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# HYBRID SIMULATION IN HEALTHCARE: A REVIEW OF THE LITERATURE

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## ABSTRACT

The use of Hybrid Simulation (HS) increased as problems have become more complex and multidimensional, with a particular focus on healthcare systems. Such complexities make it challenging for single simulation models to provide the right support for decision-making. This article reports on a preliminary review of the literature and investigates the prevalence and utilization of HS in healthcare. Thirty-three relevant papers were found in the literature, including application papers, frameworks, and review papers. Our review categorizes the M&S techniques employed and analyses the application type, software packages, trends, opportunities, and challenges of HS in healthcare. Findings show that combining Discrete Event Simulation and System Dynamics is the most common approach to developing HS models in healthcare. However, the popularity of combining Agent-Based Simulation with others is on the rise. Current limitations of the literature and opportunities for future research are discussed.

## 1 INTRODUCTION

Healthcare systems face evolving and unique challenges more frequently than other sectors as they try to cope with the lack of resources and other factors of local and national regulations (Shaibu et al. 2021). The complexity was especially exacerbated during a pandemic. The COVID-19 pandemic posed complex problems for emergency departments (Giannouchos et al. 2021). For example, first responders and emergency departments had to continuously navigate new protocols and procedures, such as the use of necessary protective gear and constraints created by the need to quarantine patients. Moreover, intensive care units (ICUs) have also suffered during the pandemic. Many patients who required ICUs care did not have bed spaces available to receive treatment for their disease. As more and more unplanned changes within healthcare organizations, simulation models can be viewed as a valuable resource to respond to (and prevent) these issues since they allow decision-makers to review the outcomes of different potential scenarios (Currie et al. 2020). Therefore, simulation modeling can be useful for examining potential reactions to planned (and unplanned) changes and their issues. According to Brailsford et al. (2019) recent studies show that single simulation modeling has some shortcomings when aiming to solve the entire healthcare system with all its complexities. Therefore, hybrid simulation (HS) modeling is perhaps a more effective way to achieve this.

Recently, there has been a marked increase in the focus on HS as a candidate for solving problems in complex systems such as healthcare. HS models mostly utilize commercial software for model development, such as a combination of Simul8 and Vensim for modeling Discrete Event Simulation (DES) and System Dynamics (SD), and AnyLogic for a combination of DES, SD, and Agent-Based Simulation (ABS) methods. However, it is quite evident that HS model building always requires coding effort, whether

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multiple packages or a single package. Different models require different coding environments and skills. According to Brailsford et al. (2019) most commercial software provides user-friendly tools to build a single model. However, those tools may not be enough to develop HS model since HS requires more than one software for model development. Therefore, developing HS by using different software requires quite good coding skills in order to make a link between the software. Combining DES and SD, for example, necessitates knowledge of both the DES and SD platforms, as well as knowledge of Java for linking the models. Many modelers may struggle with this since it requires considerable coding or multi-modeling skills. As a result, developing HS models is regarded as difficult in healthcare. Hence, the primary purpose of this literature review is to investigate the different methods followed for developing HS models and identifying the preferred software. This review aims to identify any potential literature gaps and draw up routes for further research in developing HS for healthcare systems.

The rest of the paper is organized as follows: Section 2 discusses the three main simulation methods and the shortcomings associated with each one, Section 3 provides the methodology of the literature review, Section 4 shows the analysis of the papers in the literature review, Section 5 discusses the papers in general and the gaps in the literature, and finally, Section 6 gives the conclusion and future research.

## 2 SIMULATION IN HEALTHCARE

Healthcare simulation gained researchers' attention due to the complexity of the system and the need for better approaches to overcome its uncertainties in an interactive manner between modelers and stakeholders (Brailsford 2007). The most applied simulation methods in the healthcare context are DES, SD, and ABS (Eldabi et al. 2018). The healthcare system is divided into various departments, each of which necessitates a unique analysis. Therefore, healthcare simulation is widely used to address problems in healthcare, such as health policy, healthcare system design, healthcare system operation, and decision making (Mielczarek and Uziałko-Mydlikowska 2012). For example, DES is primarily used for operational-level problems, while ABS is used for the behavior of heterogeneous agents, and SD is used for strategic-level problems. Even though simulation models have features that allow them to solve problems in healthcare, many complex problems require some other tools to overcome the complexity of the problems.

### 2.1 Hybrid Simulation in Healthcare

A hybrid simulation is a modeling approach combining at least two different simulation methods or continuous and discrete systems (Mustafee et al. 2015). In healthcare literature, HS has been widely used in many contexts, such as combining data mining techniques and simulation methods (Kovalchuk et al. 2018), optimization tools and simulation methods (Farahi and Salimifard 2021), simulation and Soft System Methodology (Powell and Mustafee 2014), and simulation methods with integer programming (Ordu et al. 2021). However, these studies are out of scope for this literature review since the focus of this study is on a combination of DES, SD, and ABS.

Even though many single models have been developed in healthcare, the increasing complexity of healthcare systems makes it difficult to use single models to answer the system as a whole (Brailsford et al. 2019). In addition, healthcare problems cannot be solved entirely by using single models since the complexity involves micro, macro, and individual levels (Eldabi et al. 2016). Many researchers attempt to develop HS model to find a better and more compact solution and have a better presentation for complex systems. Therefore, HS helps stakeholders understand the simulation process to make decisions based on a clear representation of the problem. Healthcare systems cannot be analyzed in a partial manner since all components affect each other, and it is impossible to isolate parts. Even though developing an HS model is challenging since it requires knowledge of the different simulation approaches and coding experience to model communication between the models, it is a very efficient way to analyze the integrated system. Moreover, simulation software, which is developed for specific methods, adds features to make the HS model in their environment. For example, the ability to simulate queuing processes or stochastic variables is available in most SD software solutions. (Brailsford 2015). Therefore, HS is a way to develop a better model which includes more than one of the components in healthcare systems.

### 2.2 A Framework to Investigate HS Literature

There are different frameworks to investigate HS in the literature (Chahal and Eldabi 2008; Morgan et al. 2017; Brailsford et al. 2019). In this literature review, a framework provided by Brailsford et al. (2019) is used to identify hybridization and model integration. Table 1. illustrates the framework which is used for the literature review. The papers included in this review are analyzed based on three major categories: hybridization, linking, and model validation and verification. According to Brailsford et al. (2019) four different HS techniques (sequential, enriching, interaction, and integration) are used to combine single simulation models. When we look at these HS techniques, integration is the most important and effective

Table 1: Framework to investigate HS literature.

| The Process | Definition | Method |
|---|---|---|
| Hybridization Process | The way of interaction of different simulation models | Sequential<br>Enriching<br>Interaction<br>Integration |
| Linking Process | The way of linking single models | Manual link<br>Automated link<br>Intermediate tool |
| Validation/Verification Process | The way of verifying and validate the model | Statistical methods<br>Face Validity<br>External Validation |

way to make HS since there is no clear distinction between the models as the HS model works as a whole unit. However, many studies in the literature have claimed that having fully integrated HS is difficult and requires coding knowledge and experience in at least two different simulation modeling approaches. Therefore, most of the studies used sequential (two single models run sequentially), enriching (one primary method uses limited sources from the other), and interaction (interaction of two different sub-models) formats to develop HS model. In addition, the linking process is divided into three categories: manual linking, one model output copying and pasting manually from one model to another, intermediate tool that uses other tools to link the models, such as Excel, and automated link that is done by the software itself. Moreover, the model validation process is analyzed by detecting statistical analysis, face validity, or external validity (Brailsford et al. 2019).

## 3 SEARCH METHODOLOGY

In order to start the literature review, the databases and the keywords are decided by the authors. In this case, Web of Science and Scopus are the target databases for this literature review. In order to select the related keywords, the scope of the literature review is defined. The first group of keywords is related to hybrid simulation, and they are used in order to detect hybrid simulation. Any combination of SD, DES, and ABS is used for the second group of keywords to detect all combined papers in the literature. The last group is to limit the literature to only healthcare. We restricted the search to include only articles and review papers written in English from 1970 to February 2022 (both inclusive). The keywords for the literature review are presented in Table 2.

In order to perform this review of the current literature, the articles are identified, screened, and included based on the four phases. Figure 1. shows that 278 articles are identified based on the keywords from Scopus and Web of Science. 93 articles are removed before the screening process since those articles are duplicates or not reachable online. For the screening process, unrelated articles, such as those using an

Table 2: Literature search for hybrid simulation in healthcare.

| Category | Search Terms |
|---|---|
| Hybrid Simulation | ("Hybrid Simulation")<br>OR |
| Combined Simulations | [("Discrete Event Simulation" AND "System Dynamics")<br>OR ("Discrete Event Simulation" AND "System Dynamics"<br>AND "Agent Based Simulation")<br>OR ("Discrete Event Simulation" AND "Agent Based Simulation")<br>OR ("Agent Based Simulation" AND "System Dynamics")] |
| Healthcare | AND ("Healthcare" OR "Disease") |

entirely different methodology or not related to healthcare, are removed. Therefore, 79 HS articles are found related to healthcare. In addition, some of the articles used different modeling approaches rather than DES, SD, and ABS. Those articles are removed from the literature review. Therefore, 33 articles, which include application papers, frameworks, and review papers based on DES, SD, and ABS, are included.

In addition, Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) is used for the literature review. Four phases of selecting the article from target databases are presented below:

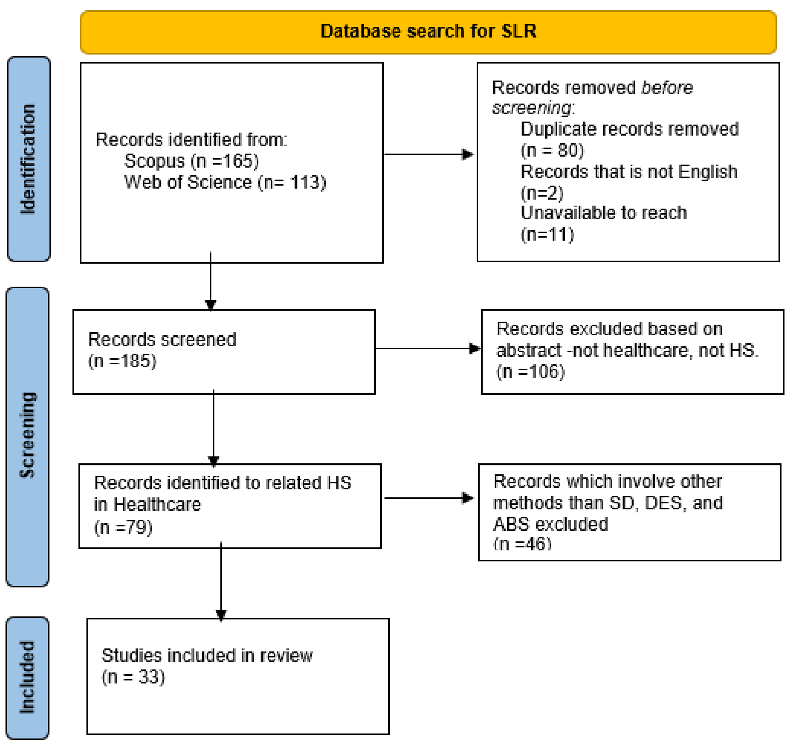


Figure 1: Phases of the literature review.

**Phase 1:** The analysis Unit: It will include what kind of paper will be analyzed (Peer-reviewed article, Articles, Conference Paper) and search engines (Web of Science, Scopus). **Phase 2:** Definition and Categorization of Context: The literature review scope will be hybrid simulation which only includes DES, ABS, and SD in healthcare. **Phase 3:** Retrieval and Delimitation of Article: Three-stage screening procedure (Title, Keyword, Year and Abstract), Overlapping detection, and Elimination. **Phase 4:** Analyzing Collected Articles: To investigate the article's methodology, findings, and challenges.

## 4 RESULTS

In this section, we present the results of our review. As has been mentioned earlier, we have read the full text of the 33 articles in our dataset and have categorized them according to the HS combination employed. In section 4.2, the combination of DES and SD; in section 4.3, the combination of DES and ABS; in section 4.4, the combination of SD and ABS; and in section 4.5, the combination of DES, ABS, and SD are presented.

### 4.1 Statistical Information-Overview

The primary focus of this literature review is to find the published papers which include hybrid simulation models, specifically DES, SD, and ABS in healthcare (Table 3). Other hybrid simulation models, such as combining one of the models with some other methods-combining DES, SD, and Soft System Methodology or DES and Integer Linear Programming-are excluded from this study since those studies are out of scope for this paper. The analyzed paper shows that more than half of the papers (52%) used a combination

Table 3: An overview of HS applications in healthcare [NA: Not Available/Mentioned, FV: Face Validity, SM: Statistical Method EV: External validity, HD: Historical Data].

| **Combining Discrete Event and System Dynamics** | | | | |
|---|---|---|---|---|
| **Authors** | **Method** | **Linking** | **Validate/ Verify** | **Software** |
| Chahal and Eldabi (2008) | Framework | NA | NA | NA |
| Brailsford at al. (2010) | Enriching | Intermediate Tool | FV-SM | Vensim/Simul8 |
| Zulkepli at al. (2012) | Interaction | Manual | NA | Vensim/Simul8 |
| Chahal et al. (2013) | Framework | Manual | FV-SM | Vensim/Simul8 |
| Ahmad et al. (2013) | Sequential | Automated | FV | AnyLogic |
| Viana et al. (2014) | Interaction | Intermediate Tool | SM | Vensim/Simul8 |
| Zulkepli and Eldabi (2015) | Framework | NA | NA | NA |
| Fakhimi et al. (2015) | Framework | NA | NA | NA |
| Mielczarek and Zabawa (2016) | Sequential | NA | SM | ExtendSim/NA |
| Morgan Et al. (2016) | Sequential | NA | NA | NA |
| Zulkepli and Eldabi (2016) | Interaction | Manual | SM | NA |
| Mielczarek and Zabawa (2017) | Sequential | Manual | NA | ExtendSim/Arena |
| Zabawa and Mielczarek (2018) | Sequential | NA | SM | ExtendSim/Arena |
| Mielczarek and Zabawa (2021) | Sequential | NA | SM/HD | ExtendSim/Arena |
| **Combining Discrete Event and Agent-Based Simulation** | | | | |
| **Authors** | **Method** | **Linking** | **Validate/ Verify** | **Software** |
| Kittipittayakorn and Ying (2016) | NA | Automated | SM | AnyLogic |
| Ying and Kittipittayakorn (2018) | Enriching | Automated | SM | AnyLogic |
| Elliott et al. (2019) | Enriching | Automated | SM | AnyLogic |
| Li et al. (2020) | NA | Automated | SM | AnyLogic |
| Henchey et al. (2020) | NA | Automated | NA | AnyLogic |
| Hamza et al. (2021) | Interaction | Automated | SM | AnyLogic |
| **Combining System Dynamics and Agent-Based Simulation** | | | | |
| **Authors** | **Method** | **Linking** | **Validate/ Verify** | **Software** |
| Djanatliev et al. (2012) | Enriching | Automated | SM | AnyLogic |
| Evenden et al. (2021) | Interaction | Automated | EV/SM | AnyLogic |
| **Combining Discrete Event, System Dynamics and Agent-Based Simulation** | | | | |
| **Authors** | **Method** | **Linking** | **Validate/ Verify** | **Software** |
| Djanatliev and German (2013) | Interaction | Automated | FV/SM | AnyLogic |
| Djanatliev and Meier (2016) | Interaction | Automated | HD | AnyLogic |

of SD and DES (17 papers). Only two papers used SD-ABS for their research. On the other hand, the combination of three methods (ABS-DES-SD) is used in two papers for application, and the rest is either a framework or literature review paper. Moreover, the combination of SD and ABS did not grab researchers' attention as much as other combinations. Only two papers used HS as a combination of these two. In addition, ABS has grabbed researchers' attention recently. Therefore, the majority of recent papers include ABS. When the table is analyzed, it is seen that most of the models are linked by using software features. In addition, validation of the models is done by using either statistical analysis or face validity for sub-models. However, the validity of combined models is not presented in the papers.

### 4.2 Discrete Event Simulation and System Dynamics

As mentioned above, most HS models use the combination of DES and SD. 17 out of 33 (52%) papers used the combination of two techniques to solve complex healthcare problems. Chahal and Eldabi (2008) conducted one of the very early studies, which is referred to popularly in the literature as a framework. In their paper, the authors developed an HS model to find a better approach for different modes of governance in the UK healthcare system. They claim that single models have their weaknesses, and the healthcare system should be analyzed from both microscopic and macroscopic perspectives. In order to develop HS, the combination of DES and SD is used. Their model presents three modes: Hierarchical, Process Environment, and Integrated mode. They suggested that using the HS model can cover both microscopic and macroscopic views of healthcare problems. This way, it can overcome detailed and dynamic complexity (Chahal and Eldabi 2011).

Zulkepli and Eldabi (2015) updated the previous framework since the framework did not present a way to simplify the model when needed. They developed a three-phase framework for some non-expert modelers in healthcare simulation. The conceptual phase, which identifies model selection for the problem, and the modeling phase, which refers to how to develop a model in different software, are presented in their framework. In addition, the model communication phase stands for identifying influences and influenced by variables to exchange data output between the models are also presented. The philosophy behind this framework is to make non-modelers understand the logic of hybridization. Moreover, Chahal et al. (2013) developed a generic conceptual HS framework using DES and SD. They realized a generic framework was needed since previous HS studies focused on model development based on the problem. The lack of a generic explanation for developing the HS model remains a clear gap in the literature. Therefore, initial thoughts of a conceptual framework for developing HS models are provided in Chahal et al. (2013). The authors introduce a three-phase framework: The first phase is problem identification, the second phase is developing models and finding the influence variables, and the last phase is the identification of the mode of interaction. The framework is applied in the London district's emergency department (ED) by using parallel interaction mode. The outcome shows that the framework can capture overall objectives and overcome dynamic and detailed complexity. Another study was conducted by Ahmad et al. (2013) for ED. They claim that lack of staff or supply causes the bottleneck in ED. Therefore, waiting time in the treatment process is the main reason for the bottleneck in the department.

Moreover, problems in ED affect not only operational but also strategic levels. HS was designed to capture interdepartmental level effects with SD and departmental level effects with DES. Hence, parallel interaction between the models is developed in order to find a better solution for ED. This gives decision-makers a more comprehensive and precise solution to the hospital system.

Some case studies have been conducted in the early stages of HS. For example, in a chlamydia infection study, process environment mode is used. Even though this is not a fully integrated model for HS, it showed better results than single models (Brailsford et al. 2010; Viana et al. 2014). In this study, SD and DES models are linked in order to predict clinic performance and the process of infection for the community, which means both operational and strategic levels are considered. Another study by Morgan et al. (2016), assumed that using a mixed-method can give a better outcome for stakeholders and modelers. Therefore, they used SD for the macro level and DES for the individual level of the problem. The model is developed iteratively for the cancer center in Scotland. They showed that it is possible to have a way to conceptualize mixed models by examining problems. Another case study was conducted by Mielczarek and Zabawa (2016) in order to find the long-term influence of population changes on demand for different age groups. They developed the HS model by using DES and SD in the Wroclaw region in Poland. They eventually used the same model to estimate the demand for healthcare services. In this model, DES generates emergency demand, whereas SD is used to predict Poland's demographic changes (Mielczarek and Zabawa 2021). In addition, the HS model is developed using sequential approach. The result shows that HS can help to see the future demand for hospital services. In this model, DES is used for individual level of analysis, which detects individuals' history, whereas SD is focused on population-level aggregated data. This study showed that the models could be applied locally and nationally (Mielczarek and Zabawa 2017; Mielczarek and Zabawa 2018; Mielczarek et al. 2018; Zabawa and Mielczarek 2018).

Integrating SD and DES is the most popular way to make HS in healthcare. Zulkepli et al. (2012) developed an integrated care system by combining these two approaches. Even though the system can be modeled using only DES, single model development for an extensive system can be complicated and lose a feedback loop. Modeling large systems using DES can exponentially increase complexity in the later stages. Hence, it is suggested that having an HS model in this case, i.e., combining DES-SD, can give efficient results at both macro and micro levels of the system. In this case, three models were developed. Hospital level and intermediate care models are developed using two separate DES models, whereas SD is used for social care, which improves the decision-making process (Zulkepli and Eldabi 2016).

Fakhimi et al. (2015) analyzed HS from the perspective of sustainability. They developed a framework by using HS and Triple-Bottom-Line (TBL) approaches. The model expressed the importance of combining continuous and discrete simulation for sustainability. In this way, HS can be effective for modeling both strategic and operational levels in healthcare while considering sustainability. The framework uses TBL modeling to select an efficient model for HS. Key performance indicators are defined in order to find a sustainable point of view for hybrid modeling. The model satisfied both sustainability and efficiency. Moreover, the framework can optimize decision-making processes and contribute sustainability of healthcare problems.

All of the above studies show that combining SD and DES, at least as utilized in the cases, would provide reliable results in healthcare modeling. A number of frameworks have been used in these case studies in order to prove the viability of HS in complex healthcare problems.

### 4.3 Discrete Event Simulation and Agent-Based Simulation

Combining DES and ABS is another way to develop HS models. ABS is a much newer approach to be utilized in this context. Therefore, fewer examples of its inclusion exist compared to DES and SD (Brailsford et al. 2019). Our literature review shows that the first paper which used these two combinations was published in 2016. Kittipittayakorn and Ying (2016) integrated DES and ABS for managing an orthopedic department. Their integrated model shows that integrating two models improves patient waiting time in the orthopedic department.

Moreover, draftees waiting time in the physical examination center are analyzed by combining DES and ABS. Their model shows that modeling a physical examination center is more than just data analysis. It is also dependent on the patient's behavior. As a result, using HS is a better way to reduce wait time. (Ying and Kittipittayakorn 2018). Even though the model gives a better outcome, as it captures the combined patient flows and behaviors better when compared to a single model, the development process required more data and coding expertise. The combination provides a better model for hospital layout design and reduces decision makers' subjectivity (Li et al. 2020). The patient flow process in the emergency department is analyzed by combining ABS and DES. The model result shows that combining the models reduced patient waiting time and helped the decision-making progress (Hamza et al. 2021). Henchey et al. (2020) proposed a framework to model capacity, access, and resource evaluation. They used HS for expanding telehealth capacity as well as reducing waiting time. Moreover, HS can optimize risk assessment by combining patients' identities, hospital resource constraints, and queuing (Elliott et al. 2019).

All studies above show that combining DES and ABS gives decision-makers a better idea of the system when the problem involves patient behavior.

### 4.4 System Dynamics and Agent-Based Simulation

When the question is raised for answering population and individual level problems, the combination of ABS and SD seems to be the best way to see the effect of the interaction between the levels. Djanatliev et al. (2012) state that improving technology is beneficial for healthcare systems. A new approach is introduced, namely Prospective Health Technology (ProHTA) for technology assessment in healthcare. They claim that using HS methods will enable us to observe an aggregated and individual level of the system. In this way, the model can represent the real-world system realistically. Therefore, they used the process environment format for the combination of ABS and SD. Moreover, Evenden et al. (2021) conducted a study on care service planning for dementia. In their model, the interaction between the model occurred twice - at the beginning of dementia and death. Their model shows that ABS is a very powerful tool to consider when modeling human behavior. ABS has not been widely used in recent studies. However, its significance is growing. Furthermore, their models demonstrate that combining ABS and SD provides both a stochastic and a deterministic view of the problem.

### 4.5 Discrete Event Simulation, Agent-Based Simulation, and System Dynamics

Most of the combined three approaches in the literature explained the benefit of having HS and developed a framework. Djanatliev and German (2013) improved the previous ProTHA model by adding process-oriented DES to their hybrid model. Domain-specific HS framework in healthcare was developed by Djanatliev and German (2015). Their framework is a three-step (identify levels, horizontal, and vertical linking) framework for making HS. It is a sustainable and reusable model for other specific domains.

Moreover, they proposed four levels: macro, meso, micro, and internal, for decision support in HS. In addition, Djanatliev and Meier (2016) used the framework for hospital process modeling. The model proposed a theoretical perspective of hospital process modeling by using hybrid simulation models. Four levels are identified and applied for hospital process modeling. The process can be modeled using DES with ABS and enriching it with the surrounding process environment. Abdelghany and Eltawil (2014) claim that the integrated simulation model outperforms when compared with single models since the model can manage the limitation of the single models. They proposed a Tri-integrated model framework that combines DES, ABS, and SD. In the framework, information passes between the models (hierarchical format) in order to minimize patient waiting time. DES provides information for SD model, and SD provides a model for ABS.

### 4.6 Software

The increases in computer power have facilitated the use of HS by modelers, which has accelerated the process of model development, integration, and analysis. The literature review shows that AnyLogic is the most common software to use in order to develop an HS model. It provides an opportunity to combine three models in one software. However, it requires some coding experience in Java. Moreover, some researchers used a combination of different software by using Excel. Arena and Simul8 are used for developing DES, whereas ExtendSim and Vensim are used for SD. The combination of the models can be done most of the time manually, and the models are not fully integrated. It is shown that using AnyLogic is promising software for HS. Djanatliev et al. (2014) suggest that AnyLogic is a reliable tool for a domain-specific framework for reusable modeling.

Moreover, AnyLogic allows modelers to create their libraries. Therefore, it might be the preferred software among HS modelers. In addition, the combination of DES and SD is the most popular HS approach, and AnyLogic (in 11 papers) is the most used software to conduct application papers for HS. The literature review shows that when ABS is involved in the model combination, AnyLogic is the preferred software since a combination of ABS with other models is less complicated. In addition, Simul8 is mostly associated with Vensim, whereas Arena is associated with ExtenSim for the combination of DES and SD. The combination of ABS with other methods by using other software than AnyLogic needs further investigation.

### 4.7 Validation and Verification

When the papers are analyzed, it is seen that most of the papers do not validate or verify their model. However, some papers validated their model, as shown in Table 3. Statistical methods or face validity are used in order to validate the model. Generally, statistical results are used to validate quantitative methods, whereas expert opinion or face validity is used for qualitative validity. Only 41% of the application papers used statistical results, and 20% used face validity and statistical methods to validate both quantitatively and qualitatively.

## 5 DISCUSSION

This review paper aims to analyze, categorize and synthesize academic literature on the application of HS in the healthcare sector. In this research, 33 relevant papers have been reviewed and analyzed. The outcome (24 papers) was presented and classified HS studies based on different model combinations, used software, and validation and verification process. It is evident from the above studies that having HS is more effective for understanding complex systems, especially in healthcare. The limitation of single models led the modelers to search for alternative ways to overcome the challenges of complex systems since decision-makers should consider the entire system and department-specific. Therefore, HS is a promising approach to optimize the problems for the entire system. Moreover, the world is rapidly changing. Sustainable and reusable models are crucial for detecting the healthcare system's problems. In addition, simulation modeling should be adjustable for rapid changes since the healthcare system might encounter global problems, and decision-makers should react to the problem as early as possible. All of these reasons proved the importance of HS even more. Therefore, there is a need for more research in the area.

All of the above studies used a well-known framework and applied it in their models. The frameworks mentioned in Chahal and Eldabi (2008) and Brailsford et al. (2019) seem to be the most common frameworks for developing hybrid simulation. A number of case studies also suggest the feasibility of implementing these frameworks. Lather and Eldabi (2020) suggest that using publicly available single models could be used in order to make HS models. A platform that allows modelers to use other researchers' models can be one way forward. Therefore, the idea of developing an open-source hub can transfer the data as an input and output for other models.

Most of the developed models in the literature are research specific. Even though some studies explain the reason for using HS and its methodology, most of them focus on problem-specific modeling. Therefore, developing a generic and applicable HS model is needed. Most of the studies did not clearly explain choosing the methodology. It is hard to understand that the developed model is applicable for other problems since most of them are highly dependent on the research objectives. Therefore, developing a framework to show how to link the single modeling approaches without being problem-specific is necessary for future research.

### 5.1 Limitations of Current Literature

The most important realization from the above literature is that modelers are developing models based on their expertise rather than what the problem needs. When modelers develop an HS model, they usually fall into the trap of adapting the problem to the best method they know (Nguyen et al. 2020). There is a need to think more about expertise bias since it may be quite challenging for researchers to select modeling approaches objectively. In addition, the validation process of the published papers is not fully explained in the papers. Most of the case sub-models are validated by using validation methods. However, HS validation is not achieved clearly. Moreover, external validity should be considered for HS. Moreover, human interaction in the problems plays a crucial role. Therefore, ABS is one of the powerful methods to detect the interaction. Hence, considering the combination of all three methods may give better results for complex healthcare problems.

## 6 CONCLUSION

HS modeling has been grabbing researchers' attention lately. People attempted to overcome the limitation of single models by using HS. In this literature review, single simulation models (DES, SD, ABS) and the limitation of the models are discussed. In addition, HS modeling approaches are investigated. The different ways of developing HS are presented. The combination of DES and SD is the most common way to develop HS for complex healthcare problems. HS has the potential to solve complex healthcare problems. In addition, fully integrated HS is not achieved in healthcare literature. Either using Excel or AnyLogic achieves the model combination of the models. Moreover, the necessity of having generic and applicable model development is detected. When ABS is involved for HS, only AnyLogic software is used. However, there are some other software that can be used in order to develop HS with ABS. In addition, using ABS is mainly combined with DES. However, involving SD in the model can give a strategic view of the problem. Therefore, developing a framework for linking single models should be investigated in future research.

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