Palacio <i>et al.</i> 2018)
	Emergency Response Planning: DES helps plan resource needs, triage procedures, and response strategies to handle high patient influxes effectively.	(Carmen, Defraeye and Van Nieuwenhuyse 2015)
	Cost-effectiveness Analysis: DES can simulate different treatment pathways to assess cost-effectiveness.	(Stahl <i>et al.</i> 2004)
	Capacity Planning: DES can support the plan for future capacity needs based on projected patient demand.	(Ferraro <i>et al.</i> 2015)
	Staff Scheduling: DES helps create optimal schedules that align with patient demand patterns.	(Singla 2020)
SD	Epidemic and Pandemic Policies: SD simulates the spread of infectious diseases, helping to understand the impact of various interventions such as vaccination, quarantine, and social distancing. It aids in planning and response strategies for controlling disease outbreaks.	(Kou and Yang 2023)
	Chronic Disease Management: SD models the progression and management of chronic diseases like diabetes, hypertension, and obesity. It helps understand the long-term effects of different interventions, policies, and patient behaviours on disease prevalence and healthcare costs.	(Kang <i>et al.</i> 2018)
	Healthcare Policy Analysis: SD is used to analyse the potential impacts of healthcare policies, such as changes in insurance coverage, funding allocations, and regulatory changes.	(Atkinson <i>et al.</i> 2015)
	Behavioural Health Interventions: SD is used to understand the impact of behavioural health interventions, such as smoking cessation, diet, and exercise programmes. It helps design effective interventions and predict their long-term outcomes on population health.	(Selya 2021)

Method	Some of the key applications include	Examples (for reference)
	Financial Sustainability: SD helps in analysing strategic financial planning and risk management.	(Kurnianingtyas, Santosa and Siswanto 2020)
	Integration of Care Services: SD models the integration of various healthcare services, such as primary, secondary, and tertiary care, to improve coordination and continuity of care.	(Rashwan, Abo-Hamad and Arisha 2015)
ABS	Disease Spread and Epidemic Modelling: ABS simulates the spread of infectious diseases by modelling individual behaviours and interactions. It helps understand how different factors, such as social behaviour, mobility patterns, and public health interventions, impact the spread of diseases like influenza, COVID-19, and others.	(Aleman, Wibisono and Schwartz 2011)
	Patient Behaviour and Decision Making: ABS models individual patient behaviours and decision-making processes, such as adherence to medication, lifestyle choices, and responses to health interventions.	(Knight, Williams and Reynolds 2012)
	Healthcare Workforce Dynamics: ABS can simulate the behaviours and interactions of healthcare workers, including job satisfaction, burnout, and workforce mobility. It helps understand workforce dynamics and planning strategies to improve retention and productivity.	(Duggirala <i>et al.</i> 2016)
	Chronic Disease Management: ABS models the long-term management of chronic diseases by simulating patient interactions with healthcare providers, adherence to treatment plans, and the progression of diseases.	(Nianogo and Arah 2015)
	Health Behaviour Interventions: ABS is used to study the effects of interventions aimed at changing health behaviours, such as smoking cessation, diet, and exercise programmes, and their impact on individual health status.	(Stephenson <i>et al.</i> 2020)
	Social Determinants of Health: ABS can incorporate social determinants of health, such as socioeconomic status, education, and environment, to study their impact on health outcomes.	(Starr and Kain 2022)

Step 4: Define the scope of the study.

After defining the simulation approach, the modelling team establishes the model's scope, part of activity 3. This initial scope, or briefing scope, provides a realistic assessment of the current healthcare system rather than defining the specific problem for the study. Its main goal is to conduct a situational analysis of the complex system, aiding the team in preparing tools and dynamics for the first facilitated workshop. The scope may include (1) a summary of stakeholder discussions, (2) an assessment of the current system's strengths and weaknesses, (3) a description of the geographical coverage and involved decision-makers, and (4) a stakeholder map. There are no specific tools and instructions for defining the scope, and the suggestions above could be used as a guide.

A.3. Conceptual Modelling Tool HS4: HS Inputs Form (THS4)

This tool, displayed in Table 31, was designed to record the findings gathered during the facilitated workshop. It was structured as a form to be used by the modelling team.

Questions are organised into each level of analysis as displayed in the third column in Table 31. The first column indicates the name of the elements to be explored. The subsequent column refers to the CATWOE element to which the questions pertain. In contrast, the fourth column should be completed with the information gathered during the facilitated workshop for the respective question.

It is worth mentioning that the second column has the initial of the elements in CATWOE as follows: C = Clients or Customers (equivalent to patients in healthcare systems), A = Actors or Staff or People who work in the system, O = Owner or Decision-makers, and E = Environment. The pair of CATWOE elements in analysis three indicates the interaction between the respective elements. For instance, O-C refers to the interaction between Owner or Decision-makers and Clients (or Patients). The respective question will gather information about this relationship.

Table 31: Input form- Analysis One Two Three for hybrid simulation

Elements ABS/DES	CATWO E	Key questions used in the workshop	Answers:
Analysis One			
Agents	C	Who are the clients (or beneficiaries) in the system?	
	O	Who are the decision-makers in the system?	
	A	Who are the people working in the system?	
Entities	E	What are the services or institutions in this system?	
	E	How do these services influence each other (positively and negatively)?	
	E	Which services are involved in the problematic situation?	
Analysis Two			
Agent behaviours and attributes	C	What are the clients' behaviours of interest?	
	O	What decision-makers' behaviours are of interest?	
	A	What are the behaviours of interest of staff (in the system)?	
	O	What decisions do the decision-makers in the system make?	
	A	What decisions do staff in the system make?	
	C	What decisions do the clients make?	
	C	What actions are being taken by clients?	
	O	What actions are being taken by decision-makers?	
Environment attributes	O	What actions are being taken by people working in the system?	
	E	What are the main changeable characteristics of the environment?	
	E	How is the system regulated? (e.g., Metrics and KPIs)	
E	How often do the regulations change?		
Analysis Three			
Interaction between elements in the system	O-C	Where and how does the interaction happen between Clients and decision-makers?	
	A-C	Where and how does the interaction between clients and staff happen in the system?	
	O-A	Where and how does the interaction happen between Decision makers and staff in the system?	
	C-A	What would cause a change in the client's behaviour from interactions with staff in the system?	
	C-O	From interactions with clients, what would cause a change in the decision-maker's behaviour?	
	C-A	From interactions between decision-makers, what would cause a change in the staff's behaviour?	
Interaction between elements and the environment	C-E	What are the interactions between clients and the environment?	
	O-E	What are the interactions between decision-makers and the environment?	
	A-E	What are the interactions between those who work in the system and the environment?	
	E-C	What changes can the environment cause in the client's behaviour?	
	E-O	What changes can the environment cause in the decision-makers?	
	E-A	What changes can the environment cause in the staff's behaviour?	

The modelling team can utilise this form in the facilitated workshop to initiate the documentation of the system definition. Alternatively, it can be employed after the workshop, specifically during activity 1. It is imperative for the modelling team to thoroughly review this document and verify its accuracy by engaging with stakeholders during the subsequent activity.

A.4. Manual for Employing the Tool HS3: Tips for Developing a Rich Picture

This manual aims to guide the development of a rich picture. A Rich Picture (RP) is a system thinking tool that assists in understanding complex systems (Conte and Davidson 2020; Lewis 1992). It captures how stakeholders see a situation at a particular time (Kotiadis and Robinson 2008).

RP diagrams are widely recognised as a commonly used tool by analysts in the initial phases of an investigation to aid in comprehending a problem (Hindle and Franco 2009). Despite being one of the most memorable and reusable tools in SSM, there is still a lack of clear guidelines for producing RPs and no requirements for analysing the after-picture (Sensuse, Gandhi and Sucahyo 2019; Berg, Bell and Morse 2019). Given the gap in the literature for rich pictures, this manual aims to summarise a few tips on developing a rich picture and offer further guidance for an efficient session using this SSM tool. Drawing from previous studies (De Pinho 2017), the following four recommendations are provided to aid facilitators in guiding a group of stakeholders towards creating a comprehensive visual representation.

1. Represent the situation and not the problem.

A Rich Picture provides a comprehensive overview of a problem's context, highlighting the representation of the entire system rather than solely focusing on the issue. By concentrating solely on the problem, the modelling team may overlook the intricacies of the scenario. To guarantee the accuracy of the Rich Picture in reflecting the situation, the facilitator should ask the group questions, such as: "Does the rich picture truly depict the situation, or is it merely my

subjective interpretation of the problem?". It is essential to confirm whether the depiction truly captures the situation or is merely a subjective interpretation of the problem.

2. Avoid wordiness.

An abundance of words can diminish the rich picture. Excessive use of words can hinder the analysis of the various elements within a system and their interactions. Consequently, lengthy texts placed over the diagram can impede the identification of patterns. To avoid this, the facilitator should check whether the ongoing representation requires extensive reading to perceive the relationships between elements depicted in the picture. If this is the case, the facilitator should encourage the group to rely on pictures rather than words.

3. The rich picture reflects the view of a group.

One of the benefits of a rich picture is to engage a group of multiple authors in building a shared view of a system or process. The facilitator should encourage all participants to share their opinions by reminding the group that there is no right or wrong answer. The facilitator should be aware of possible conflicts and manage them to keep the group focused on building a rich picture. During the session, the facilitator should confirm whether the rich picture represents a singular narrative or many narratives regarding the situation.

4. Use of a bank of pictures.

Some participants may experience constraints when illustrating the components of a system. To address this issue, it is recommended to utilise a collection of images, as demonstrated below. The moderator can explore various visuals from public databases and have them printed before the session.

Figure 30 displays a few examples of healthcare-related images that could be part of the image bank. Examples include images of home care, community services, and hospitals that could be incorporated into a session involving the creation of detailed illustrations. These images should

be accessible to all participants throughout the activity. The facilitator guides the stakeholders to choose the images that best represent their perspective of the system. Ultimately, the moderator ensures that all participants agree on the chosen representations.



Figure 30: Examples of images for a bank of pictures.

A.5. Manual for Conceptual Modelling: Identifying the Measurement in the HS Model.

This manual guides on identifying performance measurements for a DES-ABS hybrid simulation. It is designed to help facilitators understand potential measures for Agent-Based Simulation (ABS) that may be discussed during the measurement identification process in Activity 3. It builds on the initial step outlined in the PartiSim Manual for Conceptual Modelling Tool 3: Drawing the Performance Measurement (Tako and Kotiadis 2021; Tako and Kotiadis 2018a; Tako and Kotiadis 2018b). It offers additional guidance on identifying measurements related to agents within the system.

In a DES-ABS model, two types of measurements should be distinguished - performance and behaviour measurements. Key performance indicators (KPIs) or performance measures are appropriate for measuring the activities of health facilities in the care system (Tako and Kotiadis

2018b; Kotiadis 2007). Behaviour measurement or population measurement refers to metrics used to assess the population.

Based on Bateson and Martin (2021), this research proposes four types of behaviour measurements: latency, frequency, duration, and intensity. Latency refers to the time it takes for a behaviour to occur after a specific stimulus or event, providing insights into reaction times and promptness. Frequency measures how often a behaviour occurs within a given time frame, helping to understand action patterns and trends. Duration focuses on the length of time a behaviour lasts, offering data on the persistence and consistency of the activity. Intensity assesses the strength or magnitude of the behaviour, capturing the degree of force or effort involved.

For each type of behaviour measurement, Table 32 shows examples of possible KPIs in healthcare based on the concepts in Bateson and Martin (2021). While column one presents the four types of measures in Bateson and Martin (2021), the second column lists a few examples based on the literature in ABS reviewed in this research, as references in column 3.

The following paragraphs provide a comprehensive guide on how the facilitator should identify measurements for DES and ABS during the workshop they are facilitating.

Identifying measurements begins with the facilitator explaining the definitions of performance measures and behaviour or population measures. According to PartiSim (Tako and Kotiadis 2018a), providing preliminary materials can support stakeholders in discussing these performance measures.

First, the facilitator identifies KPIs or performance measurements relevant to the DES module. It can be helpful for the group to consider performance measurements related to service operations. The stakeholder team is expected to identify performance measures associated with the system designed during Activity 1 (Section 5.7.1).

Table 32: Examples of types of behaviour measurements

Type of measure	Example of measurements	Reference (examples)
Latency	<p>Reaction Time of Symptoms (time between a patient reporting a symptom and the initiation of a disease)</p> <p>Response to medication (time between taking medication and the onset of its effects)</p> <p>Cognitive response time (the time it takes for older people to respond to cognitive tests)</p>	<p>(Perez and Dragicevic 2009)</p> <p>(Chen et al. 2019)</p> <p>(Wirzberger et al. 2019; Paúl, Ribeiro and Teixeira 2012)</p>
Frequency	<p>Frequency of falls</p> <p>Medication Adherence (The number of times a patient correctly follows their prescribed medication routine)</p> <p>Social Interaction (The number of social interactions or activities an elderly patient engages in, which can reflect social well-being, mental health, and the potential for isolation)</p> <p>Healthcare visits (The number of visits an elderly patient makes to healthcare providers)</p>	<p>(Du et al. 2020; WHO 2015)</p> <p>(Chalk et al. 2017)</p> <p>(Lee and Lee 2020)</p> <p>(Ma, Shen and Nguyen 2016)</p>
Duration	<p>Duration of therapy sessions or treatment</p> <p>Duration of medication effectiveness</p> <p>Duration of Assistance Needed: The length of time an elderly patient requires assistance with daily living (ADLs), such as bathing, dressing, or grooming, reflecting functional status and independence.</p> <p>Duration mobility challenges: The period an older patient has trouble with mobility or walking can indicate changes in strength, balance, and risk of falls.</p>	<p>(Codella et al. 2015)</p> <p>(Berg et al. 2021)</p> <p>(García-Vázquez et al. 2010)</p> <p>(Podsiadlo and Richardson 1991)</p>
Intensity	<p>Severity of symptoms or adverse health condition</p> <p>Severity of functional limitations</p> <p>Intensity of Physical or Emotional Symptoms</p>	<p>(Abdulkareem et al. 2018)</p> <p>(Hermsen et al. 2014; Veloso 2013)</p> <p>(Meilstrup et al. 2015)</p>

Next, the group discusses possible behaviour measurements for the ABS modules. The facilitator guides the discussion using the model representation from Activity 1 (Section 5.7.1), highlighting the states and querying the behaviours identified in the previous workshop. The focus is on potential measures for quantifying these behaviours. Examples from Table 32 may be used to support this step.

Depending on the group's engagement in this activity, further performance measurement discussions might occur after the workshop with stakeholders. As suggested in PartiSim, two other activities are proposed to create a Performance Measurement Model (PMM). Further guidance on conducting both activities can be found in the Manual for Conceptual Modelling Tool 3: Drawing the Performance Measurement Model in PartiSim Toolset 3 (Tako and Kotiadis 2018b).

Appendix B - Outputs from applying the proposed framework in Brazil.

This appendix presents the outputs generated from applying the proposed framework in the Brazilian case study. It documents the results from selected activities undertaken during the early stages of the study, with a particular focus on problem understanding, stakeholder engagement, and initial scoping for hybrid simulation modelling. The material included provides supporting evidence for the feasibility assessment, captures stakeholder perspectives, and records the decisions and artefacts produced during workshops and preparatory activities, and serves as a complementary material to discussions in Chapter 6.

B.1. Stage 1 - Initiate study: Activity 1 - Understand the problem situation.

Below are the answers to the questions asked of stakeholders during the informal meetings as part of activity 1 in stage 1.

Aspects of understanding: System structure (network of services)	
What are the services or institutions that compound the system? How many types of services are provided?	Santo Amaro and Cidade Ademar have social and healthcare facilities following the guidelines of the municipality. Twenty-six primary care centres (UBSs), one secondary care for the whole population (AME), one secondary care exclusive for the older population (URSI), and one hospital.
What are the interactions (links) between those services?	Patients are referred to secondary care after assessing primary care. Patients cannot access other services without a referral from primary care.
Does this network of services work well?	Yes and no. Primary care provides care to all individuals residing or working in the area. It works well, but patients might not get an appointment on the day they want it. Patients might wait a month to have an appointment with clinicians. Secondary care is limited and critical. The waiting list for AME is between 6 and 12 months.
Aspects of understanding: Operation	
Which operation plays an essential role in the system?	Primary care centres. Patients are never discharged from this care; they are discharged only when they die.
On a typical day, what is the progression of activities followed?	Walk-in patients and booked patients go to primary care centres. Reception controls the flow of patients. Mondays are usually a quiet day.
Aspects of understanding: People and roles	

Whom does the system serve?	All individuals living and residing in Santo Amaro and Cidade Ademar.
Who is involved in the provision of service?	Clinicians, nurses, Community Health Workers (CGW), Nutritionists, Paediatricians, and Geriatric doctors. All medical specialities, if I consider them primary to tertiary care,
Who is affected?	It depends. The population is affected by the service we offer. However, we are affected by the decisions made by the Municipal Health Department, which is affected by the decisions made by the Brazilian Health Ministry.
Who makes decisions?	Each health centre has a manager who coordinates the day-to-day operations. They report to INTS, and INTS reports to the Municipal Health Department. The latter makes the decisions. All decisions are in the Strategic Plan.
Who would object to change?	The Municipal Health Department needs to approve all changes.
Can you identify any people who would not be happy with changes?	The population might not be happy. For example, when we reduce the agenda of some doctors or a professional is moved from the health centre, the patients complain. Any change needs to be improved in our KPIs. Otherwise, the Municipal Health Department might cut off part of our budget.
What decisions do the people make?	Managers decide the capacity and agenda in the health centres. The INTS make decisions according to the Strategic Plan.
What actions are being taken by the people in the system?	It was not covered during the informal meetings.
Do people served (patients) by the system might change their behaviour due to their experience?	Patients have the free will to follow the prescribed treatment or not. Healthcare staff cannot control what patients will do after receiving the care. Some will not return or will return when their health condition deteriorates. Sometimes, it will be too late, and they will be referred to the hospital. Some of them might wait too long to have hospital care. Some will receive care and will improve their health status.
Aspects of understanding: Rules and regulations	
What are the rules or norms in the system?	Constitution of 1988 and Pact for Life (Pacto pela Vida, in Portuguese), Strategic Plan, and guidelines for all services.
How do the norms and rules impact the problematic situation?	It was not covered during the informal meetings.
Aspects of understanding: Problem situation	
What are the problems in this system?	The patient records information system was not implemented in SACA. There is a high turnover of some specialities. Some healthcare centres cannot be expanded (lack of investments), some healthcare centre locations are not attractive to hire medical staff, geriatric doctors are an issue nationwide, there are many regulations, but many have not been implemented. Health staff lack training in how to provide care to older people. Telemedicine

	has been implemented during COVID-19, but 3G is an issue in many areas in SACA. Also, some people cannot afford to have a computer or a mobile device with the proper conditions to receive a call from doctors. Some healthcare centres also face issues with connectivity.
What is the purpose of the current system?	Provide care to individuals as per the Constitution of 1988 - universality, equity, and integrity.
Are there any specific targets that need to be reached?	We have the KPIs that the Municipal Health Department set in the Strategic Plan.
Are there any bottlenecks?	It depends. Secondary care (AME) includes some specialities such as Rheumatology. URSI has only two geriatric doctors. This speciality is a problem in Brazil.
What do you think is the cause?	For URSI. The interest of new doctors is in becoming geriatric doctors. For other specialities, I believe the difficulty in finding professionals is related to the location of the health centres in this area. Many centres are in slums, with high levels of violence.
How did the problematic situation originate?	It was not covered during the informal meetings.
What are the specific questions the model (project) should answer?	A solution to increase the capacity of services at a reduced cost. Telemedicine has been used during COVID-19. It might help the health centres in their triage. Some patients need a prescription, for example. They do not need to come to health centres.
Aspects of understanding: Improvement	
Is there room for improvement?	Yes, but it needs approval. The Municipal Health Department has to approve. In some cases, for political reasons, it will need to wait. For example, we have a project implementing a system with all patient records. This project has been on hold for more than five years. There is no budget, according to the Municipal Health Department.
What do you think could potentially improve the situation?	For older people? Better social care, review of social policies. However, this action involves political spheres at a national level. For INTS, we can make changes in the operation. Try to improve the services we offer. Small changes might benefit the population.
Have changes been implemented in the past? What results did it have?	Yes. All changes are connected to the Strategic plan. For example, the Family Health Strategy (FHS) can be implemented in UBSSs. With the work of Community Health Workers (CGW), we (INTS), together with the health centre managers, can have more information about the health profile in the UBS coverage area. It helps us in our monthly plan, and the population feel the improvement in their health condition, reduces absenteeism, etc.

B.2. Stage 1 - Initiate study: Activity 1 - Initiate Study Tool 4 - List of reading materials

Below is the list of reading materials read during the run of activity one - understanding the problematic situation.

Material	Material type	Material Suggested by	Material to be read by
Retrato da pessoa idosa na cidade de São Paulo (overview of older people in Sao Paulo)	Council report released to the media	Stakeholder 02	Modeller
Documento Norteador Unidade de Referencia a Saude do Idoso URSI (Guidelines released by the Municipal Health Secretary)	Guidelines / Policies	Stakeholder 02	Modeller
Prefeitura de Sao Paulo - informativo ao public (Sao Paulo Council website)	Website	Stakeholder 02	Modeller
The Brazilian health system: history, advances, and challenges	Book	Stakeholder 02	Modeller
Brazil's Family Health Strategy: Using Community Health Care Workers to Provide Primary Care	Article	Stakeholder 02	Modeller
Telemedicina: Como funciona? Sera que serve para voce? (Telemedicine: Does it work? Will it be applied to your necessity?)	Webinar	Stakeholder 01	Modeller
Telemedicine: challenges to dissemination in Brazil	Article	Stakeholder 03	Modeller
The Third National Telemedicine & Telehealth Service Provider Showcase Conference: Advancing Telehealth Partnerships	Article	Stakeholder 03	Modeller
URSI guidelines ("Documento Norteador URSI")	Article	Stakeholder 04	Modeller
Diretrizes Operacionais - UBS Unidade Basica de Saude	Article	Stakeholder 04	Modeller
AMA Especialidades Diretrizes Tecnicas	Article	Stakeholder 04	Modeller
Wachs, L.S., Nunes, B.P., Soares, M.U., Facchini, L.A. and Thumé, E., 2016. Prevalência da assistência domiciliar prestada à população idosa brasileira e fatores associados. Cadernos de Saúde Pública, 32, p. e00048515.	Article	Stakeholder 02	Modeller

Material	Material type	Material Suggested by	Material to be read by
Lima-Costa, M.F., de Andrade, F.B., Souza, P.R.B.D., Neri, A.L., Duarte, Y.A.D.O., Castro-Costa, E. and de Oliveira, C., 2018. The Brazilian longitudinal study of ageing (ELSI-Brazil): objectives and design. American Journal of Epidemiology, 187(7), pp.1345-1353.	Article	Stakeholder 02	Modeller
Strategic Plan 2022-25 (Planejamento Estrategico Construindo o Plano Municipal de Saude - PMS 2022-25)	Report	Stakeholder 01	Modeller

B.3. Stage 1 - Initiate study: Activity 3 - Scope for the first facilitated workshop.

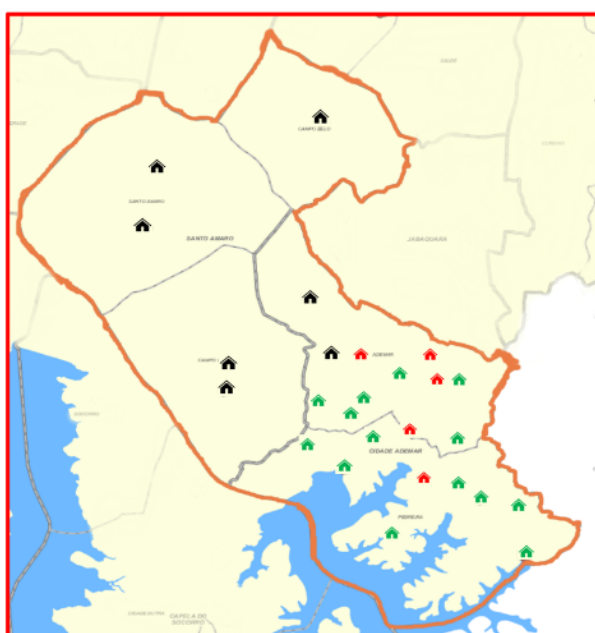
The following paragraphs bring the scope agreed upon for the first facilitated workshop, based on the information discussed during the informal online meetings and validated with stakeholders.

(1) Summary of all topics discussed with stakeholders during the initial stage (e.g., problematic situation, possible solutions)
<p>Agreements:</p> <ul style="list-style-type: none"> • The discussions in the first workshop will be limited to the healthcare system in Santo Amaro and Cidade Ademar (SACA). • Topics discussed were summarised in the document “Initiate Tool 1 - Situation of Interest” as potential problems and solutions to the health care system in SACA. This document includes the content discussed in the three informal online meetings via Zoom and content extracted from the reading of materials suggested by stakeholders. • Potential problems to be discussed in the workshop - Problems 2 to 5 and their respective potential improvements 2 to 5. • Not included in the scope: potential problem 1 (Limited capacity in long-term care centres). Stakeholders agreed that this topic should be discussed in a strategic forum with the involvement of authorities and representatives of other districts in São Paulo.
(2) Highlighting topics - Strengths and Weaknesses of healthcare in SACA
<ul style="list-style-type: none"> • The structure of primary care is designed to provide care to all individuals (walk-in or booked). Every individual seeking care will be attended to by a health professional in a 15-minute welcome appointment. Nobody leaves the health centre without care. • All national health policies have been in force in SACA. However, many services have limited capacity. For example, home care and secondary care for older people. Teams are reduced, and physical structure is restricted. In certain instances, the expansion of services requires the relocation of the centre to a different site. • Patient records are not automated, and the data management is in Excel. Each health centre used a different Excel. There is a lack of standardisation.

- Santo Amaro has only traditional health centres.
- The population in Santo Amaro has better social indexes than Cidade Ademar
- Cidade Ademar faces several social issues. One healthcare centre attends to people with good incomes and those living in houses without basic sanitation.
- Many health centres in Cidade Ademar are in areas with a high violence index.
- In Cidade Ademar, telephone reception is restricted. Some health centres face difficulties in using telemedicine during COVID-19.
- The demand for geriatric doctors has increased, but this profession is lacking in Brazil.
- There is a lack of geriatric training for all professionals in SUS.

(3) Descriptive of the geographical coverage

The area has 26 primary care centres (UBS), one secondary care centre for the whole population (AMA-E), one secondary care centre for older people (URSI), and one hospital. Below is the map with the 26 primary care centres.



Three types of Health Centres - Cidade Ademar & Santo Amaro

- 🏠 AMA/ UBS Integrada
- 🏠 Traditional
- 🏠 UBS com eSF

Borough	Neighbourhood	Address
1	CIDADE ADEMAR	V FILOMENA JD LUMARAMA UBS
2	CIDADE ADEMAR	JD NITEROI JD NITEROI UBS*
3	CIDADE ADEMAR	V CONSTANCIA UBS VICENTE O. OLIVEIRA
4	CIDADE ADEMAR	JD DOMITILA UBS SAO JORGE - CIDADE ADEMAR*
5	CIDADE ADEMAR	V JOANDA V JOANDA-AMA UBS INTEGRADA
6	CIDADE ADEMAR	J SAO CARLOS JD SAO CARLOS-CID ADEMAR-UBS*
7	CIDADE ADEMAR	AMERICANOPOLIS V IMPERIO II - UBS GILDA TERA TAHIRA*
8	CIDADE ADEMAR	AMERICANOPOLIS V IMPERIO - AMA/UBS INTEGRADA
9	CIDADE ADEMAR	V MISSIONARIA V MISSIONARIA-AMA/UBS INTEGRADA
10	CIDADE ADEMAR	JD MIRIAM JD MIRIAM-AMA/UBS INTEGRADA MANOEL S. OLIVEIRA
11	CIDADE ADEMAR	CIDADE JULIA CIDADE JULIA-UBS*
12	CIDADE ADEMAR	JARDIM PRUDENCIA UBS JARDIM MIRIAM II*
13	CIDADE ADEMAR	ELDORADO V APARECIDA-UBS*
14	CIDADE ADEMAR	DALMEIDA *SAR PAULISTA MAR PAULISTA UBS*
15	CIDADE ADEMAR	JD SELMA JD SELMA - UBS (CIDADE ADEMAR) *
16	CIDADE ADEMAR	JD APURIA JD APURIA - UBS*
17	CIDADE ADEMAR	JD SANTA TEREZINHA FQ DOROTEIA - AMA/UBS INTEGRADA
18	CIDADE ADEMAR	JARDIM SANTA TEREZINHA JD NOVO PANTANAL - UBS JARDIM PANTANAL*
19	CIDADE ADEMAR	JD RUBILENE V GUACURU-UBS*
20	CIDADE ADEMAR	LARANHEIRAS LARANHEIRAS - UBS*
21	CIDADE ADEMAR	ELDORADO MATA VIRGEM-UBS*
22	SANTO AMARO	CAMPO BELLO MASSARI UCHARA (D. AEROPORTO)-UBS
23	SANTO AMARO	JD. ARAUJO ALMEIDA ARRIETE V ARRIETE-UBS DECIO P. PEDROSO
24	SANTO AMARO	CAMPO GRANDE CAMPO GRANDE - UBS
25	SANTO AMARO	SITO AMARO SANTO AMARO-UBS SERGIO V DRAGA
26	SANTO AMARO	CHACARA STO ANTONIO CHACARA STO ANTONIO-UBS

- AMA- E (Ambulatory Medical Assistance)
These are services characterised as specific units to provide care with consultants.
- URSI (Elderly Health Reference Unit) is located in Cidade Ademar.
Multidisciplinary care for older people.

Specialists in each health centre: UBS: doctors, nurses, nursing assistants, nutritionists, psychologists, social workers, physical educators, physiotherapists, dentists, and pharmacists.

URSI: physical educators, social workers, dentists, pharmacists, physiotherapists, psychologists, speech therapists, nursing assistants, occupational therapists, and public policy management. AMA-E: several specialists, such as cardiologists, rheumatologists, and orthopaedists.

(4) Map of all stakeholders involved in the situation or the system

- Individuals residing or working in the Santo Amaro and Cidade Ademar (all ages)
- Staff: Nurses, Clinicians, Consultants, Psychologists, Nutritionists
- Managers in UBSs, URSIs, INTS

- Municipal Health Department staff
- Sub-mayor in SACA

B.4. Substage 1a - Pre-workshop: Activity 2 - Identify the stakeholder team.

Table 33 provides a comprehensive list of the stakeholders, including their job titles, roles in the research, and the specific healthcare sector (private or public) in which they are involved.

Table 33: Stakeholder team invited to the workshops.

ID	Job Title	Role	Healthcare sector
Stakeholder 01	Orthopaedist and medical coordinator	Key stakeholder	Private and Public care
Stakeholder 02	Physical educator (researcher in preventive medicine)	Project Champion	Private and Public care
Stakeholder 03	Rheumatologist (secondary care outpatient clinic)	Key stakeholder	Private and Public care
Stakeholder 04	Geriatrician and Director of Operations in SACA	Sponsor	Public care
Stakeholder 05	Nutritionist (self-employed working in care homes)	Other stakeholders	Private care
Stakeholder 06	Physical educator (researcher in public health)	Other stakeholders	Public care
Stakeholder 07	IT and Operations Manager in SACA	Key stakeholder	Public care
Stakeholder 08	Nurse (primary care) in SACA	Key stakeholder	Public care
Stakeholder 09	Community Health Agent	Key stakeholder	Public care
Stakeholder 10	Community Health Agent	Key stakeholder	Public care
Stakeholder 11	URSI manager	Key stakeholder	Public care
Stakeholder 12	Primary care clinic manager (Santo Amaro)	Key stakeholder	Public care
Stakeholder 13	Primary care clinic manager (Cidade Ademar)	Key stakeholder	Public care
Stakeholder 14	Coordinator Hospital Dia (public hospital)	Other stakeholders	Private and Public care
Stakeholder 15	Psychologist trainee	Recorder	Private care

B.5. Stage 2 - Define the problem (workshop): Activity 1 - Identify the main problem

Images taken during the workshops - Workshop 1



Figure 31: Images of the group during the problem definition brainstorming.

The table below summarises the answers from the participants in the brainstorming session for Activity 1.

Table 34: Outputs - Problem definition section

Brainstorm - problems faced by the SACA healthcare system with population ageing.
• Lack of professionals with qualifications to provide care to older people (no qualification in gerontology or geriatrics)
• Increase in demand for services in primary and secondary care (older people are likely to have several comorbidities - increase frequency at UBSs and require longer appointments)
• Lack of patient autonomy, which increases the demand for services (older people require more home visits and medical or nurse care)
• Finite resources (human resources and buildings or physical spaces) versus increasing demand for health services.
• Higher frequency of older adults in health services for walk-in or booked appointments (several comorbidities)
• The infrastructure of UBSs is not ready for older people (no age-friendly environments). For example, no SMS to remind of the appointment, and access to the building by staircase only.
• Poor or no internet signal in the Santo Amaro and Cidade Ademar areas. The patient cannot contact UBSs and vice versa.
• Limited infrastructure (most of the buildings are rented and were not primarily built for being a UBS. Hence, expansion of the physical space is not allowed or restricted)
• Lower autonomy of patients (associated with age group - “young-old or healthy older adults are less dependent)
• Growth of DCNT (non-communicable diseases) cases in the coming years due to ageing.
• Older adults demand longer appointments than other patients, but UBSs have limited resources (cannot increase service time because UBSs cannot hire more staff or expand -> because UBS cannot physically expand)

B.6. Stage 2 - Define the problem (workshop): Activity 1 - Identify the main problem

Table 35 contains the outcomes from the brainstorming session in workshop I, detailed in Chapter 6, Section 6.4.

Table 35: Brainstorm outputs for a brief definition of the study's objectives.

Brainstorm - Objectives of the study.
• Improve access to healthcare using teleconsultation.
• Improve access to healthcare.
• Increase health promotion in public health.
• Create means to prevent diseases.
• Improve cost-effectiveness.
• Cut current high costs to keep the health centres.
• Promote digital inclusion.
• Implement technologies to improve public health care.

B.7. Stage 2 - Define the problem (workshop): Activity 3 - Define the system and boundaries

Summarise the answers provided during the discussion about Transformation, as part of the first workshop discussed in Chapter 6, Section 6.4, and Figure 32 shows the preparation for the rich picture session with paper and pre-printed images.

Table 36: Transformations identified during the first workshop.

Brainstorm - Transformation (T)
SACA's older people need multidisciplinary health services in primary and secondary care, and these health services need to be met.
Health workers at SACA need a qualification in healthcare for older people à enhanced qualification.



Figure 32: Workstation for building a Rich Picture

Below are some pictures taken during workshop 1:

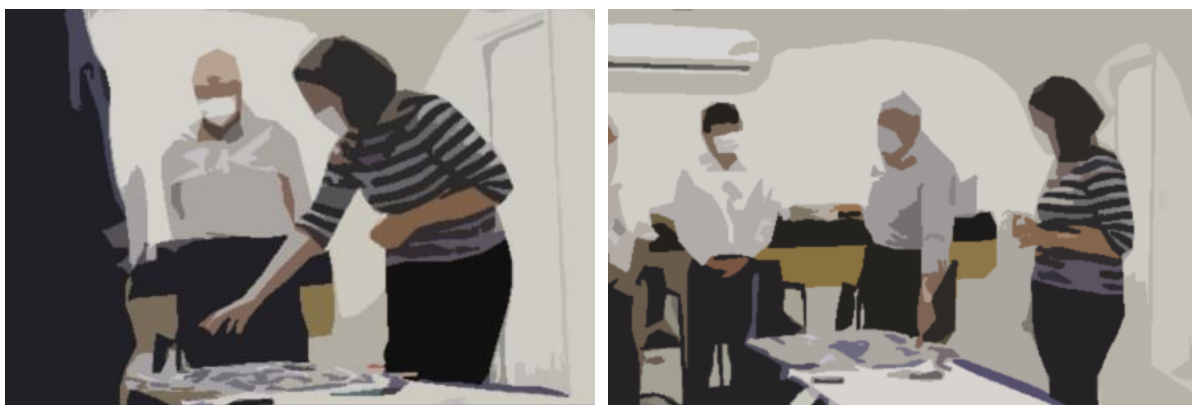


Figure 33: Images of the group during the development of the rich picture.

B.8. Stage 3 - Define Conceptual Model Workshop: Activity 1 - Draw the model representation

Below are some pictures taken during workshop 2:

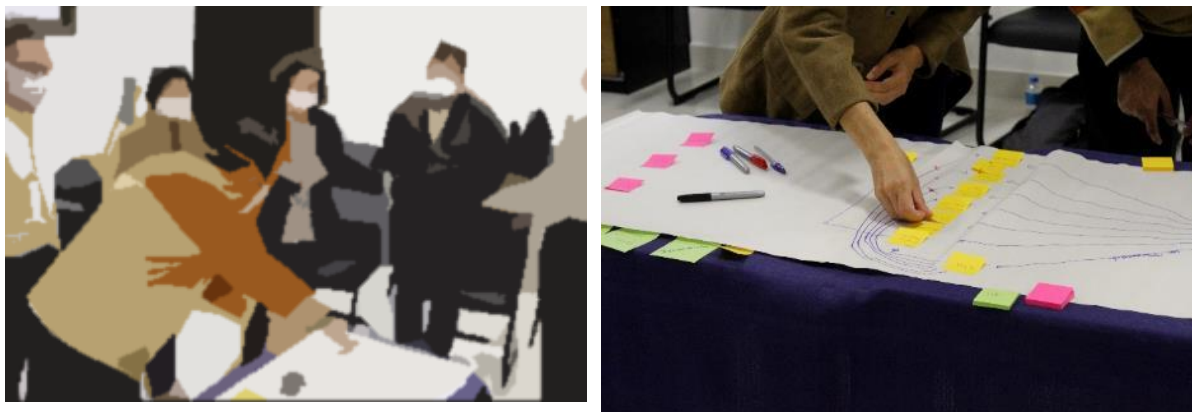


Figure 34: Images of the Workshop - developing a model representation.

B.9. Stage 3 - Define Conceptual Model Workshop: Activity 2 - Define performance measures

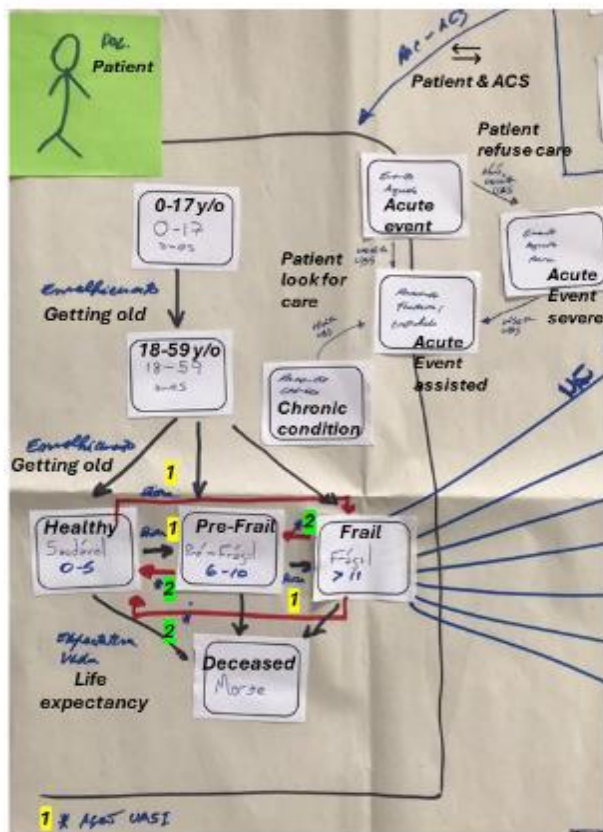
Below is the list of KPIs included in the preliminary material for Workshop 2. The KPIs below are in the Strategic Plan 2022-25, one of the materials shared with the modelling team during stage 1.

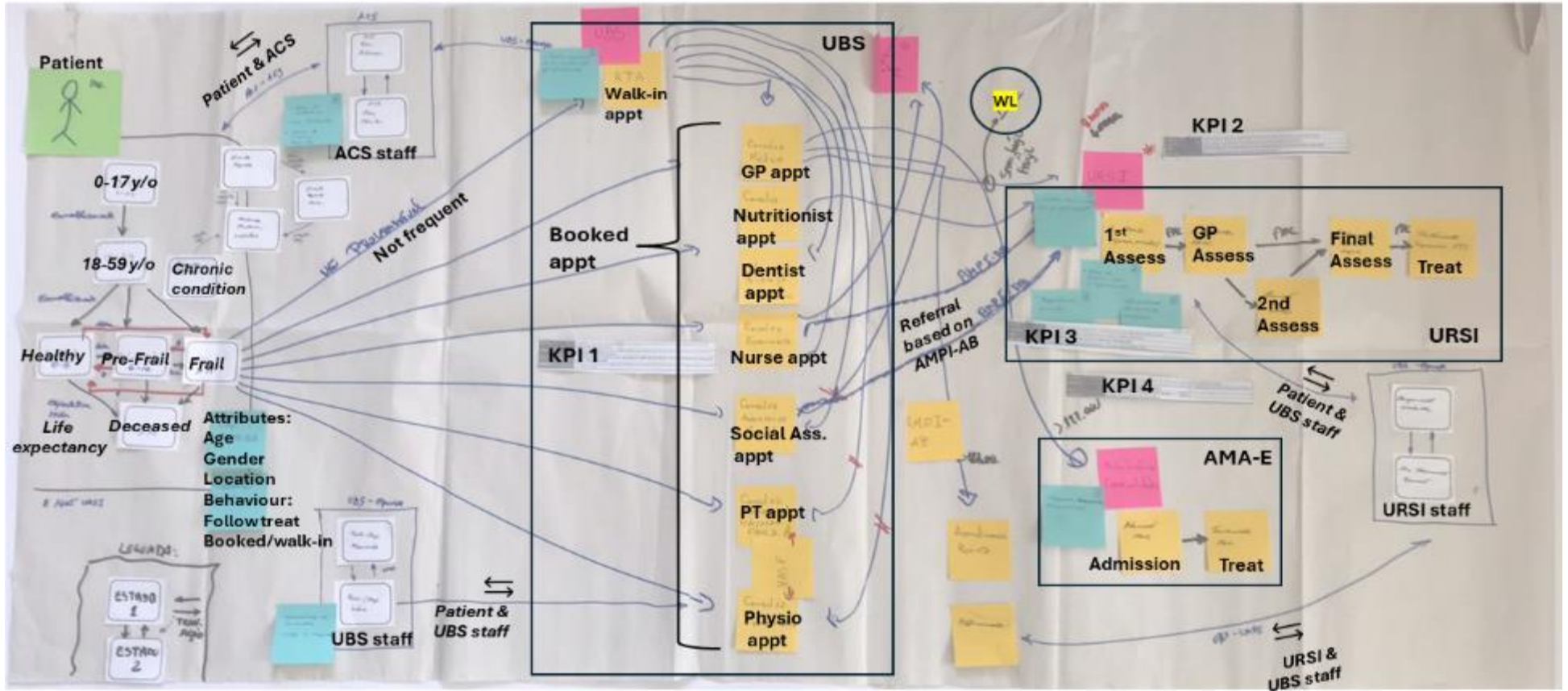
Table 37: List of KPIs selected by stakeholders during Workshop 2.

List of KPIs in the Strategic Plan 2022-25
% Number of appointments being assessed with AMPI-AB.
% URSI service coverage.
Average waiting time for being assessed by UBS (AMPI-AB).
Average Waiting Time for URSI.
Number of patients who completed their treatment at URSI per month
Number of referrals to URSI
Average Length of treatment at URSI.

B.10. Stage 3 - Define Conceptual Model Workshop: Activity 3 - Model representation with inputs and outputs

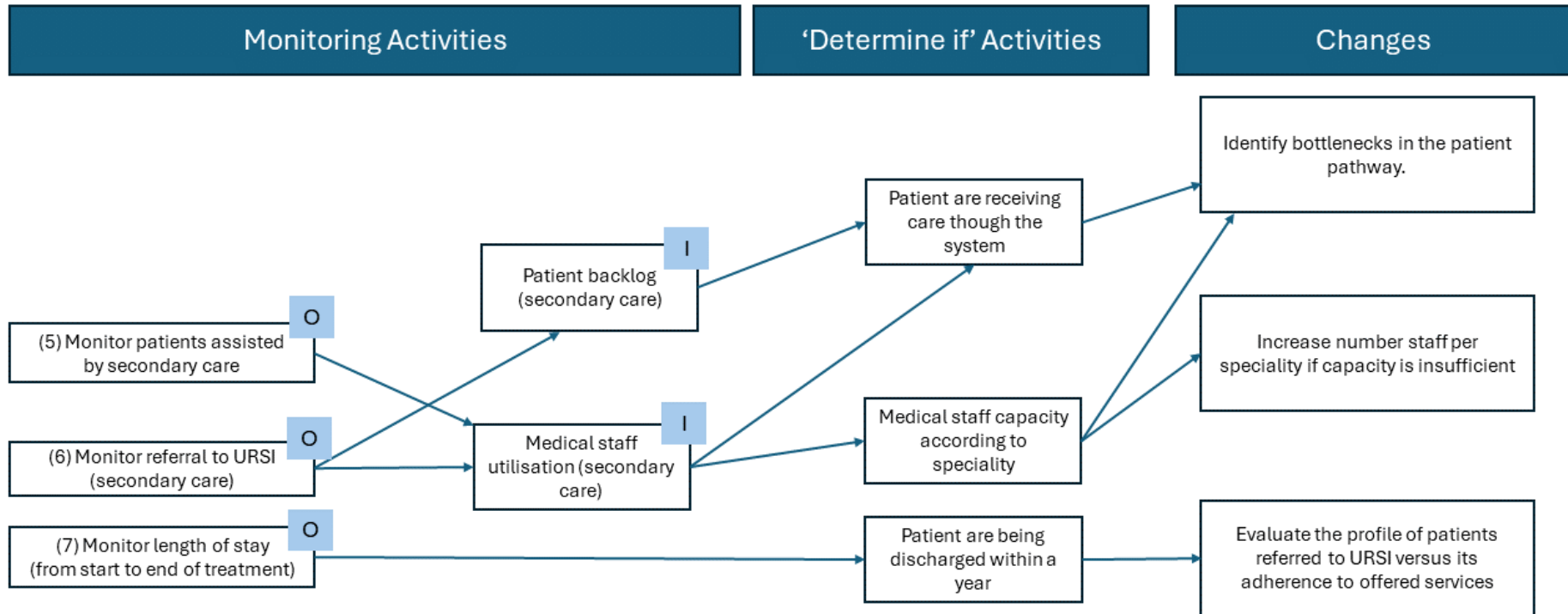
The image below shows the representation of the patient state chart developed during Activity 1 in Workshop 2.





B.11. Stage 3 - Define Conceptual Model Workshop: Performance Measurement Model (PMM)

Below is the PMM after the final PMM, which resulted from discussions and validation during the referred post-facilitated workshop meeting.



Appendix C - Outputs - Analysis One, Two, and Three from Workshops I and II

Tool HS3: Analysis one, two, and three for hybrid simulation			
Elements in DES-ABS	CATWO E elements	Key questions:	Answers
Analysis One			
Agents	C	Who are the clients (or beneficiaries) in the system?	The population who lives or works in the surrounding 26 health centres in the SACA region, with particular attention to the population over 60 years old.
	O	Who are the decision-makers in the system?	1) The São Paulo municipal health department set the policies and indicators for all São Paulo health centres. The INTS group supports the UBSs and URSI in implementing the rules and ensuring that the medical practices (e.g. correct application of vaccines) are well implemented and in use. 2) The manager in the health centres (UBS and URSI) coordinates the day-to-day activities, reports KPIs, and indicates the need for changes in the centre's operation.
	A	Who are the people working in the system?	1) Multi-disciplinary groups that work in the primary and secondary care services, offering care to the population. UBSs (primary care) have doctors, nurses, nursing assistants, nutritionists, psychologists, social workers, physical educators, physiotherapists, dentists, and pharmacists. In URSI (secondary care for older people), there are geriatricians, nurses, physical educators, social workers, dentists, pharmacists, physiotherapists, psychologists, speech therapists, nursing assistants, occupational therapists, and public policy management assistants. In AMA-E (outpatient clinics for secondary care), there are several specialists, such as cardiologists, rheumatologists, and orthopaedists. 2) ACS (Community Health Agents) are health agents who frequently visit the households, being the "eyes" of the UBSs in the community. They can advise patients about health care and bridge the gap between patients and UBSs/ eSF.
Entities	E	What are the services or institutions in this system?	The network of services in SACA encompasses hospitals, home care, UBS (primary care), URSI (secondary care), AMA-E (secondary care), care-given services (PAI), and UPAs (emergency care units), as well as social care.

Tool HS3: Analysis one, two, and three for hybrid simulation			
Elements in DES-ABS	CATWO E elements	Key questions:	Answers
	E	How do these services influence each other (positively and negatively)?	<p>1) To access secondary care, the patient needs a referral from a GP or nurse. Hence, patients who cannot access primary care cannot be referred to secondary care.</p> <p>2) URSI has limited capacity (one URSI to provide care to the old population in SACA). There is a waiting list for URSI. While the patient is waiting for care at URSI, they will likely visit UBSs more often.</p> <p>3) For care at URSIs - after being discharged from their treatment, the patient is referred to the UBS, where he/she is registered. Patients leave URSI with an appointment booked with her/his doctor at UBS.</p>
	E	Which services are involved in the problematic situation?	The services that are directly related to the problematic situation and are available in SACA are 26 UBSs (health centres for primary care), 1 URSI (secondary care) and 1 AME (secondary care).
Analysis Two			
Agent behaviours and attributes	C	What are the clients' behaviours of interest?	<p>1) Health status The population over 60 is classified according to their health status as independent, pre-frail, and frail. Each state dictates the frequency with which they access healthcare services (UBS and URSI) and which professional is demanded. When the patient is 60, he/she should have his/her health state assessed via AMPI-AB. Older people are likely to transition from one state to another; however, the pace is lower when they receive and follow the proper medical treatment. The pace is higher when they do not receive the treatment or get access but do not follow it.</p> <p>The population under 60 is also classified according to their health status as healthy or "with chronic conditions". Healthy patients look for healthcare services when they have an acute event. Patients with chronic conditions follow the annual protocol of at least one appointment with the doctor and one with the nurse. Also, they may have a home visit to the ACS, depending on how critical their health status is (stage 1, 2 or 3).</p> <p>Regardless of age, patients can develop an acute illness. Depending on its health stage, it will demand different levels of care from different health facilities.</p>

Tool HS3: Analysis one, two, and three for hybrid simulation			
Elements in DES-ABS	CATWO E elements	Key questions:	Answers
			<p>2) Adherence Patients can follow the treatment and attend the appointment (via booked or walk-in appointment) or decide not to look for healthcare services.</p> <p>3) Economic status (based on income range) The individual's social and economic conditions can aggravate their health status. Individuals with low income are likely to be the ones who financially support the whole family, have poor nutrition, and rely on public health exclusively for their care. They reduce their self-attention to their health status and do not follow the treatment most of the time. People with low income have their health conditions evolving quickly.</p>
	O	What decision-makers' behaviours are of interest?	<p>1) The municipal health department (SMS) set policies following the council's 4-year plan for health care in São Paulo. They release the 4-year plan, in which the strategic goals are set. Each plan has specific KPIs for each healthcare service in each region.</p> <p>2) Managers of UBSs control the occupancy rates of human resources. They can AGREE with occupancy and keep the same human resource structure, or can DISAGREE and decide to change it to accomplish the strategic goals.</p>
	A	What are the behaviours of interest of people working in the system?	<p>1) Multidisciplinary groups (e.g., doctors, nurses, psychologists, nutritionists, etc) attend to patients and offer treatment according to their health state, guidelines set that each patient has 15 minutes with doctors and nurses.</p> <p>2) In URSI: All professionals can be absent and unavailable as expected (absent). Each URSI has an absenteeism rate for each human resource or is available to attend to patients (during weekly opening hours).</p> <p>3) In UBS: They can be junior or senior health staff. Doctors and nurses can have experience (senior staff), provide the correct diagnosis, and not refer the patient to secondary care. Junior staff are likely to refer the patient to secondary care.</p>

Tool HS3: Analysis one, two, and three for hybrid simulation			
Elements in DES-ABS	CATWO E elements	Key questions:	Answers
	D	What decisions do the decision-makers in the system make?	<p>The health department (SMS) and the manager aim at a trade-off. They ensure that patients are getting the treatment. Managers need the minimum resources.</p> <p>1) SMS can approve the changes in the arrangement of services in UBSs when changes do not affect the 4-year municipal health plan goals.</p> <p>2) Managers of UBSs change the arrangement of health centres according to demand. For example, if the demand is low (the population does not need that service, --> service is cancelled). For instance, managers can make the profession redundant or reduce their weekly agenda if the region does not demand psychologists. Their decision is based on % occupation in the agenda.</p>
	A	What decisions do people working in the system make?	<p>1) The multi-disciplinary group attend to patients with or without booking an appointment. Depending on the patient's health status (e.g. frail), they can decide:</p> <ul style="list-style-type: none"> - If an appointment with a GP and the patient is pre-frail or frail, the doctor can refer him/her to a nurse or social worker at UBS for having his/her evaluation (AMPI-AB) and further referral to URSI (secondary care); - If an appointment with a GP and the patient is independent, the doctor can refer him/her to another professional in the UBSs (nurse, nutritionist) - preventive medicine/ health promotion protocol. - If an appointment with a nurse is needed, the patient can be referred to a GP or another health professional in the UBS or to URSI if their health state is classified as pre-frail or frail. - if an appointment with a GP and a patient is under 60 years old and has an acute event, the patient receives the treatment at UBS, or he/she is referred to AME. - If there is an appointment with a GP and a patient under 60 years old with a chronic condition, the patient receives the treatment at UBS following the periodic appointment with nurses and GPs or can be referred to an AMA-E. <p>2) In UBSs with ESF, the ACS visits the absent patient to check out the reasons for not attending the appointment and reschedule it. Their action affects absenteeism. UBS Traditional and UBS Integrated do not have ACS. Consequently, there is no</p>

Tool HS3: Analysis one, two, and three for hybrid simulation			
Elements in DES-ABS	CATWO Elements	Key questions:	Answers
			action to reschedule the patient. ACS also act when a patient does not attend their appointment at URSI.
	C	What decisions do the clients make?	<p>1) Patients decide to follow the treatment as the health staff indicates. If they do, there is an improvement in their health state. If not, they will keep the natural pace from the cycle or speed up the pace if they have a critical health condition without assistance (status: frail). For instance, independent older people over 60 years old who follow regular treatment are likely to keep this status for years or over the following decades and demand less access to health services.</p> <p>In the case of getting care from URSI, one reason for patients not attending the appointment is the location of URSI. URSI is located in a critical area for access by public transport.</p> <p>2) Patients may decide not to follow the treatment. Although the patients have an agenda of appointments over the years, they may not show up (overall absenteeism of 20% in the municipality).</p>
	C	What actions are being taken by clients?	<p>1) Patients visit the UBS (walk-in appointment) if they have an acute illness.</p> <p>2) Patients can book an appointment at the reception (with RTA) of UBSs or via an online platform.</p> <p>3) Patients with chronic conditions attend or do not attend their booked appointments with doctors or nurses.</p> <p>4) Patients visit the UBS and seek care with or are referred to another health professional, such as a nutritionist.</p> <p>5) Patients (who are monitored) may go for walk-in appointments in between booked appointments if they have an acute illness.</p> <p>6) Patients might or might not attend their appointment at URSI after being referred to this service.</p> <p>7) Patients wait for their appointment at secondary care (waiting list).</p> <p>8) While waiting for their appointment with secondary care, the patient can recur to care at UBS.</p>

Tool HS3: Analysis one, two, and three for hybrid simulation			
Elements in DES-ABS	CATWO E elements	Key questions:	Answers
	O	What actions are being taken by decision-makers?	<p>1) Decision-makers set the rules to regulate the care services and the KPIs. For instance, they approve recruiting new doctors or new health equipment.</p> <p>2) Managers (UBSs) rearrange the services to meet the population's needs. They hire or fire professionals based on their occupancy rates.</p>
	A	What actions are being taken by people working in the system?	<p>In UBS</p> <p>1) RTA staff (walk-in appointment) --> If the patient needs an appointment with a GP or another health professional, they will offer a same-day appointment.</p> <p>2) GP--> If the patient needs an appointment with another professional in the UBS, refer and book an appointment for the near future.</p> <p>4) Nurse--> If the patient (over 60y) needs a specialist, refer to a specialist in URSI.</p> <p>5) GP--> If the patient does not need to see another specialist in or out of the UBS, they book him/her to see the GP again following the guidelines for its category (independent, pre-frail, frail).</p> <p>6) GPs or Nurses are likely to refer the patient to secondary care wrongly (it happens when they do not have the proper training to support their diagnosis of some health conditions. Health staff from URSI provides this training called "medicament". This action (training) reduces wrong referrals).</p> <p>7) Considering the current long waiting list for URSI, nurses are restricting the AMPI-AB to older people who are vulnerable and dependent. Hence, only a portion of the older population is been evaluated with AMPI-AB.</p> <p>In URSI</p> <p>1) A multidisciplinary group assess the health state of the patient using the AGG tool</p> <p>2) Geriatric assess the health state of the patient</p> <p>3) A multidisciplinary group (during the weekly meeting) decide the best treatment for each patient</p> <p>4) Each specialist of the multidisciplinary group assesses the health state using the tool AGE</p>

Tool HS3: Analysis one, two, and three for hybrid simulation			
Elements in DES-ABS	CATWO E elements	Key questions:	Answers
			5) Specialists provide customised care to the patient In AME 1) Specialists provide the care according to the patients' needs
Environment attributes	E	What are the main changeable characteristics of the environment?	1) The current municipal health plan set the goal for the older population: an increase of 5% in the number of older people who access care via URSIs. 2) 100% of adults aged 60 must have their health state assessed by a staff of UBSs using the instrument AMPI-AB.
	E	How is the system regulated? (e.g., Metrics and KPIs)	At an operational level, the health system is regulated by institutions such as the Brazilian Health Ministry and São Paulo Municipal Health Department. The municipal health department has set a 4-year plan called the municipal health plan, the guidelines of which are set. There are strategic KPIs and operational KPIs. Strategic KPIs: (A) Number of groups of eSF (doctors, nurses, and ACSs) implemented; (B) Number of older adults attended by URSIs. Operational KPIs: (all of them restricted to URSI) (C) Monitor the number of users on the URSI waiting list. (D) Monitor the average wait time between referral and the start of care at URSI. (E) Monitor the number of users not attending the initial consultation at URSI. (F) Monitor the number of inappropriate referrals. (G) Monitor the percentage of treatments not completed. (active search) (H) Monitor the average length of stay at URSI.
	E	How often do the regulations change?	The participants said that there is no clear answer to this question. However, they also stated that there is a "risk" of changes in some regulations and guidelines every four years, following the governance rules of new decision-makers. The strategic goals are likely to change with every new governance.
Analysis Three			

Tool HS3: Analysis one, two, and three for hybrid simulation			
Elements in DES-ABS	CATWO E elements	Key questions:	Answers
Interaction between elements in the system	O-C	Where and how does the interaction happen between Clients and decision-makers?	Managers do not have direct interaction with patients. Managers receive complaints or suggestions from patients regarding the services via the ombudsman. They might consider the complaints in their final decision. For instance, complaints indicate a need for more appointments with nurses via RTA. The manager can allocate another resource to attend to the demand if the KPIs indicate a long waiting time for this appointment. However,
	A-C	Where and how does the interaction happen between Clients and people working in the system?	<p>1) Clients (patients) and multidisciplinary groups (people who are in the system) interact in the UBSs during their booked or spontaneous (walk-in) appointments. Periodic interactions (every six months to 1 year). Each treatment follows a guideline and depends on the patient's health state.</p> <p>2) Patients and ACS interact during home visits (the patient's house). ACS can check if patients follow the treatment and instruct them, or book an appointment with GPs or nurses via RTA.</p> <p>3) Patients and multidisciplinary groups interact in the URSI for at least six months, receiving the prescribed treatment. Treatment can improve their health state or "stabilise" their health state.</p> <p>4) Patients interact with specialists in AMA-E to treat acute illness.</p> <p>5) Patients interact with other patients during the weekly events (physical activities) promoted in the UBSs.</p>
	O-A	Where and how does the interaction happen between Decision makers and people working in the system?	The interaction between managers and staff happens in the UBSs and URSIs, especially in periodic meetings when the whole team discuss improvements and patient treatment protocols are discussed. The interaction also happens on a day-to-day basis when punctual cases are discussed. From this interaction, managers periodically rethink the arrangement of services in the UBSs. For example, hire or reduce the agenda of some professionals with low occupancy.

Tool HS3: Analysis one, two, and three for hybrid simulation			
Elements in DES-ABS	CATWO E elements	Key questions:	Answers
	C-A	From interactions with people who work in the system, what would cause a change in the behaviour of clients?	Interactions between: A) ACS and patients: Some of the patients return to attend appointments with GPs or nurses. B) Multidisciplinary group and patients: Patients improve or maintain their health status (after at least six months) or maintain the same health condition because they attend the appointments, but do not follow the treatment.
	C-O	From interactions with clients, what would cause a change in the behaviour of decision-makers?	Decision-makers and clients do not interact directly. Their interaction happens with people who work in the health centres or via complaints sent to the ombudsman. Decisions are also made based on KPIs related to staff performance. Indirect interaction with clients allows them to collect data to make decisions regarding changes in the operation of UBSs.
	C-A	From interactions between decision-makers, what would cause a change in the behaviour of people working in the system?	Interactions between managers and staff can promote or reinforce the need for changes in the arrangement of services for UBSs. If the manager is "satisfied" with staff occupancy, the same schedule and arrangement will be followed over the following months. The staff schedule will change if the manager checks that professionals are idle.
Interaction between elements and the environment	C-E	What are the interactions between clients and the environment?	The number and location of UBSs are planned according to the geography and total population. Both districts in SACA are divided into zones, and each zone has a UBS. It is said that the long distance between a household and a UBS would be around 5 KM. Hence, the proximity of UBSs and communities (households) makes access to primary care feasible. UBSs operate as a point of reference to healthcare. However, the existence of one URSI and one AMA-E in the region impacts the individual's health as it can wait for care for weeks or months. People who live in the southern area of SACA are likely to look for care at UBSs only as they find it challenging to access secondary care physically.
	O-E	What are the interactions between decision-makers and the environment?	Managers must rearrange the operation in the UBSs to provide to all patients without compromising the monthly report to SMS. All UBSs must finish the period with good performance. Otherwise, they can lose part of the financial funding.

Tool HS3: Analysis one, two, and three for hybrid simulation			
Elements in DES-ABS	CATWO E elements	Key questions:	Answers
	A-E	What are the interactions between those who work in the system and the environment?	The critical location of URSIs requires a "plan B" between the UBS and the URSI team to provide care to patients with limitations in commuting to URSI. In this case, URSI uses the UBS staff to provide care. It happens for some specialists, such as nutritionists and physical educators.
	E-C	What changes can the environment cause to the client's behaviour?	Some older people do not attend their appointments at URSI despite having the referral and the need for care services. In some cases, they abandon the treatment before its completion as they find it difficult (mobility or financially) to carry on the treatment.
	E-O	What changes can the environment cause to the decision-makers?	They have to accommodate the demand for secondary care by rearranging the operation in the UBSs. UBSs have limited physical space and a limited number of consultation rooms. In some cases, the agenda of other specialities is compromised to attend to patients from URSI, or patients are attended to at the end of the day shift when some consultation rooms are available.
	E-A	What changes can the environment cause to the staff's behaviour?	In the case of UBSs, the staff have extra patients with different demands. In some cases, they are overloaded with extra demand from secondary care.

Appendix D - Model Data Collection

This appendix contains complementary data used as parameters to model the SACA system as discussed in Chapter 7. Data was used to set up agents as patients in both DES and ABS layers in the Simul8 DES-ABS hybrid model.

D.1. Populational and Operational data

This section presents data used as input or parameters in the Simul8 model discussed in Chapter 7. While Table 38 provides the estimates for mortality rates for both genders, separated by three age ranges (SEADE 2023). This data is used in the agent-based module for patients in Section 7.2, Table 39 shows the absenteeism rates for each primary care in SACA. This data was used as parameters for the Simul8 model discussed in Chapter 7.

Table 38: Mortality rates per gender and age range

Age	Men (daily)	Women (daily)
50 - 64	1.3%	0.8%
65 - 74	1.6%	1.2%
75 or above	2.5%	3.4%

Table 39: Percentage absenteeism of patients at each primary care facility.

ID	Primary Care Facilities	Absenteeism rates
1	Ubs Jardim Umuarama	27%
2	Ubs Jardim Niteroi	21%
3	Ubs Vila Constancia-Dr. Vicente Octavio Guida	31%
4	Ubs Sao Jorge - Cidade Ademar	33%
5	Ama/Ubs Vila Joaniza - Joao Yunes	34%
6	Ubs Jd Sao Carlos - Cidade Ademar	29%
7	Ubs Vila Imperio - Dra Gilda Tera Tahira	37%
8	Ama/Ubs Vila Imperio	35%
9	Ama/Ubs Vila Missionaria	25%
10	Ama/Ubs Jardim Miriam	36%
11	Ubs Cidade Julia	19%
12	Ubs Jardim Miriam II	40%
13	Ubs V Aparecida	22%
14	Ubs Mar Paulista	23%
15	Ubs Jardim Selma - Cidade Ademar	27%

ID	Primary Care Facilities	Absenteeism rates
16	Ubs Jd Apura	22%
17	Ama/Ubs Pq Doroteia	31%
18	Ubs Jardim Novo Pantanal - Pedreira	24%
29	Ubs Cicero Sergio Cavalcante (Vila Guacuri)	14%
20	Ubs Laranjeiras	25%
21	Ubs Mata Virgem	29%
22	Ubs Jardim Aeroporto-Massaki Udihara	44%
23	Ubs Vila Arriete - Decio Pacheco Pedroso	27%
24	Ubs Campo Grande	29%
25	Ubs Santo Amaro - Dr. Sergio Villaca Braga	37%
26	Ubs Chacara Santo Antonio	30%

Table 40: Utilisation rate per health professional

Health professional	Utilisation rate	Health professional	Utilisation rate
Geriatric doctor	100%	Speech Therapist	50%
Nurse	100%	Psychologist	33%
Nutritionist	50%	Social Worker	33%
Pharmacist	65%	Occupational Therapist	33%
Physiotherapist	100%		

D.2. Database for the population in Santo Amaro and Cidade Ademar

The database that simulates the data of everyone who lives in Santo Amaro and Cidade Ademar was calculated using the Cohort 2022, estimated by SEADE (2022), and the longitudinal study ELSI-Brazil. In the next paragraphs, seven steps were followed to generate the database uploaded in SIMUL8 as a spreadsheet named ss_SACA population.

Step 1 - Estimation of people who live in SACA.

The first source was the cohort estimated by SEADE (2022). The distribution of age and gender in 2022 was estimated for each borough in São Paulo by SEADE. This distribution was used to calculate the population that lives in SACA.

Figure 35 shows the population distribution per age range and gender in both boroughs. These figures reflect the population eligible to receive healthcare via public healthcare facilities, according to the Brazilian constitution discussed in Chapter 3.

Figure 35: Population distribution per gender for each borough.

	Female	Male	Total
Cidade Ademar	268.8	257.1	525.9
Santo Amaro	72.4	47.3	119.7

Step 2 - Estimation of people who live in SACA and use public health facilities.

The National Health Agency (ANS) estimates the number of people with health insurance. Figure 36 shows the distribution of people with health insurance per age and gender in Sao Paulo, according to ANS (2022).

However, it is known that, on average, 46.7% (5.6 million) of the population in Sao Paulo has health insurance and relies on its care via primary facilities. Hence, a second source, the number of people with health insurance per age range, was diminished from the total population in SACA to support the assumption (Chapter 7) that people with health insurance do not access care via public facilities.

This estimate per age range for the city of São Paulo was used to calculate the number of people in Santo Amaro and Cidade Ademar with health insurance. A total of 344.343 people were eliminated from the database, leaving a sample of 301.313 people, corresponding to those accessing care via public healthcare.

Figure 36: Distribution of the Population with health insurance in São Paulo.

AGE	GENDER	PERCENTAGE	GENDER	PERCENTAGE
0 a 4	Male	47%	Female	46%
5 a 9	Male	46%	Female	45%
10 a 14	Male	44%	Female	44%
15 a 19	Male	41%	Female	43%
20 a 24	Male	43%	Female	51%
25 a 29	Male	47%	Female	58%
30 a 34	Male	53%	Female	63%
35 a 39	Male	56%	Female	63%
40 a 44	Male	56%	Female	61%
45 a 49	Male	49%	Female	52%
50 a 54	Male	45%	Female	46%

AGE	GENDER	PERCENTAGE	GENDER	PERCENTAGE
55 a 59	Male	45%	Female	4%
60 a 64	Male	40%	Female	4%
65 a 69	Male	41%	Female	46%
70 a 74	Male	45%	Female	49%
75 or above	Male	63%	Female	30%

Step 3 - Develop the database with individuals.

Figure 37 shows a screenshot of part of the database generated in the previous steps. The complete database covers the range from 0 to 75 years or more. Each row in the spreadsheet corresponds to one health centre grouped by gender, with respective codes and the number of people per age range. For instance, the first row corresponds to the gender of females aged 0 to 75 years or older registered in the UBS Jardim Miriam primary care facility.

DISTRICT	NOME_UBS	Gender	0 a 4	5 a 9	10 a 14	15 a 19	20 a 24	25 a 29
Cidade Ademar	AMA/UBS INTEGRADA JARDIM MIRIAM - MANOEL SOARES DE OLIVEIRA	Female	1005	1019	1150	1146	1286	1303
Pedreira	AMA/UBS INTEGRADA PARQUE DOROTEIA	Female	819	836	1002	1006	1084	1091
Cidade Ademar	AMA/UBS INTEGRADA VILA IMPERIO	Female	292	308	380	347	466	482
Cidade Ademar	AMA/UBS INTEGRADA VILA JOANIZA	Female	846	814	979	938	1171	1258
Cidade Ademar	AMA/UBS INTEGRADA VILA MISSIONARIA	Female	1146	1165	1409	1356	1649	1693
Campo Grande	UBS CAMPO GRANDE	Female	1557	1580	1802	1833	2198	2532
Santo Amaro	UBS CHACARA SANTO ANTONIO - DR.MARCILIO DE ARRUDA PENTEADO *	Female	881	825	826	957	1275	1622
Cidade Ademar	UBS CIDADE JULIA	Female	622	741	827	801	774	766
Campo Belo	UBS JARDIM AEROPORTO - DR.MASSAKI UDIHARA	Female	1557	1570	1596	1587	2408	3027
Pedreira	UBS JARDIM APURA	Female	380	379	434	425	483	524
Cidade Ademar	UBS JARDIM MIRIAM II - CIDADE ADEMAR	Female	962	988	1199	1113	1473	1437
Cidade Ademar	UBS JARDIM NITEROI	Female	602	606	691	665	797	825
Pedreira	UBS JARDIM PANTANAL - CIDADE ADEMAR	Female	738	811	899	833	959	885
Cidade Ademar	UBS JARDIM SAO CARLOS - CIDADE ADEMAR	Female	629	640	721	792	784	795
Pedreira	UBS JARDIM SELMA - CIDADE ADEMAR	Female	550	595	659	669	657	738
Cidade Ademar	UBS JARDIM UMUARAMA	Female	969	974	1162	1273	1725	1895
Pedreira	UBS LARANJEIRAS	Female	570	573	713	697	757	766
Pedreira	UBS MAR PAULISTA	Female	472	489	560	537	617	734
Pedreira	UBS MATA VIRGEM	Female	683	719	792	749	779	802
Cidade Ademar	UBS SAO JORGE - CIDADE ADEMAR	Female	611	694	785	733	801	767
Santo Amaro	UBS SANTO AMARO - DR. SERGIO VILLACA BRAGA	Female	779	835	861	860	1087	1275
Campo Grande	UBS VILA ARRIETE - DECIO PACHECO PEDROSO	Female	1025	1024	1223	1192	1462	1858
Pedreira	UBS VILA APARECIDA	Female	508	609	669	641	663	755
Cidade Ademar	UBS VILA CONSTANCIA - VICENTE OCTAVIO GUIDA	Female	770	819	891	851	1016	1137
Pedreira	UBS VILA GUACURI	Female	645	675	758	738	862	950
Cidade Ademar	UBS VILA IMPERIO II - DRA GILDA TERA TAHIRA	Female	906	950	1142	987	1172	1242
Cidade Ademar	AMA/UBS INTEGRADA JARDIM MIRIAM - MANOEL SOARES DE OLIVEIRA	Male	1006	1020	1138	1053	1165	1223
Pedreira	AMA/UBS INTEGRADA PARQUE DOROTEIA	Male	815	902	1031	907	1100	1008
Cidade Ademar	AMA/UBS INTEGRADA VILA IMPERIO	Male	319	333	355	361	467	410
Cidade Ademar	AMA/UBS INTEGRADA VILA JOANIZA	Male	819	875	945	939	1084	1211
Cidade Ademar	AMA/UBS INTEGRADA VILA MISSIONARIA	Male	1161	1234	1446	1338	1499	1614
Campo Grande	UBS CAMPO GRANDE	Male	1568	1643	1866	1898	2057	2264
Santo Amaro	UBS CHACARA SANTO ANTONIO - DR.MARCILIO DE ARRUDA PENTEADO *	Male	826	883	971	1005	1253	1611
Cidade Ademar	UBS CIDADE JULIA	Male	705	779	859	736	743	751
Campo Belo	UBS JARDIM AEROPORTO - DR.MASSAKI UDIHARA	Male	1605	1479	1534	1598	2185	2640
Pedreira	UBS JARDIM APURA	Male	384	398	436	400	449	466
Cidade Ademar	UBS JARDIM MIRIAM II - CIDADE ADEMAR	Male	1015	985	1157	1071	1372	1405
Cidade Ademar	UBS JARDIM NITEROI	Male	582	660	701	653	747	768
Pedreira	UBS JARDIM PANTANAL - CIDADE ADEMAR	Male	832	823	966	842	926	870
Cidade Ademar	UBS JARDIM SAO CARLOS - CIDADE ADEMAR	Male	576	671	781	748	818	775
Pedreira	UBS JARDIM SELMA - CIDADE ADEMAR	Male	533	564	680	649	714	687
Cidade Ademar	UBS JARDIM UMUARAMA	Male	1024	1057	1194	1318	1621	1745
Pedreira	UBS LARANJEIRAS	Male	556	589	754	701	697	694
Pedreira	UBS MAR PAULISTA	Male	499	482	586	556	600	673
Pedreira	UBS MATA VIRGEM	Male	678	714	891	802	767	705
Cidade Ademar	UBS SAO JORGE - CIDADE ADEMAR	Male	638	742	814	680	768	741
Santo Amaro	UBS SANTO AMARO - DR. SERGIO VILLACA BRAGA	Male	815	807	929	902	1063	1238
Campo Grande	UBS VILA ARRIETE - DECIO PACHECO PEDROSO	Male	1148	1106	1217	1206	1376	1652

Figure 37: Screenshot of the database with the population in SACA

A VBA code (Figure 38) created a unique database with each row representing an individual. Each row was replicated as many times as the number of individuals per age range, generating a dataset with 301.313 individuals aged between 0 and 99 years of both genders who access healthcare services in one of the primary care facilities. Besides the individual's information, each row also carries the name of the primary care centre where the individual has their registration and a unique ID.

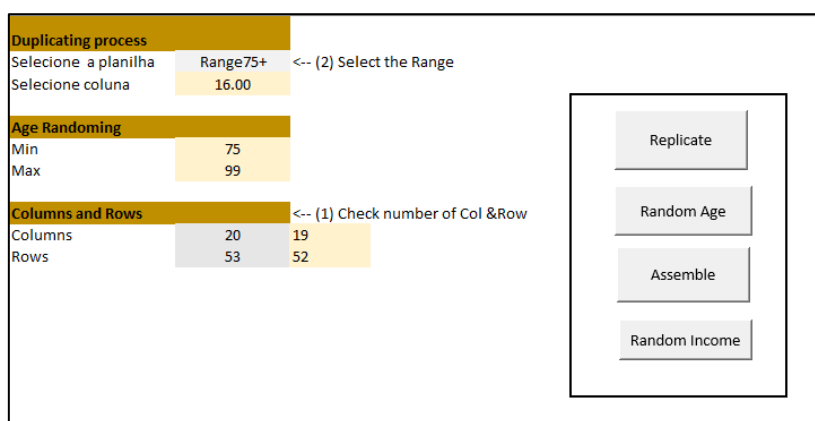


Figure 38: Screenshot of the control panel in the spreadsheet with VBA commands.

Step 4 - Estimation of income

The database generated in step 3 was used to estimate the income of each individual. At this point, stakeholders agreed upon an assumption. Only people aged 20 or above would have an income. People aged below 20 years would have their income set as zero. The income was randomly attributed to each individual. It followed the criteria above and the income distribution statistics for each borough district, as shown in Figure 39.

Individuals were associated with an income range. Income range, age, and gender comprised a key factor associated with individuals in the ELSI repository, which will be detailed in step 5. Sometimes, the repository data would not have the individual with the corresponding key “age, gender, and income”. For those cases, a second random distribution was set to select an individual with ± 1 year living in the same area and with the same gender.

Figure 39: Distribution of population per income range in the districts of SACA.

Districts in each borough	Less than 1/2 salary	De 1/2 to less than 1 salary	1 to less than 1 1/2 salary	1 1/2 to less than 3 salaries	3 to less than 5 salaries	5 to less than 10 salaries	More than 10 salaries
Campo Belo	3.12	2.55	3.81	10.99	10.82	24.95	43.76
Campo Grande	2.75	5.55	6.79	19.97	18.54	24.37	22.03
Cidade Ademar	11.61	15.75	15.02	29.69	13.66	9.89	4.37
Pedreira	15.95	19.78	17.09	28.13	12.01	5.92	1.13
Santo Amaro	2.55	1.3	3.16	11.98	17.31	24.77	38.94

Step 5 - Estimation of health status for people who use public care facilities.

At this point, this research had to overcome data restrictions- the absence of patient records with records of the patient's health status. The only score that could define the patient's health status is AMPI-AB. However, third parties cannot access the history of patients assessed with this instrument. Thus, the solution to overcome this restriction was to create a repository with previous research data that would replicate the health status of patients using the estimated score for AMPI-AB.

The database of the study ELSI-Brazil was then used as a reference to calculate the score AMPI-AB. ELSI-Brazil is a longitudinal study of ageing conducted by an esteemed institution in Brazil, the Oswaldo Cruz Foundation (Fundação Oswaldo Cruz) or Fiocruz. ELSI-Brazil aims to investigate Brazil's population ageing dynamics (Lima-Costa *et al.* 2022; Lima-Costa *et al.* 2018).

This research collected data from people in Brazil aged 50 or above in two waves. Wave 1 happened between 2015 and 2016, while wave 2 occurred between 2019 and 2021. In both waves, random samples were accessed via a questionnaire covering individual health (physical

and mental health conditions) and social determinants. For more information about ELSI, access its official website (<https://elsi.cpqrr.fiocruz.br/en/home-english/>).

In total, 3922 people in São Paulo participated in the ELSI study. The sample corresponds to people in different municipalities, from small towns to big centres such as São Paulo. To ensure a sample of individuals with health attributes similar to the population in the study, this research selected only people who live in big cities like São Paulo. This sample corresponds to group 4, region 3 in the ELSI database and contains 1664 participants. From these, 324 participants were eliminated, leaving 1340 participants to be used as a database for this research. The absence of an answer justifies the exclusion of participants from one or more selected questions to represent AMPI-AB, as shown in Figure 40.

The ELSI data covered several determinants in health and social domains. It was possible to associate the questions in the AMPI-AB questionnaire with questions in the ELSI questionnaire. Figure 40 shows the association between the instrument AMPI-AB and the ELSI-Brazil questionnaire questions. Stakeholders who participated in this research supported this comparison between questionnaires and validated all associations between primary care data and ELSI-Brazil data.

Crossing data from both instruments generated a third database with answers to AMPI-AB 17 questions for 1664 people. Besides the 17 questions in AMPI-AB, people in this dataset also have age, gender, and income. These three pieces of information formed the key to associating people in the database created in Step 3 with the people in this repository.

Step 6 - Attribute the AMPI-AB score to each person in SACA.

The next stage was to fill the SACA database with information from the ELSI-Brazil repository. The association between the two datasets was made using the Excel function VLOOKUP. The 301.313 individuals in the database for the SACA population receive a score for AMPI-AB.

Individuals below 50 received a score of zero, and people above this age received the corresponding score of an individual with the age, gender, and income.

Step 7 - Select the population of the model.

The database generated in Step 6 contains the total population of Santo Amaro and Cidade Ademar. However, this study is restricted to studying the ageing population for three years. Considering the timeline for this modelling, the population of interest in the model can be restricted to people above 56 years old. Therefore, the dataset was filtered, and only people over 55 years old were included in the spreadsheet that was uploaded to SIMUL8. This file contains 35.373 people aged 55 or above associated with one of the primary care centres. This database was uploaded in SIMUL8 as a spreadsheet (ss_SACA population), and a VL code associates each work item to a row in the database using a unique ID (label lbID).

The data to feed SACA population spreadsheets was calculated using inputs from stakeholders and the database from a longitudinal study of Ageing (ELSI-Brazil) conducted by an esteemed institution in Brazil, the Oswaldo Cruz Foundation (Fundação Oswaldo Cruz) or Fiocruz. ELSI-Brazil aims to investigate Brazil's population ageing dynamics (Lima-Costa *et al.* 2023; Lima-Costa *et al.* 2018).

This research collected data from people in Brazil aged 50 or above in two waves. Wave 1 happened between 2015 and 2016, while wave 2 occurred between 2019 and 2021. In both waves, random samples were accessed via a questionnaire covering individual health (physical and mental health conditions) and social determinants.

Additionally, to support these stages, VBA macros were employed to connect the ELSI repositories and generate 301.313 rows of patients who access primary care via the 26 health centres available in Santo Amaro and Cidade Ademar.

Figure 40: Comparison between the question in AMPI-AB and the corresponding question in ELSI.

Question in AMPI-AB	Correspondent question(s) in ELSI (Lima-Costa <i>et al.</i> 2018)
How old are you?	How old are you?
In general, compared to other people of your age, would you say that your health is excellent, good, regular or bad?	In general, how would you evaluate your health?
Do you live alone?	In total, how many people live in this home?
Do you have any of the conditions below? Diabetes Mellitus, Hypertension, Stroke, Coronary Artery Disease, Vascular Diseases, Pressure Ulcers, Anaemia, Asthma, COPD, Peptic ulcer, Osteoarthritis, Obesity, Neoplasia, Dementia, Epilepsy, Depression, Parkinson's, HIV/AIDS and limb amputation	Has any doctor ever told you that you have hypertension (high blood pressure)? Has any doctor ever told you that you have diabetes ("high blood sugar")? Has any doctor ever told you that you have angina pectoris? Has any doctor ever told you that you have heart failure? Has a doctor ever told you that you had a cerebral vascular accident (stroke)? Has a doctor ever told you that you have asthma? Has a doctor ever told you that you have emphysema, chronic bronchitis, or chronic obstructive pulmonary disease (COPD)? Has a doctor ever told you that you have arthritis or rheumatism? Has a doctor ever told you that you have depression? Has a doctor ever told you that you have or had cancer? Has a doctor ever told you that you have Parkinson's disease? Has a doctor ever told you that you have Alzheimer's disease?
How many medications do you take daily?	Are you currently taking any medication of regular or continuous use that was prescribed by your doctor? How many medications of regular or continuous use, prescribed by your doctor, have you taken in the PAST TWO WEEKS?
How many times have you been hospitalised in the last 12 months?	In the PAST 12 MONTHS, have you been admitted to a hospital for 24 hours or more? In the PAST 12 MONTHS, how many times have you been hospitalised?
How many times did you fall in the last 12 months?	In the PAST 12 MONTHS, have you had a fall? How many falls have you had in the PAST 12 MONTHS?
Do you have any difficulty seeing? (Even wearing glasses)	How do you evaluate your far vision (EVEN WHEN USING GLASSES OR CONTACT LENSES), this means recognising someone that you know on the other side of the street at a distance of 65 feet or so?

Question in AMPI-AB	Correspondent question(s) in ELSI (Lima-Costa <i>et al.</i> 2018)
	How do you evaluate your near vision (EVEN WHEN USING GLASSES OR CONTACT LENSES), this means recognising an object that is within reach or reading a newspaper?
Do you have any difficulty hearing or do people? Do you think you hear badly?	Do you use a hearing device? How do you evaluate your hearing (even when using a hearing device)? Do you find it difficult to follow a conversation if there is background noise in the environment, such as TV, radio, or children playing (even when using a hearing device)?
Check if the elderly person can touch the back of the head with both hands. Check if the elderly person can pick up a pencil from the table with one hand and put it back. Can you walk 400 meters (approximately four blocks)? Are you able to sit down or stand up without difficulty?	Do you have trouble walking one kilometre continuously? Do you have any difficulty walking 100 meters (one block)? Do you have trouble sitting still for about two hours? Do you have any difficulty stooping, kneeling or crouching? Do you have any difficulty with extending your arms above shoulder level? Do you have any difficulty picking up a coin from a table? Do you receive help with DOING YOUR PERSONAL HYGIENE?
Has any family member or friend mentioned that you are forgetting? Is forgetfulness getting worse in recent months? Is forgetfulness preventing you from carrying out any daily activities?	Currently, how do you classify your memory? I would like to know how you would classify the memory of Mr./Mrs. (name of the interviewee) NOWADAYS? COMPARED TO THE LAST MONTH, would you say that Mr./Mrs. (name of the interviewee) Memory is: Compared to 2 YEARS AGO, the memory of Mr./Mrs. (name of the interviewee) To recall issues related to family and friends (such as birthdays, careers and addresses) improved, remained unchanged or worsened? Comparing the current condition of Mr./Mrs. (name of the interviewee) To the one of 2 YEARS AGO, how is his/her ability to learn how to use a new appliance existing at home? Comparing the current condition of Mr./Mrs. (name of the interviewee) To the one from 2 YEARS AGO, how is his/her ability to learn new things (tasks/abilities) in general? Comparing the current condition of Mr./Mrs. (name of the interviewee) To the one of 2 YEARS AGO, how is his/her ability to follow a story either in a book or on television? Comparing the current condition of Mr./Mrs. (name of the interviewee) To the one from 2 YEARS AGO, how is his/her ability to make decisions on daily situations?

Question in AMPI-AB	Correspondent question(s) in ELSI (Lima-Costa <i>et al.</i> 2018)
<p>In the last month, have you felt discouraged, sad or hopeless?</p> <p>In the last month, have you lost interest or pleasure in previously pleasurable activities?</p>	<p>In the PAST WEEK, how often have you felt you could not handle your activities (started something, but could not finish it)?</p> <p>In the PAST WEEK, how often have your daily activities required a big effort from you?</p>
<p>Do you need help getting out of bed?</p> <p>Do you need help getting dressed?</p> <p>Do you need help to feed yourself?</p> <p>Do you need help taking a shower?</p>	<p>Do you receive any help with PREPARING A HOT MEAL?</p> <p>Do you receive any help with USING YOUR TELEPHONE?</p> <p>Do you receive help with TAKING/MANAGING YOUR OWN MEDICATION?</p> <p>Do you receive help with PERFORMING YOUR LIGHT HOUSEKEEPING?</p> <p>Do you get any help to walk FROM ONE ROOM TO ANOTHER on the same floor?</p>
<p>Do you need help to carry out activities outside the home?</p> <p>Do you need help with your money (paying bills, checking change, going to the bank, etc.)?</p>	<p>Do you receive help with MANAGING YOUR OWN MONEY?</p> <p>Do you receive any help with USING ANY TYPE OF TRANSPORTATION?</p> <p>Do you receive help with DOING YOUR SHOPPING?</p> <p>Do you receive help with GETTING YOURSELF DRESSED UP?</p> <p>Do you receive help with SHOWERING?</p> <p>Do you receive help with EATING YOUR FOOD?</p> <p>Do you receive help with USING THE BATHROOM?</p>
<p>Do you accidentally lose control of urine?</p> <p>Do you accidentally lose control of faeces?</p>	<p>In the LAST MONTH, have you ever lost control of urine or faeces unintentionally?</p>
<p>In the last 12 months, have you lost weight without dieting or changing any lifestyle habits? (4.5 kg or 5% loss in the last 12 months)</p>	<p>In the PAST THREE MONTHS, have you lost weight without any dieting?</p> <p>What is the range that best represents how many pounds you have lost in the PAST 3 MONTHS?</p>
<p>If you use a prosthesis, is it poorly adapted?</p> <p>Do you have problems chewing?</p> <p>Do you have problems swallowing?</p> <p>Did you stop eating any kind of food because of problems with your teeth or prosthesis?</p>	<p>Do you use any kind of removable dental prosthesis (artificial teeth) to replace your natural teeth on the LOWER PART OF YOUR MOUTH?</p> <p>Do you use any kind of removable dental prosthesis (artificial teeth) to replace your natural teeth on the UPPER PART OF YOUR MOUTH?</p> <p>Has your dentist ever told you that you have/had gum disease (periodontal disease)?</p> <p>Does your gum currently bleed?</p> <p>In the PAST 6 MONTHS, have you had difficulty eating or felt pain when drinking cold or hot beverages?</p>

D.3. Stage 4 - Develop a computer model

Below is a shortcut to the report shared with stakeholders. It contains the data used to run the statistical test as part of activity 3 in Stage 4

[Portuguese] Esse relatório contém informações fornecidas pelo gerente de TI e refere-se aos dados mensurados para os três indicadores atualmente mensurados em SACA. (This report contains the data for the three performance indicators used to validate the outputs of the computer model developed in simulation.)

1 - Numero de pacientes que completaram atendimento na URSI por mes. (Number of patients that completed its treatment at URSI per month) = 221 em media

A gerente da unidade URSI informou que 221 deveria ser usado como o valor medio para esse indicador. The URSI manager informed us that an average of 221 patients would be used for this KPI. This value was measured in April 2019, and she was confident that it was the correct figure for that month.

2 - Numero de idosos na fila para atendimento na URSI -2019 (Number of referrals to URSI)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
168	177	165	163	155	133	92	85	128	175	272	280

3- Tempo medio de permanencia na URSI (Average Length of treatment at URSI).

Valor para esse indicador foi baseado na experiencia da Gerente de TI e Gerente Administrativo da URSI. Abaixo, trecho da fala da Gerente Administrativo da URSI

“No momento não temos essa informação em sistema, mas pela minha experiência hoje gira em torno de **365-540 dias**. Tem vários fatores que afetem esse número. Um fator é o estado de saúde do idoso, mas também a conduta do médico. Se o médico pede muitos exames e há demora em realizar os exames, esse tempo de permanência do idoso pode chegar a **1.5 anos**.”

The value for this indicator was based on the experience of the IT Manager and the Administrative Manager of URSI. Below is an excerpt from the statement of the Administrative Manager of URSI:

"At the moment, we do not have this information in the system, but based on my experience, it currently ranges around 365-540 days. There are several factors that affect this number. One factor is the health condition of the elderly person, but also the doctor's conduct. If the doctor requests many tests and there is a delay in performing the tests, the length of stay for the elderly person can reach 1.5 years."

Appendix E - Computer model in Simul8

The table below provides details on all the objects used to build up the DES-ABS hybrid model for the case study in Brazil. For each object, there is an ID also used in Simul8 to identify the VL codes related to the object, the module where the object was used, the respective object name, the type of object and a brief description of the object. In the case of objects that represent activities, the description also details the routing in and out discipline.

ID	Block	Objects	Type of object	Description
POP01	Population SACA	Start point	Start point	Generate work items according to the schedule spreadsheet sp_SACA Population (daily rate of arrivals for patients above 57 years old)
POP02	Population SACA	Queue for Health State	Queue	
POP03	Population SACA	Health state	Dummy activity (Fixed = 0)	Link the ss_SACA population database and work items via VL code. Set the route out discipline based on the label (lb_decision).
POP04	Population SACA	PreOlders Healthy	Dummy activity (Fixed = 0)	Routing work items into state PreOlder Healthy in the statechart Patient.
POP05	Population SACA	PreOlderPrefrail	Dummy activity (Fixed = 0)	Routing work items into state PreOlder PreFrail in the state chart Patient.
POP06	Population SACA	PreOlderFrail	Dummy activity (Fixed = 0)	Routing work items into state PreOlder Frail in the state chart Patient.
POP07	Population SACA	OderHealthy	Dummy activity (Fixed = 0)	Routing work items into the state Healthy in the statechart Patient.
POP08	Population SACA	OlderPreFrail	Dummy activity (Fixed = 0)	Routing work items into state PreFrail in the statechart Patient.
POP09	Population SACA	OlderFrail	Dummy activity (Fixed = 0)	Routing work items into the state Frail in the statechart Patient.

ID	Block	Objects	Type of object	Description
POP10	Population SACA	Queue for home	Queue before the activity home	Routing in work items from dummy activities that set the initial state in the patient state chart.
POP11	Population SACA	Home	Dummy activity (Fixed = 0)	Set the label lb_ptabsent according to the patient's location and its respective probability distribution (disptabsence) using the VL code.
POP12	Population SACA	Queue for Pt absent1	Queue	Queue before dummy activity: Pt absent
POP13	Population SACA	Pt absent	Dummy activity (Fixed = 0)	Set route out routine based on patient absence label (lb_ptabsent).
POP14	Population SACA	Queue for 1Care	Queue	Queue for supporting the activities at the beginning of the patient pathway. Ensures the flow module is patient to the DES module.
POP15	Population SACA	Queue for Home	Queue	Queue for stocking the work items that returned from primary care and were not referred to secondary care.
UBS01	Primary care	Appointment	Dummy activity (Fixed = 0)	Represent the interaction between the patient and primary care staff.
UBS02	Primary care	Referral	Dummy activity (Fixed = 0)	Set the routing out discipline based on the label lb_UBSreferral (1 = back home; 2 = to secondary care).
UBS03	Primary care	Queue back home	Queue	Queue stocking work items before returning home after receiving primary care treatment.
URSI01	Secondary care	Queue for URSI	Queue	The waiting list for secondary care.
URSI02	Secondary care	Linking state chart	Dummy activity (Fixed = 0)	Link the work items to the state chart for the URSI staff.
URSI03	Secondary care	Online Assessment	Dummy activity (Fixed = 0)	Represent the first contact between secondary care and the patient. Patients' availabilities are checked.
URSI04	Secondary care	Queue for 1st Assesment	Queue	Represent the waiting time for patients who are booked for the first stage of their care in URSI - first assessment with a multidisciplinary group.

ID	Block	Objects	Type of object	Description
URSI05	Secondary care	1st Assesment	Activity (Average = 0.0417)	Represent the appointment with the multidisciplinary group.
URSI06	Secondary care	Queue for Geriatrist Assessment	Queue	Represent the pool of patients who are waiting for the first assessment with a geriatric doctor.
URSI07	Secondary care	Geriatric Assessment	Activity (Average = 0.0417)	Represent the appointment with the geriatric doctor.
URSI08	Secondary care	Queue for Multidisciplinary Assessment	Queue	Represent the pool of patients who are evaluated weekly by the multidisciplinary group.
URSI09	Secondary care	Multidisciplinary Assessment	Dummy activity (Fixed = 0)	Represent the weekly meeting with the whole team to discuss the best treatment for each patient. Treatment set by label (lb_treaprotocol).
URSI10	Secondary care	Queue for Start_treatment	Queue	Represent the pool of patients waiting for the start of the treatment.
URSI11	Secondary care	Start treatment	Dummy activity (Fixed = 0)	Set the start time for the treatment.
URSI12	Secondary care	Queue for Treat	Queue	Set the label lbtimenextappt to control the monthly follow-up appointments.
URSI13	Secondary care	Treatment	Activity (Average = 0.456)	Represent the monthly appointments with specialists.
URSI14	Secondary care	Queue for discharge	Queue	It controls how long the work item stays in the treatment loop, considering the duration of treatment set on the label lb_URSI_treatduration.
URSI15	Secondary care	Discharge	Dummy activity (Fixed = 0)	Set the route out discipline based on the label lb_route.

ID	Block	Objects	Type of object	Description
URSI16_	Secondary care	Finished treatment	Dummy activity (Fixed = 0)	Linking the secondary process to the beginning of the patient pathway.
URSI17	Secondary care	URSI discharge	Dummy activity (Fixed = 0)	Represents the discharge after finishing treatment in secondary care.
PAT01	Patient	PreOld Healthy	Work item state	Represent the state assumed by individuals below 60 years, with a state-healthy (AMPI Score below 6).
PAT02	Patient	PreOld PreFrail	Work item state	Represent the state assumed by individuals below 60 years, with a state pre-frail (AMPI Score between 6 and 10).
PAT03	Patient	PreOld Frail	Work item state	Represent the state assumed by individuals below 60 years, with a state pre-frail (AMPI Score above 11).
PAT04	Patient	Healthy	Work item state	Represent the state assumed by individuals above 60 years, with a state-healthy (AMPI Score below 6).
PAT05	Patient	Pre Frail	Work item state	Represent the state assumed by individuals above 60 years, with a state pre-frail (AMPI Score between 6 and 10).
PAT06	Patient	Frail	Work item state	Represent the state assumed by individuals above 60 years, with a state pre-frail (AMPI Score above 11).
PAT07	Patient	Deceased	Work item state	Set the state deceased to individuals.
PAT08	Patient	Starting Age	Work item state	State complementary to the main patient state chart.
PAT09	Patient	Getting Old	Work item state	State complementary to the main patient state chart. It adds one to the label lb_age every year.
STA01	URSI Staff	Eligibility confirmed	Work item state	Set a state for individuals who receive the first contact and accept being treated in URSI.
STA02	URSI Staff	Unable to attend	Work item state	Set the state to patients in social disparity who are not able to receive care in URSI.
STA03	URSI Staff	High frailty	Work item state	Set the state to debilitate patients with high AMPI scores with special health conditions, such as dementia.
STA04	URSI Staff	Moderate to high frailty	Work item state	Set the state for patients with borderline health conditions who might need special treatment.

ID	Block	Objects	Type of object	Description
STA05_	URSI Staff	Non-aligned carer	Work item state	Set a state for patients who were assessed by secondary care staff. Staff classify their case as not aligned with the care offered in URSI. These patients will be referred back to primary care with the recommendation of the best health facility for their case.
STA06	URSI Staff	Aligned carer	Work item state	Set a state for patients who were assessed by secondary care staff. Staff classify their case as aligned with the care offered in URSI.

Model coding.

Below are the main codes developed in SIMUL8 for linking state charts and workflow in the DES module, as well as the code for setting transitions between states in the respective state charts.

Linking the work items to the database for the SACA population

```

VL SECTION: POP03_Demographics Route In After Logic
  SET lb_AMPI = ss_populationSACA[4,1+lbID]
  SET lb_gender = ss_populationSACA[2,1+lbID]
  SET lb_Age = ss_populationSACA[3,1+lbID]
  SET lb_location = ss_populationSACA[6,1+lbID]
  SET lb_identifystaff = ss_populationSACA[9,1+lbID]
  SET lb_Decision = ss_populationSACA[10,1+lbID]
  SET lb_AMPIgroup = ss_populationSACA[12,1+lbID]
  SET lb_livingalone = ss_populationSACA[13,1+lbID]
  SET lb_notransport = ss_populationSACA[14,1+lbID]
  SET lb_income = ss_populationSACA[15,1+lbID]
  SET lb_AMPIinitial = lb_AMPI
  SET Deceased = 0

```

UBS Health staff decision-making for each patient

```

VL SECTION: UBS01_Appointment Route In After Logic , lcl_ctrldemand:[NUMBER] ,
LOCALDATA: Local2:[NUMBER]
  SET lb_ctrldemand = distctrldemand
  'Setting the control of demand in place in UBS
  IF lb_ctrldemand = 0
    SET lb_UBSreferral = 1
  'Setting the algorithm for primary care staff - their decision process to refer or not a
  patient to secondary care
  ELSE
    IF lb_Age < 60
      SET lb_UBSreferral = 1
    IF lb_Age >= 60
      IF lb_URSI_completetreat = 1
        SET lb_UBSreferral = 1
      ELSE IF lb_URSI_completetreat = 0
        IF lb_AMPI < 11
          SET lb_UBSreferral = 1
        ELSE IF lb_AMPI > 10
          SET lb_UBSreferral = 2
      IF lb_wrongreferral = 1
        SET lb_UBSreferral = 2

```

Interaction between staff and patients - decision on the eligibility for URSI services

```

VL SECTION: URSI02_Linking state chart Route In After Logic
'Setting the algorithm for eligible people in social disparity
SET lb_elegible2care = 1
'A) People living alone in areas away from URSI and with an income lower than 3
IF lb_livingalone = 1
  IF lb_income <= 2
    IF [lb_location = 20] | [lb_location = 21] | [lb_location = 22] = 1
      SET lb_unable = 1
    ELSE
      SET lb_unable = disprobunable
  IF lb_income >= 5
    SET lb_unable = 1
  ELSE
    SET lb_unable = 0
ELSE IF lb_livingalone = 0
  SET lb_unable = 0
'B) Frail people living alone
IF Frail = 1
  IF lb_livingalone = 1
    SET lb_unable = 1
  ELSE
    SET lb_unable = 0

```

Treatment at URSI - length of stay and discharge from service

```

VL SECTION: URSI14_Queue for Discharge On Entry Logic , LOCALDATA:
lcltime:[NUMBER]
'Check the time in treatment
SET lcltime = Simulation Time-lb_URSI_starttreat
IF lcltime <= lb_URSI_treatduration+60
  SET lb_routel = 2
  IF lb_countloop <= 12
    IF lb_AMPI > lb_AMPIinitial
      SET lb_URSI_treatduration = lb_URSI_treatduration+90
    ELSE
      SET lb_URSI_treatduration = lb_URSI_treatduration
  ELSE IF lcltime >= 0
    SET lb_routel = 1
'Set whether the patient has improved their health condition
SET lb_healthcondition = disptimproveURSI

```

Improvement in the state, updating the AMPI-AB score after completing treatment at URSI

```

VL SECTION: URSI16_Finished treatment Route In After Logic
  SET gbl_countpfinish = gbl_countpfinish+1
  'Adjusting the labels for patients who have their AMPI Score
  SET lb_AMPIimprove = disptimproveURSI
  IF lb_AMPIimprove = 1
    SET lb_AMPI = lb_AMPI-1
  ELSE IF lb_AMPIimprove = 0
    SET lb_AMPI = lb_AMPI
  'Adjusting labels for patients that improved their AMPI Score
  IF lb_AMPI <= 5
    SET lb_AMPIgroup = 1
  IF lb_AMPI >= 11
    SET lb_AMPIgroup = 3
  ELSE
    SET lb_AMPIgroup = 2

```

Example - Patient state code for supporting transition between stages

```

VL SECTION: PAT02_PreOld Prefrail On Join State Logic
  'Setting referral to primary care
  SET lb_UBSreferral = 1
  SET lb_timenextstep = 365
  'Joining from a state healthy, pre-frail or (ELSE IF) from the model in T0
  IF lb_AMPIgroup = 1
    SET lb_AMPIgroup = 2
    SET lb_AMPI = 6
  IF lb_AMPIgroup = 3
    SET lb_AMPIgroup = 2
    SET lb_AMPI = 10
  ELSE
    SET lb_AMPIgroup = 2
  'Setting labels for mortality rate
  LOOP 1 >>> i >>> 62
    IF lb_Age = ss_mortality[1,i+1]
      SET lb_mortalityrate = ss_mortality[lb_gender+2,i+1]
  Break

```

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