Proceedings of the 2020 Winter Simulation Conference
K.-H. Bae, B. Feng, S. Kim, S. Lazarova-Molnar, Z. Zheng, T. Roeder, and R. Thiesing, eds.

A REVIEW OF HYBRID SIMULATION IN HEALTHCARE

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ABSTRACT

Hybrid Simulation (HS) has been applied to healthcare systems, but there is still limited literature and an opportunity to develop research. This review explores applications of HS in healthcare, to outline research gaps and foster new research in HS to solve complex real healthcare problems. The twelve application papers found through a systematic literature search covered nearly all hybrid combinations. Discrete Event (DES) and System Dynamics (SD) were found to be the most popular combination, and AnyLogic, the most used HS tool. We found that none of the papers we reviewed used the SD-ABS approach, which raises questions about the need and challenges associated with certain combinations. HS in healthcare applications, for the most part, are published in conference proceedings. We discuss opportunities for research and, in particular, the potential for HS application in problems related to communicable disease and healthcare services planning.

1 INTRODUCTION

Simulation has modeled many aspects of the healthcare system (e.g., Emergency Room (ER), home care, and surgery and recovery) over the last 40 years. Eldabi et al. (2018) argued that healthcare problems have multiple aspects and rarely possible to capture all of them in one single model using one method. Hybrid simulation (HS) provides modelers with the flexibility to combine simulation methods to conduct the modeling of complex systems. Indeed, mixing simulation methods is useful in representing different aspects of a complex system that cannot be tracked by a single simulation method. Hybrid simulation can be defined as "*one single conceptual simulation model that, when implemented in computer software, uses more than one simulation paradigm*" (Mustafee et al. 2017).

The number of HS publications in healthcare corresponds to 22% of articles in HS (Brailsford et al. 2019), which is indicative of the importance and potential for HS in this application domain. Most of the papers have a theoretical or methodological approach, discussing the framework (Zulkepli and Eldabi 2015), providing a taxonomy (Lynch and Diallo 2015) and boundaries between the concept of HS and multi-methodologies in OR (Mustafee et al. 2015a). Not much is put forward to explore the implementation of HS in healthcare (Brailsford et al. 2010). This paper puts forward an analysis of HS applied to healthcare. More specifically, the main contributions of this work are to (1) identify gaps in the combinations of simulation methods forming HS models in healthcare; (2) be the first study to use Brailsford et al. (2019) framework to analyze the hybridization process of these applications in healthcare; and (3) look at the opportunities of applying stakeholder engagement to HS in healthcare given the growing interest in single simulation methods (Tako and Kotiadis 2015).

The paper has further six sections. Section 2 provides an overview of the literature in simulation and Hybrid Simulation, discussing terminology, model type, and HS framework variables. Section 3 describes the methodology adopted in this review. Section 4 brings broad findings to the selected papers, and sections 5 and 6 are dedicated to discussing the gaps found by this review and the conclusion, respectively.

2 BACKGROUND LITERATURE

2.1 Simulation in Healthcare

This section will address the main simulation techniques of Discrete Event Simulation (DES), System Dynamics (SD), and Agent-Based Modeling (ABM) (Brailsford et al. 2019). Table 1 shows some examples of papers of single simulation techniques to problems that are comparable to the ones we have found when exploring applications using HS. We have categorized these into three main healthcare areas. The category of hospital management includes all hospital departments as well as outpatient clinics. Disease management explored the spread of the transmission process of communicable diseases, disease screenings, and health policies. Healthcare system planning encompasses all efforts to evaluate policies that affect a whole system (e.g., social and health care). Some papers focus on a more significant number of healthcare categories to ours (e.g., Roberts 2011). However, we have purposefully kept to fewer categorizations due to the limited number of HS application papers that we are subsequently exploring with the same categorization.

Table 1: Examples of works that applied single simulation methods.

Category	Authors	Method	Main problem	Management lens
Hospital Management	Lane et al. (2000)	**SD**	Evaluate the waiting time in an A&E by testing hypotheses related to restrictions of bed capacity.	Operational
	Chen, et al. (2015).	**DES**	Improving appointment scheduling at an outpatient center.	Operational
	Pessoa et al. (2015)	**DES**	Improve surgical center management at a hospital, with a historic low volume of surgeries as a consequence of restriction on capacity.	Operational
Disease management	Kasaie et al. (2013)	**ABS**	Study Tuberculosis (TB) transmission dynamics and the role of various contact networks by using a hierarchically structured population.	Operational
	Evenden et al. (2005)	**SD**	Study the Chlamydia infection dynamics within a population, incorporating the behavior of different risk groups.	Operational
Healthcare system planning	Bayer et al. (2010)	**DES**	Evaluate changes in protocols that address the delivery of stroke care, leading cause of death, and severe long-term disability.	Operational
	Rashwan et al. (2015)	**SD**	Analyzing the dynamic flow of elderly patients in the Irish healthcare system and how it affects the demand for healthcare services.	Strategic

DES is frequently applied to hospital management type of problems such as the planning of healthcare services process (Katsaliaki and Mustafee 2011) and to improve patient flow at healthcare facilities (Abdelghany and Eltawil 2017). SD is applied for evaluating public health policies (Katsaliaki and Mustafee 2011) and for comprehending the complicated relationship between operating rooms and other hospital departments as well as the dynamic of disease in a specific population (Günal and Pidd 2010). In contrast, ABS is commonly employed when the complex interaction between heterogeneous agents or elements (clinicians versus patients; mosquitos versus humans) is essential to comprehend the dynamics of a system (Nianogo and Arah 2015). In the case of healthcare systems, "*everything affects everything else*" (Eldabi et al. 2018). Besides, "*it is impossible to isolate one part of a healthcare system from the rest of the system without severely compromising the usefulness of the model in practice*" (Mustafee et al. 2015b). In this regard, Hybrid simulation (HS) captures different parts of a system and is thought to overcome the drawbacks of modeling with single approaches (Brailsford 2015).

2.2 Hybrid Simulation and Hybrid Model

A few terms have been employed to HS. For instance, the mix of simulation methods (Morgan et al. 2017), composite models (Viana et al. 2014), a hybrid model (Chahal and Eldabi 2008), modeling & simulation approach (Fakhimi et al. 2014) and multi-paradigm model (Diallo et al. 2010) are some of those synonyms. Few authors recognized a difference between HS and the hybrid model (or multi-methodology). Mustafee et al. (2015) differentiate the HS definition from Hybrid System Modeling (HSM). For those authors, HS encompasses the exclusive application of simulation methods, while HSM is 'the combined application of simulation with methods and techniques from disciplines such as applied computing, computer science, system engineering' to any stage of modeling lifecycle.

Additionally, simulation methods can be grouped in several ways. Mustafee et al. (2017) argued that there are three most common simulation methods to be mixed: DES, SD, and ABS, and consequently four HS models: DES-SD, DES-ABS, SD-ABS, and DES-SD-ABS. In contrast, Arisha and Rashwan (2016) included Monte-Carlo Simulation (MC) as a fourth simulation technique, broaden the number of possible HS models.

DES-SD model is not a new topic in the OR community, being the most popular hybrid approach yet. Brailsford et al. (2019) show that the DES-SD combination is 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). Monte Carlo (MC) has not been a popular method in HS (Arisha and Rashwan 2016), representing only 3% of the HS models in their review.

2.3 Hybrid Simulation Framework and Components

The simulation lifecycle is defined as the group of stages that guide modelers over the cycle of simulating a real-world problem. Robinson (2004) proposed the framework of a four-key stage (conceptual modeling, model coding, experimentation, and implementation) in developing a simulation project.

Similarly, Chahal and Eldabi (2008) proposed a framework for the DES-SD model in healthcare. However, their framework covers the initial phases exclusively for defining the problem and for selecting the variables for this type of model. Zulkepli and Eldabi (2015) introduced a similar framework, also for the DES-SD model in healthcare, however, with three stages (conceptual, modeling, and communication phases), covering the whole stages for a simulation process, similar to Robinson (2004). Brailsford et al. (2019) put forward a framework to describe five areas of variability when mixing simulation methods, regardless of the context (Table 2).

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

Areas of variability in HS	DEFINITION	CATEGORIES
Model Hybridization *(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 the exchange of data 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 (collect for this study) or secondary (collected not only for this study).	S1 - Real-world S2 - Illustrative S3 - Mixed (primary and secondary data)
Verification & Validation *(Stage 3: Experimentation)*	States the approach used to ensure the accuracy of results and the adherence of the model 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

The inclusion of those areas of variability into a framework is useful to understand the development of a hybrid simulation model (Onggo 2014). The categorization from Table 2 was included in Table 3 in order to understand the mixing simulation methods in HS better. We are not aware of the framework being adopted as such for the analysis of HS literature.

A few studies proposed frameworks with ABS. For instance, Nasirzadeh et al. (2018) also proposed a framework for combining SD-ABS with five main steps: (1) Selecting simulation method, (2) Determining the modeling system hierarchy, (3) Defining information flow path; (4) Selecting HS type and (5) Defining interface variables. Although this framework has similarities with the DES-SD frameworks cited above, this work was only tested and applied to construction projects. On the other hand, Mittal and Krejci (2019) proposed a DES-ABS generic framework for a regional food hub, with two main steps with a focus on the integration of both methods.

3 SEARCH & METHODOLOGY

Figure 1 shows the phases of the systematic literature review adopted in this review.

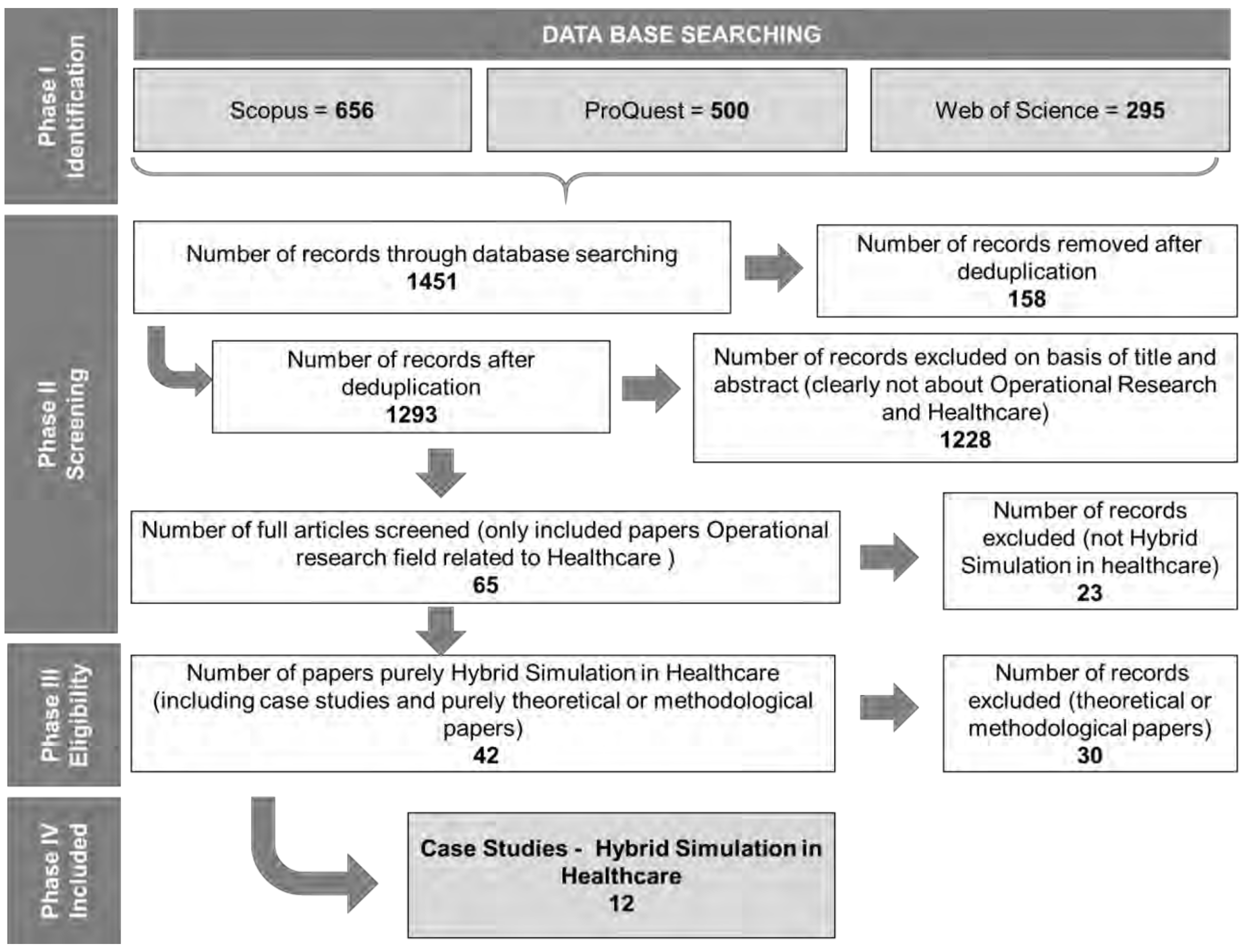

Figure 1: Phases through the systematic literature review.

This study adopted the flow of information through four main phases - identification, screening, eligibility and included (Figure 1), based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) guidelines, used for many review papers in healthcare (Shamseer et al. 2015; Cassidy et al. 2019). The first phase was carried out using the search for the following keywords: "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*" AND "healthcare*" through three electronic databases: Scopus, ProQuest, and Web of Science.

4 ANALYSIS OF PAPERS

4.1 Publications Overview

We have identified 12 articles of hybrid simulation in healthcare. Although this review identification phase has not restricted the year of publication, the subsequent filters naturally resulted in case studies published after 2012. Most of the studies were published as conference proceedings. Five papers were from Norway, three from Poland, two from the UK, one from Canada, and another from the US. Furthermore, the five Norwegian papers have Viana as the principal author, and Mielczarek and Zabawa authored the three Polish articles. Regarding the framework (Brailsford et al., 2019), all papers have used real-world data (S1) to feed the model. The most common hybridization was sequential (H2) and interaction (H3). In terms of the integration process, five papers presented an automated (H1) integration, and one has the support of an intermediate tool (I3). In general, it was not possible to evaluate all the areas of variability in the framework for all papers, since most of them have not reported information about the V&V and implementation. The next sections will explore each of the combinations of simulation approaches found in the twelve papers as well as the value-added through the hybridization by showing a comparison between a single approach (Table 1) and the HS models (Table 3).

4.2 Discrete Event Simulation and System Dynamics

Seven cases applied the DES-SD combination in simulation, making it the most common hybrid combination. While five papers addressed the hospital management problem, two were dedicated to disease management issues. None have addressed questions related to healthcare system planning. Likewise, all papers have explored the operational and strategic perspectives of the problem in the analysis.

Half of the DES-SD models reported the commercial packages used with noted differences in these or combinations to enable HS. For instance, He et al. (2013) developed their DES model in Flexsim (SD software) for representing the orthopedic clinic. Viana et al. (2014) used two software: Vensim and Simul8, and Tejada et al. (2014) modeled in Arena. Mielczarek and Zabawa (2017) also used Arena but combined with ExtendSim9.

Regarding the areas of variability (Table 2), six papers reported their model hybridization as sequential (H2), which means that the models remained independent with each method fulfilling a specific purpose, and they had a small overlapping, where information was exchanged between them. In Viana et al. (2014) and Tejada et al. (2014), the DES part represented a hospital outpatient clinic. However, SD was used to model the infection process of Chlamydia infection in the community, and the impact of policies on the screening and treatment of breast cancer in the US, respectively. In both works, the conceptual model clearly shows the DES apart of the SD model as well as the key element that connects both methods into an HS model. Similarly, He et al. (2013), Mielczarek and Zabawa (2016), Mielczarek and Zabawa (2017), and Mielczarek et al. (2018) presented the same pattern in their conceptual model.

All papers had the model input source classified as real-world (S1), and two papers mentioned implementation as potential but not real (IM2). Additionally, only Viana et al. (2014) explained the use of excel (I3) to integrate both methods as well as the challenges of connecting two distinct commercial packages that use different programming languages.

Some of these papers (He et al. 2013; Viana et al. 2014; Tejada et al. 2014; Morgan et al. 2016) briefly discussed the stakeholder involvement; however, none of them explicitly cited official facilitated approaches, frequently used in simulation studies that apply stand-alone methods.

Table 3: Summary of papers included in this review.

Category	Authors	HS model	Software	Management lens	Real problem or study purpose	Stakeholder engagement
Disease management	Tejada et al. (2014)	**DES-SD** (H2,S1)	Arena	Strategic	Evaluating the costs incurred for screening exams on treatment of breast cancer.	Discussions experts
	Gao et al. (2014)	**DES-SD-ABS** (H3,I1,S1)	AnyLogic	Strategic	Comprehending the rising rates of diabetes and diabetic ESRD.	NOT REPORTED
	Viana et al. (2014)	**DES-SD** (H2,I3,S1, IM2)	VENSIM SIMUL8	Strategic	Comprehending the relationship between the disease spread and the increase on demand at clinics.	Discussion with clinic staff
Hospital Management	Viana et al. (2018)	**DES-ABS** (H3,I1,S1, IM2,V3)	AnyLogic	Strategic; operational	Comprehending the demand uncertainty due to an increase in the size of the hospital's catchment area in Norway.	Collaboration with clinic staff
	He et al. (2013)	**DES-SD** (H2,S1, IM2)	Flexsim	Strategic; operational	Quantifying the potential impact of an overbooking policy, not only from a strategic but also from an operational.	Interview with key stakeholders
	Morgan et al. (2016)	**DES-SD** (H3,S1)	Not Reported	Strategic; operational	Planning the radiotherapy treatment, giving the treatment complexity and changes in treatment regime.	Semi-structured/ Unstructured interviews.
	Mielczarek and Zabawa (2016)	**DES-SD** (H2,S1)	Not Reported	Strategic; operational	Studying the influence of long-term population changes on the demand for healthcare services	NOT REPORTED
	Mielczarek and Zabawa (2017)	**DES-SD** (H2,S1)	Arena; Extend Sim 9	Strategic	Estimating the level and structure of the demand for healthcare services	NOT REPORTED
	Mielczarek et al. (2018)	**DES-SD** (H2,S1)	Not Reported	Strategic; operational	Evaluating the increase on demand for healthcare services, giving the age structure of Polish population.	NOT REPORTED
	Viana et al. (2016)	**DES-ABS** (H3,I1,S1, IM2)	AnyLogic	Strategic; operational	Analysing the effects of long-term demographic changes on future demand for healthcare services.	Series of workshops
Healthcare system planning	Viana et al. (2017)	**DES-ABS** (H3,I1,S1, IM2)	Anylogic	Strategic	Evaluating the effectiveness of the home hospital service.	Supported by stakeholders
	Viana et al. (2012)	**DES-SD-ABS** (H3,I1,S1, IM2)	AnyLogic	Strategic; operational	Evaluating the impact of ageing on demand for treatment against a visual impairment in the elderly.	Fully stakeholder-driven

4.3 Discrete Event Simulation and Agent-Based Model

Three studies combined a DES-ABS simulation (Viana et al. 2016; Viana et al. 2017 and Viana et al. 2018). Viana et al. (2016) have represented an obstetrics department at a Norwegian hospital, by having DES modeling the hospital system with its obstetric wards and ABS for patient entities, containing demographic and patient pathways information. Yet, Viana et al. (2017) and Viana et al. (2018) have modeled home hospital services and overdue pregnancy outpatient clinics, respectively. Similar to DES-SD models, the DES-ABS combination had DES representing a medical facility (hospital or outpatient clinic). However, ABS was used to model different kinds of behavior or communication within the agents.

Viana et al. (2017) and Viana et al. (2018) had its start point upon their previous experience in modeling the obstetrician department (Viana et al. 2016). Besides all similarities, only the latter addressed the model conceptualization, presenting two models: a pure DES and a hybrid DES-ABS model. According to Viana et al. (2016), the dynamic of building the DES model before the HS model supported the stakeholders' comprehension of the HS model. All studies have used AnyLogic software, which enabled all simulation methods to be modeled in the same software. Nothing was mentioned over validation and verification in Viana et al. (2016) and Viana et al. (2017). However, Viana et al. (2018) stated that the clinic staff judged the model accuracy. Additionally, an interface between AnyLogic and software R allowed post hoc analysis. This paper has provided further details on validation.

Regarding the other areas of variability in HS, all works had the model hybridization classified as interaction (H3), the model integration process was automated (I1), the input source was real-world (S1), and the implementation was potential, but not real (IM2).

All articles mention the involvement of stakeholders in the conceptualization phase. Viana et al. (2016) mentioned that a 'series of workshops' supported the data collection; however, the approach used during the workshops was not explained in the paper.

4.4 Discrete Event, System Dynamics and Agent-Based Model

DES-SD-ABS model represents the most complete and complex approach in the HS spectrum. By joining the three most popular methods in simulation, the modelers explore the three levels of a system: macro, 'meso', and micro (Djanatliev and German 2013), offering a top-down and a bottom-up perspective. According to Brailsford et al. (2019), from a total of 139 papers, 14 papers have been published this combination of simulation, with 8 of these being case studies and six frameworks. This review searched two papers in the DES-SD-ABS model: one for disease management problem (Gao et al. 2014) and another for health system planning (Viana et al. 2012).

Viana et al. (2012) developed a model in which DES represented the clinic, SD models were used for modeling the process of sight loss for each eye, and ABS explored the social care scenarios by representing the 'health, history, and other individual-level information. Gao et al. (2014) developed a model for evaluating the impacts of upstream and downstream interventions to patients with the diagnosis of diabetes. While DES captured the impact of resources available, SD characterized *"the evolution of the health, body weight, and (pre-diabetes) diagnosis status of non-diabetics"*. ABS modeled the individuals with diabetics in order to *"capture social network effects and geographical information*" (Gao et al. 2014).

Regarding the areas of variability in HS, there is no information about model input source or verification and validation. If we compare this to stand-alone DES studies, this is unusual. Pessoa et al. (2015) and Chen et al. (2015), papers cited in Table 1, have validated the proposed model. For instance, Pessoa et al. (2015) applied statistical tests, and Chen et al. (2015) compared the model outcomes with current data. In terms of model implementation, both papers had it as potential but not real (IM2), repeating the same pattern of previous models. Model hybridization was by interaction (H3) and model input classified as automated (I1). Both classifications might be a consequence of using AnyLogic. Yet, the model integration process was stated as the real-world (S1).

Finally, the involvement of stakeholders was not clearly detailed over both papers. Viana et al. (2012) only stated that a "*fully stakeholder-driven"* approach guided the model development, not giving full details on which methods were employed in their study. Likewise, Gao et al. (2014) did not explain the methods adopted for collecting data or developing the model.

4.5 Hybrid Simulation versus Single Method Approach

The comparison of papers in similar healthcare contexts of stand-alone methods (Table 1) and HS model (Table 3) provided some initial thoughts that would ultimately need to be explored in a more comprehensive study. Firstly, regarding the management lens, HS brought another perspective to problem-solving, while single approach papers analyzed the problematic situation from an operational perspective only. Combining

SD and ABM with DES brought a strategic perspective when comparing to papers, only deploying DES to model the system. A possible explanation for this might be in the nature of SD. Modeling a system as stocks and flows and allowing this macro-level modeling. Similarly, ABS depict the behavior, however, at an individual level (Siebers et al. 2010), which can enhance both the operational and strategic understanding.

Secondly, applications using single methods and those using HS have been chosen to address similar problems in all categories (e.g., disease management, hospital management), but we note that HS could capture more relevant details, allowing a higher 'closeness' to the problematic situation. Consequently, "*this higher level of details would allow for asking questions not answerable through a more general model*" (Mustafee et al. 2015a). For instance, Viana et al. (2014) built a model to address questions related to the spread of an infectious disease. Instead of building a pure SD model (Rashwan et al. 2015), they included a DES model, representing the medical facility's capacity for the disease treatment. As a consequence, the model allowed the researchers to make conclusions about the increase of untreated patients in the long-term, giving the clinic performance and operational restrictions. In contrast, Evenden et al. (2005) applied a pure SD approach to understanding the same disease; however, representing the dynamics of infection exclusively.

Further comparisons of the review papers through Table 1 and Table 3 were not possible. A possible explanation for this might be that HS papers in healthcare are still only found as conference papers and, by their nature, are less detailed than journal articles. This makes comparisons with single methods challenging and potentially misleading. However, future research should address these comparisons, which will ultimately reveal the added value that can be gained from hybridization.

5 DISCUSSION

5.1 Potential Application Areas and Challenges for HS

Healthcare systems are multi-faceted systems in constant changes, influencing and be influenced by many agents within (e.g., health policies, health entities, patients) and outside (e.g., economy, politics) its boundaries. In the comparisons, we generally found that stand-alone studies using one simulation method are likely to limit their approach to one dimension of the system, as it was shown in section 2.1 and section 4.5.

In line with previous studies, we showed the prevalence of the DES-SD model and the lack of studies that applied DES-ABS or DES-SD-ABS models in healthcare. Equally, frameworks (Chahal and Eldabi 2008; Zulkepli and Eldabi 2015) were already proposed to DES-SD models in healthcare; however, not much is reported for the other hybrid combinations (Mustafee et al. 2015a). Nasirzadeh et al. (2018) are one of the few examples of studies, which proposed a framework for the SD-ABS model; however, it was only applied to construction projects. Under certain assumptions, this study might support modelers to develop an SD-ABS framework to healthcare, giving its lessons learned in proposed it to the complex environment of construction projects.

This review confirmed a few challenges faced by HS regardless of the application context, but these would also be relevant to healthcare problems. Eldabi and Young (2005) argued that there is still a significant gap in developing models in which human behavior, 'especially as related to patient choice.' We believe that this might be due to difficulties in collecting a high level of details, especially related to intangible variables (e.g., psychological and social factors). *"Higher level of details demands more components, and when these components do not exist, more assumptions"* are added to the model (Mustafee et al. 2015a). Future researches could be devoted to this issue by exploring the application of the DES-SD-ABS and SD-ABS models. Especially the second one, which did not have any case in this review.

Furthermore, this review sustained that validation and verification might be a challenge for HS modeling in healthcare. Only Viana et al. (2018) have briefly explored this theme to their DES-ABS model. A possible explanation for this might be that validation is already a complex process for stand-alone methods, and considering that HS involves different methods, it becomes more complex and requires a mix of distinct approaches (e.g., quantitative and qualitative). Eldabi et al. (2018) argued that the validation of the SD and ABS model differs from the DES validation. While DES requires statistical methods, the SD involves a face validity with the expert analysis over the whole simulation lifecycle. In contrast, ABS traceability would require a micro-level analysis of each relationship between agents in the system. Micro-level analysis potentially increases the time and costs to develop and implement a model, which can make it unfeasible from a business standpoint (Mustafee et al. 2015a). A long time to develop a model might also be the justification of the high number of papers, which reported their study as *"potential, but not really"*. Similar to Viana et al. (2016), it is probable that they were in the early stages by the time of their publication. However, the nature of healthcare problems is such that a valid model validity could be an arguably safer model to use for decision making.

Finally, our review put forward examples of HS models in addressing multidimensional problems of the healthcare system. Many context areas still not covered, and further research should be undertaking to investigate the potential of HS in addressing these. For example, HS could be applied to study the impact of infectious diseases. Currie et al. (2020) showed the contribution of simulation to reduce the effect of COVID-19. HS could support key regional (country) and organizational decisions over the three phases (preparedness, response, and recovery) of the COVID-19 pandemic to address decisions related to the social distance, staffing, hospital capacity, and health & well-being. The benefits of HS can also be used for modeling non-communicable diseases (e.g., diabetes), study the impact of new medical interventions or changes on policies that can affect the entire healthcare system. Additionally, HS could potentially support Global Challenges relating to healthcare. With the primary goal of *"involving and protecting health worldwide"* (United Nations, 2020), United Nations has an agenda with several priorities in health, since communicable diseases (e.g., tuberculosis and venereal disease) to universal health coverage. Giving the complexity of each country, HS could cope with demographic trends, epidemiological profiles (e.g., SD method of HS modeling this), behavior (e.g., ABS of HS modeling this), and health care services (e.g., DES method of HS modeling this) in an integrated view for each region (country or macro-regions).

5.2 Stakeholder Engagement

It is argued that simulation studies that involve stakeholders throughout its lifecycle are keener to implement its findings (Young et al. 2009). Several studies explored the topic for stand-alone simulation methods in healthcare (Tako and Kotiadis 2015; Lame et al. 2019). In our review, none of the HS studies consider stakeholder engagement in the simulation lifecycle. Studies outside the healthcare domain (Jones et al. 2019) recently showed the gains of engaging stakeholders throughout the HS modeling process, so there is potential.

This study considers the use of soft OR methods for the involvement of stakeholders shown to be useful in stand-alone simulation studies (Tako and Kotiadis 2018). Some of THE studies we reviewed have mentioned the use of interviews or workshops for understanding the problematic situation; however, the use of those qualitative methods is not enough to infer that soft OR methods were part of their approach. Thus, future research should be devoted to exploring the benefits of using soft OR approaches throughout the HS modeling, highlighting the gains of involving the stakeholders from conceptualization to model implementation.

6 CONCLUSION

Simulation has been applied to the healthcare system over the last decades, and HS has shown promise and potential. However, there are still opportunities for further research. We identify that stakeholder engagement is still a domain to explore in HS, similarly to the manner it has been applied to single methods. Additionally, we also encourage more HS case studies to be reported in healthcare, those combining SD-ABS models, which was not found by this review, and DES-SD-ABS that might bring a novel worldview to HS in healthcare in connecting different dimensions of the system enabling a strategic and operational lens.

REFERENCES

Abdelghany, M., and A. B. Eltawil. 2017. "Linking Approaches for Multi-Methods Simulation in Healthcare Systems Planning and Management". *International Journal of Industrial and Systems Engineering* 26(2):275-290.

Arisha, A., and W. Rashwan. 2016. "Modeling of Healthcare Systems: Past, Current, and Future Trends". In *Proceedings of the 2016 Winter Simulation Conference*, edited by P. Frazier, T. M. Roeder, R. Szechtman, and E. Zhou, 1523-1534: Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Bayer, S., C. Petsoulas, B. Cox, A. Honeyman, and J. Barlow. 2010. "Facilitating Stroke Care Planning Through Simulation Modelling". *Health informatics journal* 16(2):129-143.

Brailsford, S. C. 2015. "Hybrid Simulation in Healthcare: New Concepts and New Tools". In *Proceedings of the 2015 Winter Simulation Conference*, edited by L. Yilmaz, W. K. V. Chan, I. Moon, T. M. K. Roeder, C. Macal, and M. D. Rossetti, 1645–1653. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Brailsford, S. C., S. M. Desai, and J. Viana. 2010. "Towards the Holy Grail: Combining System Dynamics and Discrete-event Simulation in Healthcare". In *Proceedings of the 2010 Winter Simulation Conference*, edited by B. Johansson, S. Jain, J. Montoya-Torres, J. Hugan, and E. Yucesan, 2293-2303. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Brailsford, S. C., T. Eldabi, M. Kunc, N. Mustafee, and A. F. Osorio. 2019. "Hybrid Simulation Modeling in Operational Research: A State-of-the-Art Review". *European Journal of Operational Research* 278(3):721-737.

Cassidy, R., N. S. Singh, P. R. Schiratti, A. Semwanga, P. Binyaruka, N. Sachingongu, C. M. Chama-Chiliba, Z. Chalabi, J. Borghi, and K. Blanchet. 2019. "Mathematical Modeling for Health Systems Research: A Systematic Review of System Dynamics and Agent-Based Models". *BMC Health Services Research* 19(1):1-24.

Chahal, K., and T. Eldabi. 2008. "Applicability of Hybrid Simulation to Different Modes of Governance in UK Healthcare". In *Proceedings of the 2008 Winter Simulation Conference*, edited by S. J. Mason, R. R. Hill, L. Mönch, O. Rose, T. Jefferson and J. W. Fowler, 1469–1477. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Chen, Y., Y. H. Kuo, H. Balasubramanian, and C. Wen. 2015. "Using Simulation to Examine Appointment Overbooking Schemes for a Medical Imaging Center". In *Proceedings of the 2015 Winter Simulation Conference*, edited by L. Yilmaz, W. K. V. Chan, I. Moon, T. M. K. Roeder, C. Macal, and M. D. Rossetti, 1307-1318. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Currie, C. S., J. W. Fowler, K. Kotiadis, T. Monks, B. S. Onggo, D. A. Robertson, and A. A. Tako. 2020. "How Simulation Modelling Can Help Reduce the Impact of COVID-19". *Journal of Simulation* 14(2):83-97.

Djanatliev, A., and R. German. 2013. "Prospective Healthcare Decision-Making by Combined System Dynamics, Discrete-Event and Agent-Based Simulation. In *Proceedings of the 2013 Winter Simulation Conference*, edited by R. Pasupathy, S. -H. Kim, A. Tolk, R. Hill, and M. E. Kuhl, 270-281. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Diallo, S. Y., J. J. Padilla, and A. Tolk. 2010. "Why is Interoperability Bad: Towards a Paradigm Shift in Simulation Composition". In *Proceedings of the Fall Simulation Interoperability Workshop*. September 20th – 24th, Orlando, Florida, 20-24.

Eldabi, T., and T. Young. 2007. "Towards a Framework for Healthcare Simulation. In *Proceedings of the 2007 Winter Simulation Conference,* edited by S.G. Henderson, B. Biller, M. H. Hsieh, J. Shortle, J. D. Tew and R. R. Barton, 1454-1460. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Eldabi, T., S. Brailsford, A. Djanatliev, M. Kunc, N. Mustafee, and A. F. Osorio. 2018. "Hybrid Simulation Challenges and Opportunities: a Lifecycle Approach". In *Proceedings of the 2018 Winter Simulation Conference*, edited by M. Rabe, A. A. Juan, N. Mustafee, A. Skoogh, S. Jain, and B. Johansson, 1500-1514. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Evenden, D., P. R. Harper, S. C. Brailsford, and V. Harindra. 2005. "System Dynamics Modeling of Chlamydia Infection for Screening Intervention Planning and Cost-Benefit Estimation". *IMA Journal of Management Mathematics* 16(3):265-279.

Fakhimi, M., A. Anagnostou, L. Stergioulas, and S. J. Taylor. 2014. "A Hybrid Agent-Based and Discrete Event Simulation Approach for Sustainable Strategic Planning and Simulation Analytics". In *Proceedings of the 2014 Winter Simulation Conference*, edited by A. Tolk, S. Y. Diallo, I. O. Ryzhov, L. Yilmaz, S. Buckley, J. A. Miller, 1573 -1584. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Gao, A., N. D. Osgood, W. An, and R. F. Dyck. 2014. "Tripartite Hybrid Model Architecture for Investigating Health and Cost Impacts and Intervention Tradeoffs for Diabetic End-stage Renal Disease". In *Proceedings of the 2014 Winter Simulation Conference*, edited by A. Tolk, S. Y. Diallo, I. O. Ryzhov, L. Yilmaz, S. Buckley, J. A. Miller, 1676-1687. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Günal, M. M., and M. Pidd. 2010. "Discrete Event Simulation for Performance Modelling in Health Care: A Review of the Literature". *Journal of Simulation* 4(1):42-51.

He, Y., M. Li, S. Sala-Diakanda, J. Sepulveda, A. Bozorgi, and W. Karwowski. 2013. "A Hybrid Modeling and Simulation Methodology for Formulating Overbooking Policies". In *Proceedings of IIE Annual Conference.* June 30th, San Juan, Puerto Rico, 1358-1366.

Jones, W., K. Kotiadis, and J. O'Hanley. 2019. "Engaging Stakeholders to Extend the Lifecycle of Hybrid Simulation Models". In *Proceedings of the 2019 Winter Simulation Conference,* edited by N. Mustafee, K. -H. G. Bae, S. Lazarova-Molnar, M. Rabe, C. Szabo, P. Haas, and Y. -J. Son, 1304-1315. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Kasaie, P., D. W. Dowdy, and W. D. Kelton. 2013. "An Agent-Based Simulation of a Tuberculosis Epidemic: Understanding the Timing of Transmission". In *Proceedings of the 2013 Winter Simulation Conference*, edited by R. Pasupathy, S. -H. Kim, A. Tolk, R. Hill, and M. E. Kuhl, 2227-2238. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Katsaliaki, K., and N. Mustafee. 2011. "Applications of Simulation within the Healthcare Context". *Journal of the Operational Research Society* 62(8):1431-1451.

Lamé, G., O. Jouini, and J. Stal-Le Cardinal. 2019. "Combining Soft Systems Methodology, Ethnographic Observation, and Discrete-Event Simulation: A Case Study in Cancer Care". *Journal of the Operational Research Society* 1-18.

Lane, D. C., C. Monefeldt, and J. V. Rosenhead. 2000. "Looking in the Wrong Place for Healthcare Improvements: A System Dynamics Study of an Accident and Emergency Department". *Journal of the Operational Research Society* 51(5):518-531.

Lynch, C. J., and S. Y. Diallo. 2015. "A Taxonomy for Classifying Terminologies that Describe Simulations with Multiple Models". In *Proceedings of the 2015 Winter Simulation Conference*, edited by L. Yilmaz, W. K. V. Chan, I. Moon, T. M. K. Roeder, C. Macal, and M. D. Rossetti, 1621-1632. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Mielczarek, B., and J. Zabawa. 2016. "Modeling Healthcare Demand Using a Hybrid Simulation Approach". In *Proceedings of the 2016 Winter Simulation Conference*, edited by T. M. K. Roeder, P. I. Frazier, R. Szechtman, E. Zhou, T. Huschka, and S. E. Chick, 1535-1546. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Mielczarek, B., and J. Zabawa. 2017. "Simulation Model for Studying Impact of Demographic, Temporal, and Geographic Factors on Hospital Demand". In *Proceedings of the 2017 Winter Simulation Conference*, edited by W. K. V. Chan, A. D'Ambrogio, G. Zacharewicz, N. Mustafee, G. Wainer, and E. Page, 4498-4500. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Mielczarek, B., J. Zabawa, and W. Dobrowolski. 2018. "The Impact of Demographic Trends on Future Hospital Demand Based on a Hybrid Simulation Model". In *Proceedings of 2018 Winter Simulation Conference*, edited by M. Rabe, A. A. Juan, N. Mustafee, A. Skoogh, S. Jain, and B. Johansson, 1476–1487. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Mittal, A., and C. C Krejci. 2019. "A Hybrid Simulation Modeling Framework for Regional Food Hubs". *Journal of Simulation* 13(1):28-43.

Morgan, J. S., V. Belton, and S. Howick. 2016. "Lessons from Mixing OR Methods in Practice: Using DES and SD to Explore a Radiotherapy Treatment Planning Process". *Health Systems* 5(3):166-177.

Morgan, J. S., S. Howick, and V. Belton. 2017. "A Toolkit of Designs for Mixing Discrete Event Simulation and System Dynamics". *European Journal of Operational Research* 257(3):907-918.

Mustafee, N., J. Powell, S. C. Brailsford, S. Diallo, J. Padilla, and A. Tolk. 2015a. "Hybrid Simulation Studies and Hybrid Simulation Systems: Definitions, Challenges, and Benefits". In *Proceedings of the 2015 Winter Simulation Conference*, edited by L. Yilmaz, H. K. Chan, I. C. Moon, T. Roeder, C. M. Macal, and M. D. Rossetti, 1678-1692. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Mustafee, N., M. H. Sahnoun, A. Smart, P. Godsiff, D. Baudry, and A. Louis, A. 2015b. "Investigating Execution Strategies for Hybrid Models Developed Using Multiple M&S Methodologies". In *Proceedings of the 2015 Spring Simulation Multi-Conference,* April 12th-15th, Alexandria, Virginia, 78-85.

Mustafee, N., S. C. Brailsford, A. Djanatliev, T. Eldabi, M. Kunc, and A. Tolk. 2017. "Purpose and Benefits of Hybrid Simulation: Contributing to the Convergence of its Definition". In *Proceedings of 2017 Winter Simulation Conference*, edited by W. K. V. Chan, A. D'Ambrogio, G. Zacharewicz, N. Mustafee, G. Wainer, and E. Page, 1–15. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Nasirzadeh, F., M. Khanzadi, and M. Mir. 2018. "A Hybrid Simulation Framework for Modelling Construction Projects Using Agent-Based Modelling and System Dynamics: An Application to Model Construction Workers' Safety Behavior". *International Journal of Construction Management* 18(2):132-143.

Nianogo, R. A., and O. A. Arah. 2015. "Agent-Based Modeling of Non-Communicable Diseases: A Systematic Review". *American Journal of Public Health* 105(3):e20-e31.

Onggo, B. S. 2014. "Elements of a Hybrid Simulation Model: a Case Study of the Blood Supply Chain in Low-and Middle-Income Countries". In *Proceedings of the 2014 Winter Simulation Conference*, edited by A. Tolk, S. Y. Diallo, I. O. Ryzhov, L. Yilmaz, S. Buckley, J. A. Miller, 1597-1607. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Pessoa, L. A. M., M. P. E. Lins, A. C. M. da Silva, and R. Fiszman. 2015. "Integrating Soft and Hard Operational Research to Improve Surgical Centre Management at a University Hospital". *European Journal of Operational Research* 245(3):851-861.

Rashwan, W., W. Abo-Hamad, and A. Arisha. 2015. "A System Dynamics View of the Acute Bed Blockage Problem in the Irish Healthcare System". *European Journal of Operational Research* 247(1):276-293.

Roberts, S. D. 2011. "Tutorial on the Simulation of Healthcare Systems". In *Proceedings of the 2011 Winter Simulation Conference*, edited by R. S. Jain, R. R. Creasey, J. Himmelspach, K. P. White, and M. Fu, 1403-1414. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Robinson, S. 2004. *Simulation: The Practice of Model Development and Use*. 2nd ed. Chichester: John Wiley.

Shamseer, L., D. Moher, M. Clarke, D. Ghersi, A. Liberati, M. Petticrew, P. Shekelle, and L. Stewart. 2015. "Preferred Reporting Items for a Systematic Review and Meta-Analysis Protocols (PRISMA-P) 2015: Elaboration and Explanation". *BMJ* 349:g7647.

Siebers, P. O., C. M. Macal, J. Garnett, D. Buxton, and M. Pidd. 2010. "Discrete-Event Simulation is Dead, Long Live Agent-Based Simulation!". *Journal of Simulation* 4(3):204-210.

Tako, A. A., and K. Kotiadis. 2015. "PartiSim: A Multi-Methodology Framework to Support Facilitated Simulation Modelling in Healthcare". *European Journal of Operational Research* 244(2):555-564.

Tako, A. A., and K. Kotiadis. 2018. "Participative Simulation (PartiSim): A Facilitated Simulation Approach for Stakeholder Engagement". In *Proceedings of 2018 Winter Simulation Conference*, edited by M. Rabe, A. A. Juan, N. Mustafee, A. Skoogh, S. Jain, and B. Johansson, 192-206. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Tejada, J. J., J. S. Ivy, R. E. King, J. R. Wilson, M. J. Ballan, M. G. Kay, K. M. Diehl, and B. C. Yankaskas. 2014. "Combined DES/SD Model of Breast Cancer Screening for Older Women, II: Screening-and-Treatment Simulation". *IIE Transactions* 46(7):707-727.

United Nations. 2020. Sustainable Development Goals. https://www.un.org/sustainabledevelopment/health/ accessed 20th March 2020.

Viana, J., S. Rossiter, A. A. Channon, S. C. Brailsford, and A. Lotery. 2012. "A Multi-paradigm, Whole System View of Health and Social Care for Age-Related Macular Degeneration". In *Proceedings of the 2012 Winter Simulation Conference,* edited by C. Laroque, J. Himmelspach. R. Pasupathy. O. Rose., and A. M. Uhrmacher, 1-12. Piscataway. New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Viana, J., S. C. Brailsford, V. Harindra, and P. R. Harper. 2014. "Combining Discrete-Event Simulation and System Dynamics in a Healthcare Setting: a Composite Model for Chlamydia Infection". *European Journal of Operational Research* 237(1):196-206.

Viana, J., K. Rand-Hendriksen, T. B. Simonsen, M. Barra, and F. Dahl. 2016. "Do Hybrid Simulation Models Always Increase Flexibility to Handle Parametric and Structural Changes?". In *Proceedings of the 2016 Winter Simulation Conference*, edited by T. M. K. Roeder, P. I. Frazier, R. Szechtman, E. Zhou, T. Huschka, and S. E. Chick, 1439-1450: Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Viana, J., V. M. Ziener, M. S. Holhjem, I. G. Ponton, L. J. Th∅gersen, and T. B. Simonsen. 2017. "Optimizing Home Hospital Health Service Delivery in Norway Using a Combined Geographical Information System, Agent Based, Discrete Event Simulation Model". In *Proceedings of the 2017 Winter Simulation Conference*, edited by W. K. V. Chan, A. D'Ambrogio, G. Zacharewicz, N. Mustafee, G. Wainer, and E. Page, 1658-1669. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Viana, J., T. B. Simonsen, F. A. Dahl, and K. Flo. 2018. "A Hybrid Discrete Event Agent Based Overdue Pregnancy Outpatient Clinic Simulation Model". In *Proceedings of the 2018 Winter Simulation Conference*, edited by M. Rabe, A. A. Juan, N. Mustafee, A. Skoogh, S. Jain, and B. Johansson, 1488-1499. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Young, T., J. Eatock, M. Jahangirian, A. Naseer, and R. Lilford. 2009. "Three Critical Challenges for Modeling and Simulation in Healthcare". In *Proceedings of the 2009 Winter Simulation Conference*, edited by M. D. Rossetti, R. R. Hill, B. Johansson, A. Dunkin, and R. G. Ingalls, 1823–1830. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Zulkepli, J., and T. Eldabi. 2015. "Towards a Framework for Conceptual Model Hybridization in Healthcare". In *Proceedings of the 2015 Winter Simulation Conference*, edited by L. Yilmaz, H. K. Chan, I. C. Moon, T. Roeder, C. M. Macal, and M. D. Rossetti, 1597-1608. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

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