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Integration of discrete event simulation with other modeling techniques to simulate construction engineering and management: an overview

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Abstract: Although Discrete Event Simulation (DES) has been the preferred simulation technique in construction operation studies, it suffers from limitations, such as narrowed focus at the operational level. To minimize the effect of DES limitations, researchers have proposed the integration of DES with other simulation techniques, such as agent-based modeling (ABM), system dynamics (SD), and virtual environments (VE). However, limited studies have discussed whether this integration process minimizes DES' limitations and to what extent. This study summarizes 99 journal manuscripts in the existing literature published between 2010-2020, focusing on integrating DES with ABM, SD, and VE. This study found that the integration of DES with ABM, SD, and VE addressed multiple of DES' limitations, namely, the lack of human behaviors in process-oriented modeling, the limited strategic perspective, and challenges related to the verification and validation of DES models' outputs. Ultimately, this study calls for future studies to evaluate the simultaneous integration of DES, ABM, and SD modeling techniques so the complexity of construction projects can be truly accounted for, as comprehensive simulation tools will require the integration of multiple methods to counterbalance their limitations.

Keywords: discrete event simulation, DES, construction engineering and management, modeling.

1. Introduction

Simulation in construction is the development and application of computer-based tools to represent construction systems, so, the behavior of these systems can be understood (AbouRizk, 2010). Among multiple analytical tools available for construction engineering and management researchers—real-world experiments, mathematical modeling, and simulation—simulation has been recognized as the most convenient due to the lower cost than real-world experiments and more realistic features than mathematical modeling (AbouRizk, 2011; Puri and Martinez, 2013). Furthermore, it has been identified that simulation plays a key role in the management of construction projects, specifically in project planning and control activities (Abourizk, 2010; Abourizk et al., 2011).

There are multiple techniques available to simulate construction systems, such as agent-based modeling (ABM), system dynamics (SD), and discrete event simulation (DES). Each simulation technique focuses on different aspects of construction projects and systems; for instance, while agent-based models focus on construction projects' elements (e.g., workers), discrete event simulation focuses on modeling construction processes (e.g., earthmoving processes). Discrete Event Simulation (DES) –the focus of this study— is a simulation technique that focuses on quantitatively analyzing operations and processes that take place throughout the life cycle of constructed facilities (Martinez, 2010). Of note, discrete event simulation has been identified as the most suitable and convenient technique to model construction operations among multiple researchers (Louis and Dunston, 2017; Rekapalli and Martinez, 2011).

DES is a simulation technique that represents a construction system through a sequence of processes in which the state of resources related to these processes (e.g., materials, workers, information) changes in discrete steps. These characteristics make DES an ideal simulation technique for studying construction operations, as construction activities must follow the project schedule's sequence, and each activity may involve a unique combination of resources. DES has been the prevalent simulation tool to study construction operations (Abourizk, 2010; Martinez, 2010), beginning with the introduction of CYCLONE by Daniel Halpin in the 70s. For more details about the history and evolution of DES in CEM research until 2010, the reader can refer to Abourizk (2010).

Existing studies have applied DES to understand a wide variety of topics regarding construction operations during a project, such as production and fabrication of materials and elements (Hu and Mohamed, 2014; Liu et al.,2015), planning and scheduling (Jung et al., 2016; Lee et al., 2019; Sadeghi et al., 2016), change orders (Du et al., 2016; Han et al., 2012), and productivity (Khanh and Kim, 2020; Lee et al., 2010). Of note, researchers have been able to apply DES to operations before construction starts (e.g., fabrication, planning), and once construction has started (e.g., productivity measurements, change orders management). However, as with every method, DES has limitations that are important to be acknowledged, such as the need to discretize continuous data (Puri and Martinez, 2013), the lack of capacity to add feedback processes (Peña-Mora et al., 2008), and model verification and validation challenges (Zankoul et al., 2015). Of note, to compensate for these limitations, researchers have begun to integrate DES with other simulation techniques often used in the construction engineering and management (CEM) domain, such as agent-based modeling (e.g., Abdelkhalek and Zayed, 2020), system dynamics (e.g., Hwang et al., 2016; Xu et al., 2018), and virtual environments (e.g., Abbasi et al., 2020; Sacks et al., 2015). For instance, efforts have been made to propose a framework to integrate multiple simulation techniques, such as DES, SD, and ABM (Bokor et al., 2019). However, the framework proposed by Bokor et al. (2019) left other simulation techniques compatible with DES unattended, such as virtual environments (VE).

With the constant evolution of modeling techniques applied in the state of the art, a research gap is identified regarding a comprehensive review and discussion of the application of DES with multiple simulation techniques used in the construction engineering and management domain. Consequently, this study aims to review the existing literature on DES in the construction engineering and management domain between 2010 and 2020 to identify the advantages of integrating DES with other simulation techniques (i.e., ABM, SD, VE) and whether such integration leads to overcoming some of the identified limitations from DES. Consequently, this study contributes to CEM practitioners and researchers to develop a more comprehensive understanding of the capabilities of the DES modeling approach to address research and practical problems in the CEM domain.

2. Literature review

A bibliographic search was made in the Scopus database to identify research articles published between 2010 and 2020 related to Discrete Event Simulation and Construction. The Scopus database is recognized in the literature as an international database with peer-reviewed publications (de Freitas and Costa, 2017; Linnenluecke et al., 2020), and it contains more index articles than the WoS database (Singh et al., 2021). An initial search using the keywords discrete event modeling and construction resulted in 410 research articles—i.e., manuscripts published in journals only. Then, these manuscripts were screened (i.e., reviewing the title and abstract) to verify that they were from the construction engineering and management domain. This screening process resulted in 153 research manuscripts. Ultimately, a detailed screening process of the full research papers was performed to double-check that the research manuscripts fit the aim of this study. This process resulted in 99 research manuscripts selected that were published in academic journals between 2010 and 2020. This search process was developed, so the articles selected for this study were representative of construction engineering and management literature, following the steps typically used in systematic reviews (e.g., Kitchenham et al., 2009; Moher et al., 2009). Once the group of articles to be analyzed was defined, the main topics in the literature were identified and grouped.

The following section starts by discussing the existing literature on the application of DES in CEM and identifying its limitations, followed by a discussion of other simulation techniques, namely System Dynamics (SD), Agent-Based Modeling (ABM), and Virtual Environments (VE). Then it discusses studies in the literature that have applied DES combined with SD, ABM, and VE.

Table 1 shows the manuscripts analyzed and the main topics identified in the existing literature. Figure 1 conceptualizes the main ideas discussed in the literature review section regarding DES limitations and integration with other modeling techniques.

Table 1. Selected articles from literature review.

Summary of selected literature review	References
Applying discrete event simulation only	
Fabrication of products	(Bohács et al., 2016; Brodetskaia et al., 2013; Cheng and Tran, 2016; Golzarpoor et al., 2017; Heravi and Firoozi, 2017; Hu et al., 2018; Hu and Mohamed, 2014; Khan et al., 2017; Lau et al., 2014; Sneha and Tezeswi, 2016; Wang et al., 2018)
Planning and scheduling	(Al-Emran et al., 2010; Alvanchi et al., 2012a; Alvanchi et al., 2012c; Beiert et al., 2010; Dallasega et al., 2019; Gonzalez and Echaveguren, 2012; Hassan et al., 2016; Jung et al., 2016; Lee et al., 2019; Lindhard et al., 2019; Osman et al., 2017; Sadeghi et al., 2015; Shin et al., 2011; Yuan et al., 2020; Zhang et al., 2012)
Productivity	(Afifi et al., 2020; Arashpour and Arashpour 2015; Arashpour et al., 2014; Aziz et al., 2017; Baniassad et al., 2018; Khanh and Kim, 2020; Kisi et al., 2017; Montaser and Moselhi, 2014)
Construction processes	(Akhavian and Behzadan, 2018; Akhavian and Behzadan, 2014; Athigakunagorn and Limsawasd 2020; Chen et al., 2020a; Corona-Suarez et al., 2014; Fayed and Azeldin, 2018; Feng et al., 2018a; Feng et al., 2018b; Frough et al., 2019; Golabchi et al., 2016; Jiang et al., 2016; Jung et al., 2016; Krantz et al., 2019; Kim and Kim, 2016; Larsson et al., 2016; Larsson and Rudberg, 2019; Lee et al., 2010; Li et al., 2017; Limsawasd and Athigakunagorn, 2017; Louis and Dunston, 2017; Puri and Martinez, 2013; Sadeghi et al., 2016; Seo et al., 2016; Shawki et al., 2015; Nadoushani et al., 2018; Vidalakis et al., 2013; Weiszer et al., 2020; Younes et al., 2020; Yu et al., 2020; Zankoul and Khoury, 2016; Zhang, 2015a; Zhang, 2015b; Zhong et al., 2015)
Others-change orders, response to disasters, DES implementation	(Cabrera, 2010; Du et al., 2016; Karimidorabati et al., 2016; Longman and Miles, 2019; Nassar, 2010; Martinez, 2010)
Applying discrete event simulation and system dynamics	
Planning and scheduling	(Hwang et al., 2016; Li et al., 2018; Xu et al., 2018)
Productivity	(Alvanchi et al., 2012c; Dang et al., 2018; Moradi et al., 2017)
Integration of DES and SD	(Alvanchi et al., 2011; Moradi et al., 2015)
Applying discrete event simulation and agent based modeling	
Productivity	(Matejević et al., 2018)
Construction processes	(Abdelkhalek and Zayed, 2020; Kim and Kim, 2010; Jung et al., 2018; Zankoul et al., 2015)
Applying discrete event simulation and virtual environments	
Construction operations	(Abbasi et al., 2020; Chen et al., 2020; Chen and Huang, 2013;

	Elnimr et al., 2016; Zhong et al., 2015)
Project assessment	(Gurevich and Sacks, 2014; Krantz et al., 2015; Mawlana et al., 2015)
Integration of DES and VE	(Lu and Olofsson, 2014; Sandoval et al., 2018; Rekapalli and Martinez, 2011; Sacks et al., 2015)
Applying discrete event simulation and system dynamics and agent based modeling	
Planning and scheduling	(Goh et al., 2016)
Construction processes	(Conrads et al., 2017)

2.1. DES in construction engineering and management and its limitations

Existing studies have applied DES to understand a wide variety of topics, such as fabrication of products (e.g., Bohács et al., 2016; Cheng and Tran, 2016; Hu and Mohamed, 2014; Liu et al.,2015), planning and scheduling (e.g., Alvanchi et al., 2012a; Jung et al., 2016; Lee et al., 2019; Sadeghi et al., 2016), productivity (e.g., Afifi et al., 2020; Khanh and Kim, 2020; Lee et al., 2010), construction processes (e.g., Akhavian and Behzadan, 2018; Krantz et al., 2019; Louis and Dunston, 2017; Zhong et al., 2015). Of note, researchers have also applied DES to topics that are more difficult to group together and are classified as others, such as response to disasters (e.g., Longman and Miles, 2019) or change orders (e.g., Du et al., 2016).

Concerning the study of fabrication of products for construction projects, Hu, and Mohamed (2014) proposed a DES model to plan and schedule industrial construction fabrication. The main advantage of the proposed DES-based model is that it allowed accounting for the wide variability and uniqueness of the fabrication process. Similarly, Lau et al. (2014) proposed a DES model to simulate the production process of iron ore mining operations. Lau and colleagues (2014) applied DES to optimize resource allocation and use regarding the configuration of the productive process. The second most common construction engineering and management problem studied using DES is planning and scheduling (e.g., Alvanchi et al., 2012a; Jung et al., 2016; Lee et al., 2019; Shin et al., 2011).

Studies using DES for planning and scheduling activities have generally been focused on simulating unique conditions of the operations being studied. For instance, Alvanchi et al. (2012a) applied DES to study off-site construction planning due to the complexity of off-site fabrication in shops. Of note, the authors found that with the proposed model that, a project's duration could be reduced roughly by 10% with off-site fabrication (Alvanchi et al., 2012a). Similarly, Lee et al. (2019) applied DES to study scheduling alternatives of modular building construction. Interestingly, Lee and colleagues (2019) found that a DES-based simulation approach facilitates evaluating the schedule of multiple alternatives, including project characteristics for each case. Additionally, Jung and colleagues (2016) applied a DES-based approach to study the influence of weather delays on the construction of high-rise buildings. The authors concluded that if vertical weather profiles are ignored during the construction of high-rise buildings, the project can be affected by considerable time losses (Jung et al., 2016).

When it comes to the use of DES to study the productivity of construction processes, the literature has mainly been focused on how productivity varies under different situations during a construction project. For instance, Arashpour et al. (2014) analyzed disruptions in productivity in residential projects due to rework. Namely, Arashpour and colleagues analyzed the influence of timing and extension of rework on productivity, finding that nonfrequent but extended interruptions due to rework resulted in the most disruptive for the construction of residential projects. Simlarly, Khan and Kim (2020) studied the productivity of concrete tracks for multistory building projects using DES. The authors found that simulated productivities were higher than actual productivities, thus, showing alternatives for improvement in the process. Notably, the authors emphasized that DES is a method that should be applied before construction activities begin so improvements in construction processes can be made in advance of construction (Khan and Kim, 2014). Furthermore, authors have also studied how to achieve optimal conditions in construction operations. For instance, Kisi and colleagues (2017) implemented DES in the context of estimating the optimal productivity in labor-intensive construction operations.

Concerning the study of construction processes, the literature has explored the optimization of a wide variety of construction processes focused on different characteristics, such as crew distribution, weather conditions, and sustainability (e.g., Feng et al., 2018; Golabchi et al., 2016; Krant et al., 2019; Lee et al., 2010; Seo et al., 2016; Yu et al., 2020; Zhang, 2015a). For instance, Yu et al. (2020) applied DES to optimize the process of recycling asphalt pavement accounting for the cost, quality, and environmental impact of the process. The authors found that the optimization of the process was highly sensitive to the type of truck used to undertake the process and the number of trucks involved. Similarly, Feng et al. (2018) applied DES to optimize construction methods based on the environmental cost and time. The simulation of construction processes included material consumption and construction equipment. The authors found with the modeling that, on average, for a building construction project, environmental cost, financial cost, and time can be reduced in 26%, 20%, and 10%, respectively. Along the same lines, Zhang (2015a) implemented DES to estimate emissions from construction processes, finding that the proposed model may contribute to assessing emission plans for construction operations aiming to reduce emissions.

Concerning the simulation of construction processes from a construction workers' standpoint, Seo et al. (2016) developed a model to simulate the physical demand over construction workers and corresponding muscle fatigue. Then, the authors assessed the influence of muscle fatigue on construction operations, namely, time and cost performance, on the planning of operations. The authors found that excessive physical demand of workers leads to a reduced time and cost performance of operations.

Regarding existing studies classified as others (see Table 1), Du et al. (2016) used DES to optimize the change orders process. Notably, Du et al. (2016) modeled potential improvements to the change orders' management process and found that using a DES model outperformed subjective decision-making often applied in change orders' management. In general, for most construction operations modeled and simulated with DES, researchers proposed the DES model as a framework to optimize the resources involved in the simulated construction activities. Concerning the modeling of disasters using DES, Longman, and Miles (2019) applied DES to model housing recovery. The authors developed a DES tool and applied in the context of recovery due to an earthquake in Nepal in 2015. The tool allowed to simulate multiple scenarios of the housing recovery process and to identify key resources needed for construction, such as materials and skilled workers.

Despite that DES has been the most common simulation tool in CEM research, multiple limitations of DES have been identified in the existing literature. One often limitation discussed about DES in the CEM literature is that this method is process-centric and, as such, the focus of the simulations may be too narrow (Moradi et al., 2015; Peña-Mora et al., 2008). Additionally, DES has been identified to suffer from a limited capacity to add feedback loops into the simulation process of construction operations (Moradi et al., 2017; Peña-Mora et al., 2008). Similarly, it has been discussed that the lack of feedback loops in the simulation process limits DES in the inclusion of the contextual conditions of construction processes being simulated (Hwang et al., 2016). Another limitation is that construction activities are continuous, while DES simulates them as discrete events (Puri and Martinez, 2013). Puri and Martinez (2013) claimed that this limitation is often ignored in DES studies; of note, it was found that using different discretization in simulations resulted in different simulation outputs (Puri and Martinez, 2013). In summary, DES has been the preferred simulation tool by CEM researchers in the past due to the process-oriented nature of this method, which aligns with the nature of the activities in construction projects. However, as with every method, DES also suffers from limitations (see Figure 1).

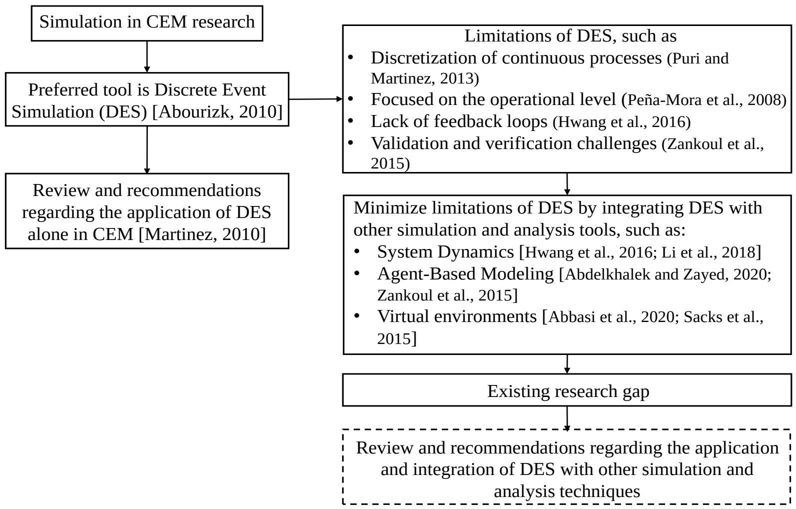

Figure 1. Visualization of literature related to the study and an existing gap.

2.2. System dynamics, agent-based modeling, and virtual environments in CEM

Multiple simulation techniques have been used in CEM research in addition to discrete event simulation, such as agent-based modeling, system dynamics, and virtual environments. Here, a brief discussion of each of these simulation techniques is presented in the context of CEM research so to better understand how they interact with DES in section 2.3.

System Dynamics (SD) is a simulation technique to study complex systems focusing on interactions among systems' variables, structure, and understanding of feedback effects among their variables (Sterman, 2000). SD is focused on the study of complex systems at the strategic level; thus, making SD an excellent technique for studying problems related to management actions and initiatives (Alvanchi et al., 2012b; Peña-Mora et al., 2008; Hwang et al., 2015). As such, SD has been used to study. As discussed by Peña-Mora et al. (2008), SD represents an excellent alternative to account for strategic levels of analysis in combination with the operational focus of DES.

Agent-Based Modeling (ABM) is a simulation technique to study complex systems focused on the system's individual components (i.e., agents). The logic is that the system behavior will emerge by understanding the behavior of individual components and how these can interact (Macal and North, 2010). In recent years, ABM has started to be more implemented by CEM researchers to capture the complexity of the environment of construction projects (Ahn and Lee, 2015; Araya, 2020; Khodabandelu and Park, 2021; Osman, 2012); namely, it has been applied to study site operations (Watkins et al., 2009), resource allocations (Farshchian and Heravi, 2018), infrastructure management, BIM (Cheng et al., 2018), and COVID-19 (Araya, 2022). It has been suggested that the recent and higher capacity of ABM to model human behaviors combined with DES maturity in CEM may be a successful combination (Abdelkhalek and Zayed, 2020).

With the advancement of computers and technology during recent decades, virtual environments have been applied by CEM researchers to model and simulate real-life project conditions in a virtual environment. The main advantage of virtual environments is that they allow studying construction projects without spending actual resources by using virtual resources (Leite et al., 2016). Additionally, virtual environments have been proposed as a rich source of data and information to support simulation approaches for construction projects' lifecycle (Lu and Olofsson, 2014). In this review, virtual environments refer to techniques such as Building Information Modeling (BIM), Augmented Reality (AR), and Virtual Reality (VR). As virtual environments may have the capacity to feed DES-based frameworks with data, the integration of DES and virtual environments may facilitate the validation and verification of DES-based frameworks.

2.3. DES combined with analysis tools and simulation techniques

As limitations of DES have been identified in CEM literature, researchers have made efforts to overcome such limitations by combining DES with other simulation techniques, such as agent-based modeling, system dynamics, and virtual environments. This section discusses efforts made during the last decade to integrate DES with other simulation techniques.

2.3.1. DES and system dynamics (SD)

In recent years, some authors have integrated DES and SD to study construction engineering and management problems (e.g., Hwang et al., 2016; Li et al., 2018; Moradi et al., 2015; Xu et al., 2018). The main topics identified from the analyzed literature refer to productivity and planning and scheduling (see Table 1). Regarding studies about productivity, Alvanchi et al. (2012c) simulated a construction project to assess the influence of the evolution of the workforce skills and its influence on human resources policies. The authors found that cost saving from human resources policies was highly feasible. Moreover, that the model provided a tool to evaluate the implementation of multiple human resources policies by construction companies. Similarly, Moradi et al. (2017) applied a SD-DES model to evaluate the labor productivity in construction projects accounting for the context and operational factors. The authors found that in doing so, labor productivity can be estimated more accurately due to the integration of the context and operational factors.

Concerning existing studies about planning and scheduling, Hwang et al. (2016) studied the response and planning of facility restoration due to disasters by integrating DES and SD. Hwang and colleagues (2016) applied this combination as DES provided the capabilities to model the uncertainty of construction processes in the context of disaster recovery; however, SD allowed to simulate the complex and dynamic environment that construction often faced under disaster conditions. Ultimately, the authors concluded that integration between DES and SD enabled an in-depth analysis accounting for operational and strategic factors faced in restoration processes (Hwang et al., 2016). More recently, DES has been integrated with SD to study schedule issues in different types of construction projects. Xu et al. (2018) proposed a DES-SD framework to study the schedule risk in infrastructure projects. The authors proposed a structure in which the different construction processes were defined using DES, while the modeling within each process was using SD (Xu et al., 2018). DES was focused on resources and micro-level behaviors, while SD was focused on complexities with infrastructure schedules at the system level. The authors found that the proposed framework may improve schedule risk analysis in infrastructure projects (Xu et al., 2018). Similarly, Li et al. (2018) proposed a DES-SD framework to study prefabricated housing production schedule risks. The authors used DES to model in detail the behavior at the activity level, while SD was used to analyze the problem at the system level and evaluate the influence of managerial decisions (Li et al., 2018).

2.3.2. DES and agent-based modeling (ABM)

Limited studies exist regarding the integration of DES and ABM in CEM research, which has focused on studying productivity and construction operations (see Table 1). Matejević et al. (2018) studied the productivity of building reinforced concrete slabs combining ABM and DES. The authors found that by the integration of both modeling approaches productivity of building reinforced concrete slabs can be more precisely estimated, and, as such, benefit how such a process can be managed. Regarding construction processes, Zankoul et al. (2015) explored the use of ABM and DES to study earthmoving operations. The authors found that simulating earthmoving operations with both methods could generate similar results. Further, the authors discussed the integration of ABM and DES to study earthmoving operations. The authors concluded that proposing a multimethod framework can counterbalance the strengths and limitations between ABM and DES, namely, human behavior of systems can be included through ABM on the study of construction processes using DES (Zankoul et al., 2015). More recently, Abdelkhalek and Zayed (2020) integrated DES and ABM to study the inspection process of concrete bridges. DES was used to replicate the sequence of tasks involved in the inspection process, and ABM was used to simulate the behavior of the different participants involved during the inspection process (e.g., inspectors). The authors concluded that the proposed hybrid framework could support decision-makers in the planning of inspection activities by accounting for inspectors' behavior and the time and cost related to the inspection process. Such capacity was mainly due to the integration between DES and ABM (Abdelkhalek and Zayed, 2020).

2.3.3. DES and virtual environments

Concerning the literature on the interaction between DES and VE, studies can be divided into construction operation studies, project assessment, and integration of DES and VE (see Table 1). Regarding construction operations, Elnimr et al. (2016) combined DES and 3D visualization to model crane movements during construction projects. The hybrid environment proposed by Elnimr and colleagues (2016) identified the feasible paths for the crane movements and defined the shortest obstacle-free path for each event, accounting for dynamically changing construction site layouts. Of note, multiple studies have combined DES and virtual environments to study planning activities regarding transportation projects (Chen and Huang, 2013; Mawlana et al., 2015). Chen and Huang (2013) combined a DES-based simulation with 3D visualization to study transport operations. The authors concluded that simulating DES-based results using 3D visualization provides more intuitive results; namely, it can facilitate site planning by minimizing environmental constraints in route planning (Chen and Huang, 2013). Similarly, Mawlana et al. (2015) combined DES with 4D modeling to evaluate the feasibility of constructive sequences of urban highway projects. Namely, the proposed approach identifies clashes between activities due to the variation in the duration of construction tasks (Mawlana et al., 2015).

When it comes to the study of project assessment, Mawlana et al. (2015) integrated BIM and DES to evaluate urban highway reconstruction projects. The authors proposed a framework to evaluate feasible sequences of a highway to be constructed or demolished, avoiding spatial interference during operations. Along the same lines, Krantz and colleagues (2015) integrated DES and BIM to evaluate the embodied energy and greenhouse emissions from the construction of infrastructure projects. Krantz et al. (2015) found that by integrating BIM and DES detailed enough information can be generated from infrastructure projects to apply embodied energy and greenhouse emissions calculations, which may improve the lifecycle assessment of such projects.

Regarding the integration of DES and VE, Sacks et al. (2015) implemented a hybrid simulation environment combining virtual reality and DES. Sacks and colleagues (2015) used the hybrid environment to study the decision-making of construction crew leaders in a DES-controlled site. The study demonstrated that virtual reality and DES combined environment could analyze the decision-making process related to human behavior in a construction environment (Sacks et al., 2015). Similarly, Rekapalli and Martinez (2011) integrated DES and virtual reality to visualize and improve a model to study earthmoving operations. The authors found that an environment that can integrate DES with virtual reality can improve not only the validation but also the credibility of DES models by providing an easier understanding of models' logic and results (Rekapalli and Martinez, 2011). Lu and Olofsson (2014) proposed a BIM-DES integrated framework. The authors used a cast-in-place concrete slab of a residential building project as an example to test the framework. The authors found that a BIM-DES framework is efficient as both approaches counterbalance their limitations. BIM provides large amounts of information to feed the DES model, while DES evaluates construction performance that provides feedback for the BIM decision-support process.

2.3.4. DES and ABM, and SD

Notably, two studies in the existing literature have applied SD, ABM, and DES simultaneously (Conrads et al., 2017; Goh et al., 2016; see Table 1). Conrads et al. (2017) implemented an integrated DES, ABM, and SD simulation framework to study maintenance strategies for cutting tool replacements in mechanized tunneling. The framework can be used for developing maintenance strategies accounting for the complexities existing in the construction and maintenance of tunneling construction. Similarly, Goh and Colleagues (2016) studied the safety behavior of construction workers and the role of planning on safety. The authors proposed a hybrid simulation framework integrating DES as the main piece of the framework to model the construction processes, ABM to simulate entities and resources, and SD to simulate cognitive and physiological aspects of agents. The authors emphasized that the integration of DES, ABM, and SD provides a more natural representation of the complexities in construction activities.

3. Discussion

DES is recognized as the most common simulation tool used in CEM research. As with every method, DES has limitations, which have been documented in the existing literature (see Figure 1). In recent years, CEM researchers have sought the integration of DES with other simulation techniques to minimize such limitations (see Table 1). This context motivated this study to review and assess what limitations of DES can be overcome by the integration with other simulation techniques, namely ABM, SD, and VE. Ninety-nine journal manuscripts were reviewed that have implemented DES or that integrated DES with other simulation techniques. In doing so, DES limitations were identified, and which of these limitations could be addressed by integrating DES with other modeling techniques. The following discussion is organized by each of the DES's limitations identified in the literature (see Figure 1) and what method is better suited to address such limitations.

Narrow focus and lack of feedback loops

DES can simulate the complex nature of construction processes; however, important limitations of DES are the restricted capacity to include feedback loops in the simulation process and the narrow focus at the operational level (Moradi et al., 2015; Peña -Mora, et al., 2008). As contextual conditions may highly influence construction processes (e.g., high uncertainty of resources for construction processes during a disaster recovery; the influence of big picture level of policies), these limitations make it very difficult for DES to simulate construction operations in these contextual-dependent scenarios (Hwang et al., 2016).

System Dynamics' main advantages are precisely the big picture type of analysis and the capacity to apply feedback loops into the simulation process to capture the dynamic interactions among multiple variables. As such, the integration of DES with SD addresses some of the most important limitations of DES. For instance, Hwang et al. (2016) proposed a DES-SD hybrid framework to study the facility restoration process in the context of disaster recovery. In practicality, the hybrid framework can represent the uncertainty of contextual conditions to evaluate their impact on operational aspects of facility restoration, such as time and cost (Hwang et al., 2016). Similarly, Xu et al. (2018) proposed a DES-SD hybrid approach to study the impact of risks related to infrastructure projects. Xu and colleagues (2018) concluded that the DES approach provided understanding at the microscopic level, while SD provided understanding at the macroscopic level. In summary, the literature suggests that integrating DES with SD provides a powerful framework capable of analyzing the system under study at the operational and strategic levels. Integrating SD and DES is suggested to address DES's limitations regarding narrow focus and lack of feedback (Figure 2).

Process oriented without human behaviors

As a process-centered simulation technique, DES focuses on simulating how resources move around the different construction processes, yet, DES has limited capacity to incorporate human-behavior in the simulation of construction processes. By integrating DES with ABM, this limitation can be overcome, as ABM allows to account for humans' individual behavior involved in the system being simulated (see Figure 2). For instance, Abdelkhalek and Zayed (2020) used an ABM-DES framework to include bridge inspectors' behavior in the simulation of the bridge inspection process.

Despite the fact that ABM seems to be suited to address this DES limitation, during the last decade, only a few studies have implemented a DES-ABM framework in CEM literature (e.g., Abdelkhalek and Zayed 2020; Jung et al., 2018; Zankoul et al., 2015). This can be due to ABM being a recent simulation technique in CEM research. However, this context can be seen as an opportunity by combining DES –a well-known technique in CEM literature— with a less known ABM technique, it can provide not only a way to minimize a DES's limitation but also an alternative to expanding the application of ABM in the CEM literature, as suggested by Abdelkhalek and Zayed (2020).

Verification and validation challenges

As with every simulation technique, one of the main challenges of DES relates to the verification and validation of the proposed modeling framework. Given this limitation, researchers have used virtual environments (VE) to represent DES models to provide an easier way to observe, verify, and validate the complex operations being simulated using DES, as well as to check that the outputs of the DES framework are credible (Rekapalli and Martinez, 2011).

Multiple types of complex construction operations have been simulated using a DES-VE hybrid framework, such as transportation (Chen and Huang, 2013), earthmoving (Rekapalli and Martinez, 2011), cast-in-place concrete operations (Lu and Olofsson, 2014), and crane operations (ElNimr et al., 2016). In all these studies, the authors concluded that combining DES with VE provides an effective framework to verify and validate models simulating complex construction operations. The main advantage of the integration between DES and VE is that it provides an environment in which the sequence of complex operations can be easily observed, and modelers can identify simulation flaws. Consequently, to minimize the limitation of DES regarding the validation and verification process, integration with virtual environments (VE) is suggested to be implemented (Figure 2).

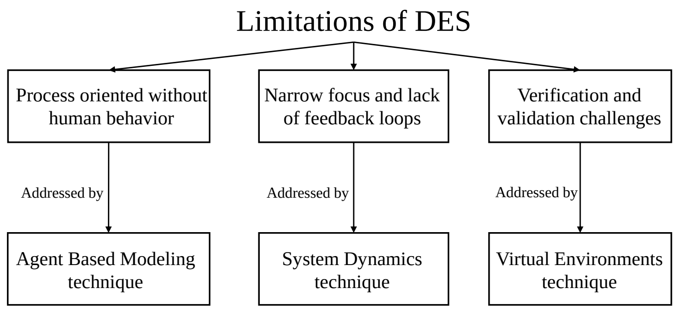

Figure 2. Limitations of DES addressed by integration with other simulation techniques.

Discretization of continuous activities

As the name suggests, Discrete Event Simulation (DES) represents actual work activities using a discrete sequence of steps. In doing so, it takes continuous activities in real life and simplifies them into a series of discrete events, which is an inherent limitation of DES. Given the acceptance of using DES to model construction operations in CEM literature, limited attention has been given to this issue of discretizing activities that are, in fact, continuous (Puri and Martinez, 2013). Puri and Martinez (2013) were the first authors –and so far, the only ones— in the CEM research community to discuss this limitation of DES. The authors claimed that a strategy must be developed to overcome this limitation of DES; otherwise, the way construction operations are modeled will continue to be biased and thus, leading to incorrect decisions for construction engineers and managers (Puri and Martinez, 2013). For instance, Puri and Martinez (2013) found that by modifying the values used to discretize a paving operation, the estimation of the duration of the process changed drastically. As such, the accuracy of the simulation outputs was dependent upon the selection of the discretization unit (Puri and Martinez, 2013).

From all the limitations of DES explored in this study, this is probably the only one in which there is no clear candidate regarding what method or approach can be integrated with DES to overcome this limitation. This represents the main challenge for CEM researchers that use DES, to find an approach to overcome this existing limitation. Future studies should focus on how this limitation of DES can be addressed by developing or finding methods that integrate with DES to overcome this limitation.

31 *Study contribution*

Having a clear idea of how researchers and practitioners can improve their capacity to simulate complex construction operations by integrating multiple simulation methods contributes to the CEM body of knowledge. Although DES has been the preferred simulation tool for construction operations among CEM researchers in the past, a gap exists in the literature regarding how the limitations of DES can be addressed. As such, this study contributes to the literature by reviewing and discussing whether the integration of DES with other simulation techniques (i.e., ABM, SD, and VE) addresses these limitations. Namely, this study found that integrating DES with ABM, SD, and VE addresses the lack of human behavior simulation, simulation at the strategic level, and lack of feedback loops, and verification and validation challenges, respectively. However, limited efforts have been made to address the discretization of continuous activities, which is an inherent limitation of DES.

This study can be understood as a guideline for CEM researchers and practitioners using DES regarding which alternative simulation method can be integrated with DES to minimize the influence of specific DES limitations. In practicality, this study contributes to the CEM literature by providing an overview of the existing literature about DES and discussing whether the integration with alternative simulation methods has addressed its limitations. Ultimately, given the complexity of construction operations, the author believes that it may be necessary to explore the possibilities of integrating more than two simulation methods, as Goh et al. (2016) and Conrads et al. (2017) have done. In doing so, a higher level of complexity from construction operations might be captured in research studies.

4. Conclusions

This study provides an overview of existing literature applying DES in the construction engineering and management realm. In doing so, it analyzes efforts made by CEM researchers to integrate DES with other simulation techniques –ABM, SD, and VE— to minimize DES' limitations. This study analyzed 99 journal manuscripts about DES and the integration of DES with other simulation techniques published between 2010 and 2020. This study found that integrating DES with ABM, SD, and VE addresses the primary limitations of DES. Namely, limited human-behavior within the simulation model, focus on the operational level of operations and lack of feedback loops that account for contextual conditions, and difficulties in verifying and validating simulation models. However, it was found that the limitation of DES concerning the discretization of continuous activities has not been yet addressed in the literature. This study contributes by providing an overview of which simulation methods are a better fit to compensate and minimize the limitations of DES, which is very important as DES is the main simulation tool used in CEM literature. CEM researchers can use this study in the future to make a more informed decision regarding how the limitations of DES can be minimized by combining DES with other simulation methods. Ultimately, concerning future studies, it is recommended to continue exploring the feasibility of simultaneously integrating DES, SD, and ABM modeling methods to increase the complexity of construction operations that can be modeled and simulated by researchers.

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