Research Paper **Open Access**

Orsolya Bokor, Laura Florez, Allan Osborne and Barry J. Gledson

Overview of construction simulation approaches to model construction processes

DOI 10.2478/otmcj-2018-0018
Received December 14, 2018; accepted January 3, 2019

Abstract: Construction simulation is a versatile technique with numerous applications. The basic simulation methods are discrete-event simulation (DES), agent-based modeling (ABM), and system dynamics (SD). Depending on the complexity of the problem, using a basic simulation method might not be enough to model construction works appropriately; hybrid approaches are needed. These are combinations of basic methods, or pairings with other techniques, such as fuzzy logic (FL) and neural networks (NNs). This paper presents a framework for applying simulation for problems within the field of construction. It describes DES, SD, and ABM, in addition to presenting how hybrid approaches are most useful in being able to reflect the dynamic nature of construction processes and capture complicated behavior, uncertainties, and dependencies. The examples show the application of the framework for masonry works and how it could be used for obtaining better productivity estimates. Several structures of hybrid simulation are presented alongside their inputs, outputs, and interaction points, which provide a practical reference for researchers on how to implement simulation to model construction systems of labor-intensive activities and lays the groundwork for applications in other construction-related activities.

Keywords: agent-based modeling, discrete-event simulation, fuzzy logic, hybrid simulation, masonry, scheduling, system dynamics

***Corresponding author: Orsolya Bokor,** Northumbria University, Faculty of Engineering and Environment, Newcastle upon Tyne, United Kingdom; E-mail: orsolya.bokor@northumbria.ac.uk
Laura Florez, Allan Osborne and Barry J. Gledson, Northumbria University, Newcastle-upon-Tyne, United Kingdom

1 Introduction

When a system is analyzed and various scenarios are tested, usually, it is not possible to experiment on the actual system; a model is required. Such a model could be either physical or mathematical (Law, 2015). In the case of construction processes, it is generally the latter, which could be divided into two groups based on whether there is an exact solution or only a numeric evaluation is possible (Law, 2015). In the latter case, simulation is applied.

Simulation has evolved together with the development of computers. Gordon (1961) suggested a general purpose simulation program to solve problems in diverse fields ranging from telecommunications to manufacturing. Teicholz's link–node model developed in 1963, which helped with the selection of the equipment used for earthworks, could be considered the forerunner of construction simulation (AbouRizk et al., 2011). Since then, several different approaches have been proposed. The existing literature on construction simulation mostly uses one of the following as case studies: earthworks – e.g., AbouRizk and Halpin (1992), Lorterapong and Moselhi (1996), and Alzraiee et al. (2012); reinforced concrete works – e.g., Moradi et al. (2015), Khanzadi et al. (2017), and Nojedehi and Nasirzadeh (2017); or civil engineering works – e.g., AbouRizk and Sawhney (1993), Robinson Fayek and Oduba (2005), and AbouRizk (2010), which are mostly machine-driven works. However, it is arguably more important to simulate labor-driven operations because labor resources (especially skilled) tend to be scarcer and contain more risk than do equipment or materials. The examples in this paper are, therefore, from masonry construction: masonry is a labor-intensive work, as well as being a traditional element of construction projects, such as housing and public institutions.

This paper focuses on simulation approaches. First, the basic simulation methods are introduced, followed by an overview of the hybrid simulation approaches. Next, a framework is presented for the utilization of simulation, complete with examples of modeling of masonry works. The application of the framework is illustrated by an example that involves obtaining more precise productivity rates of masonry works. Finally, the possible application of the developed framework for other similar labor-intensive works are advised and directions of future research in the topic are set.

2 Basic simulation methods

One of the basic simulation methods available is discrete-event simulation (DES), which focuses on, and models, the process itself. DES is based on the concept of entities and resources to describe their flow and sharing across a system. Entities are passive objects (no interaction or characteristics are attached to them), and they travel through the workflow, where they are processed, delayed, queued, seized, and divided. The first notable construction simulation tool using DES was Halpin's CYCLic Operations Network (CYCLONE) developed in 1973, which was intended to be a general purpose simulation system (AbouRizk et al., 2011). Martinez (2010) has described a methodology for conducting DES and pointed out the possible problems that one may encounter when modeling, which could put the model's validity in jeopardy. Activity durations in DES models can be described by probability distribution functions such as the ones used in the Program Evaluation and Review Technique (PERT). Law (2015) attempted to collect all the available functions (ranging from uniform to Weibull, including the Johnson and Pearson systems) with their properties and explained their usage in the case of simulation. AbouRizk and Halpin (1992, p. 537) suggest that flexible functions are needed due to the "diversified nature of construction duration data" and advise using the beta function because of its familiarity in the construction field. Hajdu and Bokor (2016) argue that a careful three-point estimation is more important than the type of distribution function selected. Monte Carlo simulations performed on hypothetical and real-life projects showed that a 10% difference in the three-point estimation causes greater deviations than the chosen distributions (Hajdu and Bokor, 2016).

Another basic simulation method is system dynamics (SD), as developed by Forrester (1961). SD is a top–down method that concentrates on the various influencing factors and the relationships among them to show the entire system's workings and behavior with feedback loops. SD can be used for both qualitative and quantitative modeling: the former focuses on creating a causal loop diagram (balancing and reinforcing relationships), while the latter determines stocks and flows and expresses the links with equations (Kunc, 2017). SD is a model that works with aggregates, i.e., the items in the same stock are considered equal, and the system is defined as a set of structural dependencies. Mawdesley and Al-Jibouri (2009) used SD to determine the areas that should be improved by management to increase productivity. The model contained planning, control, motivation, safety, and disruptions as the most significant factors. Several strategies were tested, and it was found that the first two factors needed the management's particular attention (Mawdesley and Al-Jibouri, 2009).

In contrast to SD, agent-based modeling (ABM) has a bottom–up approach – there is no global system behavior. The system's behavior emerges from how individual, heterogeneous agents interact with each other and with their environment based on defined rules. Siebers et al. (2010) argue that ABM has an advantage over DES in cases where the focus is not on the process but on how the individual agents, who can learn and adapt, affect the system. Son et al. (2015) emphasize similar positive properties through examples of project teams in large-scale construction projects. They recommend ABM for modeling, e.g., the international construction market with countries and firms as agents (Son et al., 2015). Sawhney et al. (2003) advise using ABM to increase construction safety on site by modeling the construction environment, workers with their various tolerance levels toward risk (agents) and safety management practices. Watkins et al. (2009) used ABM to determine how site congestion affects productivity with two agent types being defined: workers (with variables such as skill level) and activities. Dabirian et al. (2016) applied the same two agents to estimate labor costs better. Hsu et al. (2016) used ABM to assess team member selection models. In their research, the agents were the workers with attributes such as experience and skills. It was concluded that interdependence-based selection is preferable to skill-based assignment (Hsu et al., 2016).

3 Hybrid simulation approaches

The approaches described herein are often used individually but can also be applied in combination. A benefit of the combined approach is that the various advantages of each method can be utilized and their shortcomings can be balanced. The most suitable approach should be selected for each component of the model and, depending on the question that needs to be answered, such combinations will provide more accurate representations of reality (Borshchev and Filippov, 2004; Borshchev, 2013).

Different names exist for these combined approaches, including “hybrid”, “multi-method”, and “multi-paradigm” simulations (Mustafee et al., 2015). Mosterman (1999) defined the composite of discrete and continuous simulation as “hybrid simulation”. Balaban et al. (2014) argue that ABM might not be considered a paradigm; hence, those approaches where ABM is paired with another method may not be called multi-paradigm. According to them, there is also a distinction between mixed/hybrid and multi-methods (Balaban et al., 2014). Both Mustafee et al. (2015) and Balaban et al. (2014) agree that proper definitions are needed.

Furthermore, the three basic simulation methods can be mixed with other methods, such as neural networks (NNs) or fuzzy logic (FL) (Balaban et al., 2014), which can also be considered hybrid approaches (AbouRizk, 2010; Nojedehi and Nasirzadeh, 2017). In this paper, however, the term “hybrid simulation” refers to any method in which a basic simulation method is combined with either another basic simulation method or FL.

3.1 Combinations of the basic simulation methods

Fahrland (1970) suggested the combination of DES and SD to create improved, more realistic, and efficient models with many possible applications ranging from aerospace missions to nuclear power plant start-ups. While DES concentrates on the process and deals with issues at the operational level, SD is suitable for modeling at the strategic level, thus complementing each other (Peña-Mora et al., 2008). With the help of the combined DES-SD systems, it is possible to coordinate managerial and operational decisions to increase productivity (Peña-Mora et al., 2008; Alvanchi et al., 2011). In the interest of obtaining more realistic project duration data, Alzraiee et al. (2015) complemented DES with SD as well. The latter was used to take the influencing factors (e.g., weather and overtime) into consideration (Alzraiee et al. 2015).

DES can also be combined with ABM. In operational research, instead of pure ABM, often a hybrid model is used in which the entities of the DES are active ABM agents (Siebers et al., 2010). The same is true in health care, where simple DES models are rare, and instead, ABM is used within DES (Mustafee et al., 2015) – see, e.g., Borshchev (2013).

Lättilä et al. (2010) urged that researchers should combine SD with ABM to combine the positive features of both approaches. They also mentioned that both systems could be used to model the same problem and then the results could be compared (Lättilä et al., 2010). Nasirzadeh et al. (2018) proposed an integrated SD-ABM simulation approach to model construction workers’ safety behavior and its effect on the project duration. In the ABM model, contractors were chosen as agents, and each of them had their SD models showing the influencing factors. There was a constant flow of information between the models (Nasirzadeh et al., 2018). Khanzadi et al. (2017) also used an integrated SD-ABM simulation approach to see how site congestion affects productivity.

Additionally, Borshchev (2013) provided an example for combining all three basic methods whereby DES is used to model the supply chain process, SD describes the market, and agents represent the participants.

3.2 Use of FL

Mixing the basic methods is not the only option available to improve the accuracy of model outputs. Another possibility is to use, e.g., FL. Zadeh (1980) stated that the nature of the problem determines whether probability theory, FL, or a combination of these is required for the solution. FL is preferred in cases of uncertainty and imprecise data, which are “nonstatistical in nature” (Zadeh, 1980, p. 421). Ayyub and Haldar (1984) proposed the use of FL for including uncertainties given in linguistic terms in project schedules. Weather conditions and the experience of the workers were arbitrarily selected as factors in their example. The modified activity durations were calculated based on the frequency of occurrence of the factors, their negative effects on the duration, and the membership functions (Ayyub and Haldar, 1984). Fayek and Oduba (2005) analyzed two activities from a real-life industrial construction project with the help of FL and collected the factors affecting productivity (in two submodels to decrease the size of the model) and the related “if–then” rules. Triangular and trapezoidal membership functions were used, complete with experts’ estimates for the end points. These results were then compared to actual project data (Robinson Fayek and Oduba, 2005). With the number of factors increasing, the amount of rules grows exponentially; therefore, Shaheen et al. (2009) proposed to gather the related factors under blocks. Lorterapong and Moselhi (1996) introduced fuzzy network scheduling (FNET), in case there is no available historical data or fair expert estimate. The proposed method produces more realistic results in the backward pass, affecting criticality, than previous efforts at using fuzzy sets in network scheduling (Lorterapong and Moselhi, 1996).

Raoufi et al. (2016) provided an extensive overview of the combinations of FL with DES, SD, and ABM in construction, showing the advantages of integrating FL into the basic methods and giving advice on the appropriate choice of a hybrid technique.

AbouRizk and Sawhney (1993) developed the Subjective and Interactive Duration Estimation System (SIDES) with the aim of determining more realistic beta distribution functions for activity durations in DES with the help of FL. The users of the application had to define the two end points of the function; however, fitting was based on the selected influencing factors expressed in linguistic terms (AbouRizk and Sawhney, 1993). Zhang et al. (2005) also suggest the application of FL in DES in cases when there is no field data to use. Even when there is, FL could be used to incorporate "vagueness, imprecision and subjectivity" (Zhang et al., 2005, p. 727).

Khanzadi et al. (2012) integrated FL into SD to determine the ideal concession period in case of build–operate–transfer projects. The influencing factors with their causal loops made up the SD module, while the magnitude of the factors was calculated by FL (Khanzadi et al., 2012). De Salles et al. (2016) applied the same combination to evaluate business decision policies. The critical factors influencing the system were modeled in SD, while FL translated the policies given in linguistic terms into the SD model (De Salles et al., 2016). Nojedehi and Nasirzadeh (2017) also combined SD with FL, while the former part of the model contained the most important factors influencing labor productivity; the latter component was used to express the effect of those factors that could not have been done with crisp values. With the help of the model, possible solutions for improving productivity were tested to contribute to better managerial decisions (Nojedehi and Nasirzadeh, 2017).

Raoufi and Robinson Fayek (2015) combined FL with ABM to investigate how gang performance is affected by the workers' personalities and the interactions between the workers and their environment. Two layers of agents were defined: workers and gangs. The "what-if" rules of agent behavior were expressed in linguistic terms, which were translated using FL (Raoufi and Robinson Fayek, 2015).

3.3 The structure of hybrid simulation models

Selecting the methods that will make up the hybrid to solve a given problem is only the first step. Next, the structure must be determined. There are numerous options that explain how the methods could be combined. Moradi et al. (2015) defined three possible ways in which the DES and SD models could be linked. First is the hierarchical format (Fig. 1), which could be either an SD- or a DES-dominant one. In this case, there is a vertical interaction between the strategic (SD) and operational (DES) models. The second one is the phase-to-phase format, where the two models run in separate phases. The third type is the integrated format (Fig. 2), which allows constant bidirectional interactions (Moradi et al., 2015). Alvanchi et al. (2011) also identified three structures of DES–SD hybrid models similar to the ones mentioned earlier. These are the DES-dominant, SD-dominant (Fig. 1), and parallel models (Fig. 2). In the case of the first two, the direction of the interaction is toward the dominant part, while in the parallel models, the interaction is bidirectional (Alvanchi et al., 2011).

Swinerd and McNaught (2012) defined three classes for SD–ABM hybrid simulation. Figure 2 shows how in the case of the integrated simulation, there is continuous feedback both ways between the two modules. Per Figure 1, sequential simulation means that first, the SD module runs, and its output becomes the input for the ABM module or vice versa. The third class is interfaced hybrid design (Fig. 3), where the modules run parallel and their outputs are combined (Swinerd and McNaught, 2012).

Borshchev (2013) described the six most frequently used variations of the integrated structure (Fig. 2)

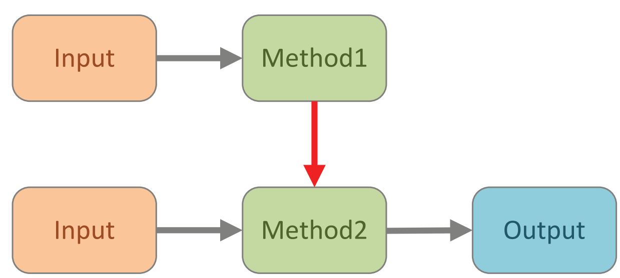

Fig. 1: Dominant structure of hybrid simulation (in this case, Method 2 is dominant)

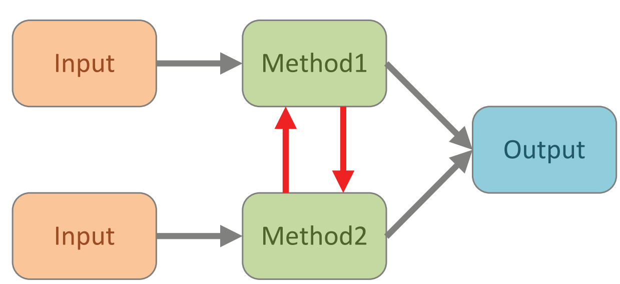

Fig. 2: Integrated structure of hybrid simulation

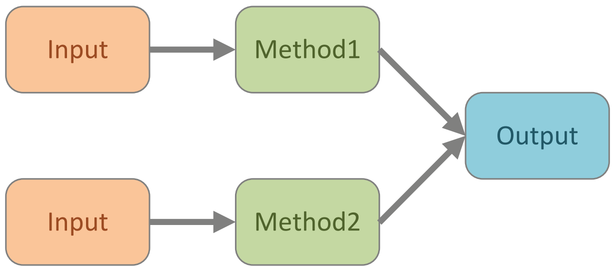

Fig. 3: Parallel structure of hybrid simulation

and provided examples for all of them. These are the following:
- agents in an SD environment;
- agents interacting with a DES model;
- DES model linked to an SD model;
- SD inside every agent;
- DES inside every agent;
- agents as entities in a DES model.

3.4 Interface variables in the hybrid simulation

After the most suitable structure is selected, the interaction points between the components need to be defined. These interface variables are the ones that may affect the variables in the other component. Creating hybrid models provides the opportunity of having dynamic variables, which would otherwise be static using a basic simulation method (Alvanchi et al., 2011). Furthermore, applying a hybrid approach can mean the combination of a continuous (e.g., SD) and a discrete (e.g., DES) method, meaning that time advancement has to be defined (Alvanchi et al., 2011; Alzraiee et al., 2012). It is important, therefore, to be aware of how the interacting variables may change due to linking of the components of the hybrid system. According to Alvanchi et al. (2011), there are five types of interactions:
- In the case of one discrete variable and one continuous variable,
  - a discrete change in the discrete variable causes a discrete change in the continuous one;
  - a discrete change in the discrete variable causes a change in the functional description of the continuous one; and
  - a continuous change in the continuous variable causes a discrete change in the discrete one.
- In the case of two continuous variables,
  - a continuous change in one continuous variable causes a continuous change in the other.
- In the case of two discrete variables,
  - a discrete change in one discrete variable causes a discrete change in the other.

4 Simulation framework

A framework for modeling with construction simulation can be seen in Figure 4. The first step is to analyze the problem that needs to be solved. Then the question, which the simulation results should answer, must be phrased. Depending on the complexity of the question or the part of the reality to be modeled, the left or right path should be chosen. The next step is to select the most suitable simulation approach. The choice could be made based on the purpose of the investigation and the required level of abstraction. The basic methods provide different levels of abstraction.

If the focus is on the process itself, DES might be the most appropriate method, as it could be used at the operational level. It provides information on activity and project durations and resources. In DES, e.g., the workflow of the masonry process can be modeled. For the construction masonry unit, the description of the workflow can be found in Florez and Castro-Lacouture's work (2014), whereas Dawood et al. (2001) provide the same for brickwork. For example, if the objective is to see one factor's effect on the activity durations in a process, it is probably enough to choose a proper probability distribution function for the activity distributions in DES. However, if the effects of several factors are to be taken into account, the combination of DES with, e.g., SD could be the right choice.

SD concentrates on causal relationships on a macro level and tracks the changes of the continuous variables. In the case of masonry, it could be used, e.g., to include the factors influencing labor productivity. If the aim is to understand the workings of the system, it could be applied on its own in a qualitative manner (Kunc, 2017).

ABM may be used at all levels of abstraction. By defining the agents with their attributes and rules of behavior, the workings of the global system are revealed. The agents, for instance, could be masons and laborers working on a project. The most critical variables concerning the workers are described in Florez (2017). The different wall sections could also be agents, and there are possible classifications

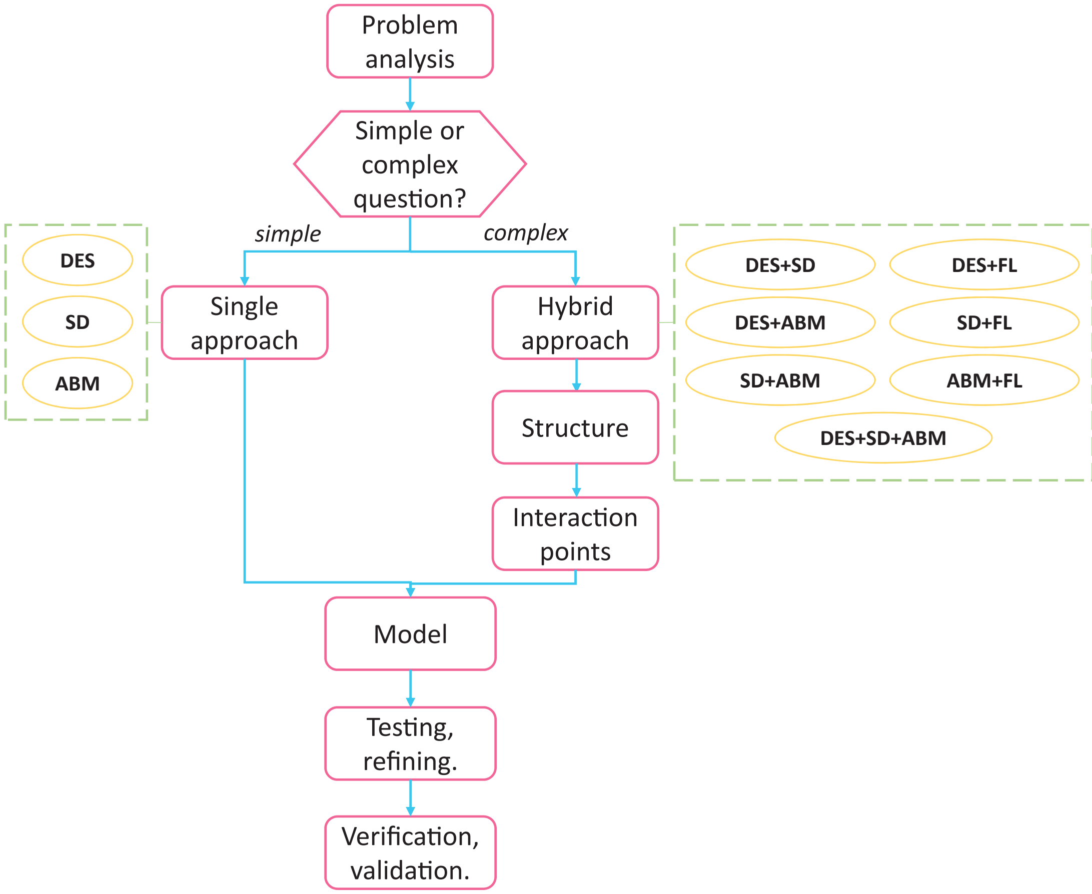

Fig. 4: Construction simulation framework

for walls in masonry construction (Thomas and Završki, 1999; Florez, 2017).

FL is useful in case the variables are subjective and could not be easily expressed with crisp values. FL is not enough on its own; however, it could be paired with one of the basic simulation methods. It could be applied, e.g., to express the effect of various factors on the activity durations in DES.

If a hybrid solution seems appropriate, after choosing the most suitable approach, the structure must be determined. Of the three structures that have been presented thus far, if they were to be theoretically ranked according to the level of interaction between the two components, parallel would be the lowest and integrated the highest. In the case of the parallel structure (Fig. 3), the components are running simultaneously, and their outputs are combined. The second possibility is the dominant structure (Fig. 1), which means that one approach is more dominant than the other; therefore, the output of one approach becomes the input of the other, and the final output comes from the second. Since FL is not a simulation method, its combination with a basic simulation method (DES, SD, or ABM) could belong in this category, where the dominant approach is the selected basic method. The last option is the integrated structure (Fig. 2). In this case, the interaction between the components is bidirectional and continuous.

The next step in this branch (Fig. 4) is to define the interface variables described in Section 3.4.

Based on the selected simulation approach, its structure, and interaction points, if applicable, and the required input data, the simulation model could be produced. The necessary input information is listed in Table 1. The table also contains the output that each approach provides.

After the preliminary model is ready, it needs to be tested and refined. The improved model must be checked, as well. Verification confirms that the model is a correct reflection of reality; whereas, validation is performed to show that the model's accuracy is adequate for the simulation problem. Verification and validation do not only happen at the end, but they are performed after every step in the model development process (Sargent, 2015).

5 Application of the framework – an example

Despite the efforts to use prefabricated elements, construction projects can still be considered labor-intensive works. One of the most labor-intensive processes is masonry works. As skilled labor resources are becoming scarce, the importance of accurate productivity rates and efficient resource management is increasing. The framework described in Section 4 can be of help.

Using the flowchart shown in Figure 4, the first step is to name the problem at hand. In this example, the objective is to get better, more realistic productivity rates. Since countless factors are affecting these estimates, many of which need to be considered, the right path is selected. At this point, the appropriate hybrid approach needs to be picked. Based on Table 1, the output of DES coincides with the aim of the task. Therefore, DES needs to be one component of the hybrid model. The other can be SD because it will be able to express the effects of the influencing factors on the activity duration. The next step is to determine the structure of the approach. The proposed structure for this example is shown in Figure 5.

The structure in Figure 5 is a DES-dominant one, which means that the output of SD influences the input of DES, and the final output comes from the DES component.

The inputs of the SD component are the set of influencing factors, such as attributes of walls and workers, and their effects on the productivity rates. This information can come from three sources (Kunc, 2017): expert opinion, numerical data sets, and facilitation processes for nonlinear functions. The inputs of the DES part are the workflow (the activities performed in the process linked together), the resources assigned to the activities, and the activity durations modified by the SD component. The latter is the interaction variable connecting the two components.

The final outputs of the hybrid system are the process duration and resource usage. The dimension of the former depends on the units used for the activities. The easiest is probably to use blocks per time unit, in which case, the resulting process duration needs to be converted into hours per square meter so that these rates could be simply applied in future scheduling and cost calculations.

6 Conclusion

Construction simulation is a useful technique that replicates reality and provides valuable information on construction works. Simulation considers time changes and the dynamic nature of processes to model the operation of a system. It can be applied, for instance, to model a construction operation to determine activity durations and resource usage more precisely, which can be used to make more realistic schedules and cost calculations.

This paper gave an overview of the basic simulation methods (DES, SD, and ABM) and the hybrid approaches, which are the combinations of the basic methods. It also provided examples from the literature for the application

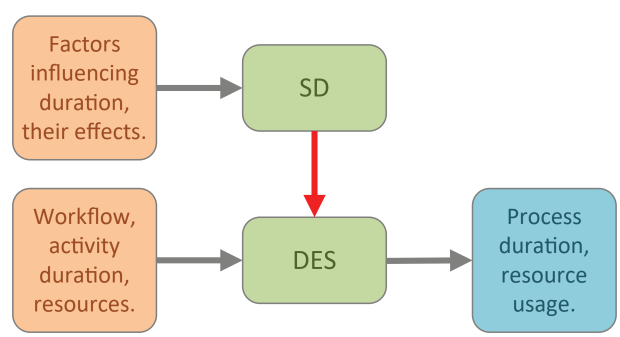

Fig. 5: Example of DES-SD hybrid approach (DES-dominant structure)

Tab. 1: Input and output of the basic simulation approaches

		Input	Output
Methods	Discrete event simulation (DES)	Activities (activity durations, resources) Relationships	Process duration Resource usage
	System dynamics (SD)	Influencing factors Stocks and flows	Changes of factors over time Effects of factors
	Agent-based modeling (ABM)	Agents (attributes, rules of behavior)	Behavior of the system
Technique	Fuzzy logic (FL)	Factors affecting duration Frequency of occurrence Adverse consequences	Crisp values

of various approaches. In the second half of the narrative, a framework for construction simulation was introduced complete with examples from masonry works.

Since construction projects are complex and dynamic and additionally involve complicated behavior, uncertainties, and dependencies, probably the most suitable simulation approaches could be found among hybrid simulation solutions. These combine the advantages of the selected techniques in order to better model reality.

The hybrid simulation model introduced in Section 5 needs to be tested by using real-life case studies of construction projects. Due to the versatility of ABM, ABM-dominant hybrid simulation approaches could probably also be applied for obtaining realistic productivity rates. The results of these must be compared with those provided by DES-dominant hybrid simulation. Moreover, the possible application of different structure options should also be analyzed. Furthermore, whether the system could be used in case of other labor-intensive works must be investigated.

References

AbouRizk, S., Halpin, D., Mohamed, Y., & Hermann, U. (2011). Research in modeling and simulation for improving construction engineering operations. *Journal of Construction Engineering and Management*, *137*(10), pp. 843-852.

AbouRizk, S. M. (2010). Role of simulation in construction engineering and management. *Journal of Construction Engineering and Management*, *136*(10), pp. 1140–1153.

AbouRizk, S. M., & Halpin, D. W. (1992). Statistical properties of construction duration data. *Journal of Construction Engineering and Management*, *118*(3), pp. 525-544.

AbouRizk, S. M., & Sawhney, A. (1993). Subjective and interactive duration estimation. *Canadian Journal of Civil Engineering*, *20*, pp. 457-470.

Alvanchi, A., Lee, S. H., & AbouRizk, S. (2011). Modeling framework and architecture of hybrid system dynamics and discrete event simulation for construction. *Computer-Aided Civil and Infrastructure Engineering*, *26*(2), pp. 77-91.

Alzraiee, H., Zayed, T., & Moselhi, O. (2012). Methodology for synchronizing discrete event simulation and system dynamics models. In: Laroque, C., Himmelspach, J., Pasupathy, R., Rose, O., & Uhrmacher, A. M. (eds.) *Proceedings of the 2012 Winter Simulation Conference (WSC)*. IEEE, Berlin, Germany, pp. 1-11.

Alzraiee, H., Zayed, T., & Moselhi, O. (2015). Dynamic planning of construction activities using hybrid simulation. *Automation in Construction*, *49*, pp. 176-192.

Ayyub, B. M., & Haldar, A. (1984). Project scheduling using fuzzy set concepts. *Journal of Construction Engineering and Management*, *110*(2), pp. 189-204.

Balaban, M., Hester, P., & Diallo, S. (2014). Towards a theory of multi-method M&S approach: Part I. In: Tolk, A., Diallo, S. Y., Ryzhov, I. O., Yilmaz, L., Buckley, S., & Miller, J. A. (eds.) *Proceedings of the 2014 Winter Simulation Conference*. IEEE, Savannah, GA, USA, pp. 1652-1663.

Borshchev, A. (2013). Multi-method modeling. In: Pasupathy, R., Kim, S. -H., Tolk, A., Hill, R., & Kuhl, M. E. (eds.) *Proceedings of the 2013 Winter Simulation Conference*. IEEE, Washington DC, USA, pp. 4089-4100. Available at https://informs-sim.org/wsc13papers/includes/files/410.pdf.

Borshchev, A., & Filippov, A. (2004). From system dynamics and discrete event to practical agent based modeling : reasons, techniques, tools. In: Kennedy, M., Winch, G. W., Langer, R. S., Rowe, J. I., & Yanni, J. M. (eds.) *Proceedings of the 22nd International Conference of the System Dynamics Society*. System Dynamics Society, Oxford, UK. Available at: http://www2.econ.iastate.edu/tesfatsi/systemdyndiscreteeventabm-compared.borshchevfilippov04.pdf.

Dabirian, S., Khanzadi, M., & Moussazadeh, M. (2016). Predicting labor costs in construction projects using agent-based modeling and simulation. *Scientia Iranica*, *23*(1), pp. 91-101.

Dawood, N., Hobbs, B., & Fanning, A. (2001). Standardization of brickwork construction: identification and measurement of standard processes. In: Akintoye, A. (ed.) *Proceedings 17th Annual ARCOM Conference*. ARCOM, Salford, UK, pp. 321-329. Available at http://www.arcom.ac.uk/-docs/proceedings/ar2001-321-329_Dawood_Hobbs_and_Fanning.pdf.

De Salles, D. C., Gonçalves Neto, A. C., & Marujo, L. G. (2016). Using fuzzy logic to implement decision policies in system dynamics models. *Expert Systems with Applications*, *55*, pp. 172-183.

Fahrland, D. A. (1970). Combined discrete event continuous systems simulation. *Simulation*, *14*(2), pp. 61-72.

Florez, L. (2017). Crew allocation system for the masonry industry. *Computer-Aided Civil and Infrastructure Engineering*, *32*(10), pp. 874-889.

Florez, L., & Castro-Lacouture, D. (2014). Labor management in masonry construction: a sustainable approach. In: *31st International Symposium on Automation and Robotics in Construction and Mining (ISARC 2014): Automation, Construction and Environment*. International Association for Automation & Robotics in Construction (IAARC), Sydney, Australia, pp. 529-536.

Forrester, J. W. (1961). *Industrial dynamics*. Productivity Press, Portland, Oregon.

Gordon, G. (1961). A general purpose systems simulation program. In: *Proceedings of the December 12-14, 1961, Eastern Joint Computer Conference: Computers - Key to Total Systems Control - AFIPS '61 (Eastern)*. ACM Press, Washington, DC, USA, pp. 87-104.

Hajdu, M., & Bokor, O. (2016). Sensitivity analysis in PERT networks: Does activity duration distribution matter? *Automation in Construction*, *65*, pp. 1-8.

Hsu, S. C., Weng, K. W., Cui, Q., & Rand, W. (2016). Understanding the complexity of project team member selection through agent-based modeling. *International Journal of Project Management*, *34*(1), pp. 82-93.

Khanzadi, M., Nasirzadeh, F., & Alipour, M. (2012). Integrating system dynamics and fuzzy logic modeling to determine concession period in BOT projects. *Automation in Construction*, *22*, pp. 368-376.

Khanzadi, M., Nasirzadeh, F., Mir, M., & Nojedehi, P. (2017). Prediction and improvement of labor productivity using hybrid system dynamics and agent-based modeling approach. *Construction Innovation*, *18*(1), pp. 2-19.

Kunc, M. (2017). System dynamics: a soft and hard approach to modelling. In: Chan, W. K. V., D'Ambrogio, A., Zacharewicz, G., Mustafee, N., Wainer, G., & Page, E. (eds.) *Proceedings of the 2017 Winter Simulation Conference*. IEEE, Las Vegas, NV, USA, pp. 597-606.

Lättilä, L., Hilletofth, P., & Lin, B. (2010). Hybrid simulation models - When, why, how? *Expert Systems with Applications*, *37*(12), pp. 7969-7975.

Law, A. M. (2015). *Simulation Modeling and Analysis*. 5th edn. McGraw-Hill, New York.

Lorterapong, P., & Moselhi, O. (1996). Project-network analysis using fuzzy sets theory. *Journal of Construction Engineering and Management*, *122*(4), pp. 308-318.

Martinez, J. C. (2010). Methodology for conducting discrete-event simulation studies in construction engineering and management. *Journal of Construction Engineering and Management*, *136*(1), pp. 3-16.

Mawdesley, M. J., & Al-Jibouri, S. (2009). Modelling construction project productivity using systems dynamics approach. *International Journal of Productivity and Performance Management*, *59*(1), pp. 18-36.

Moradi, S., Nasirzadeh, F., & Golkhoo, F. (2015). A hybrid SD–DES simulation approach to model construction projects. *Construction Innovation*, *15*(1), pp. 66-83.

Mosterman, P. J. (1999). An overview of hybrid simulation phenomena and their support by simulation packages. In: Vaandrager, F. W., & van Schuppen, J. H. (eds.) *Hybrid Systems: Computation and Control*. Springer, Berg en Dal, The Netherlands, pp. 165-177.

Mustafee, N., Powell, J., Brailsford, S. C., Diallo, S., Padilla, J., & Tolk, A. (2015). Hybrid simulation studies and hybrid simulation systems: definitions, challenges, and benefits. In: Yilmaz, L., Chan, W. K. V., Moon, I., Roeder, T. M. K., Macal, C., & Rossetti, M. D. (eds.) *Proceedings of the 2015 Winter Simulation Conference*. IEEE, Huntington Beach, CA, USA, pp. 1678-1692.

Nasirzadeh, F., Khanzadi, M., & Mir, M. (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), pp. 132-143.

Nojedehi, P., & Nasirzadeh, F. (2017). A hybrid simulation approach to model and improve construction labor productivity. *KSCE Journal of Civil Engineering*, *21*(5), pp. 1516-1524.

Peña-Mora, F., Han, S., Lee, S., & Park, M. (2008). Strategic-operational construction management: hybrid system dynamics and discrete event approach. *Journal of Construction Engineering and Management*, *134*(9), pp. 701-710.

Raoufi, M., & Robinson Fayek, A. (2015). Integrating Fuzzy logic and agent-based modeling for assessing construction crew behavior. In: *Annual Conference of the North American Fuzzy Information Processing Society - NAFIPS*. IEEE, Redmond, WA, USA.

Raoufi, M., Seresht, N. G., & Robinson Fayek, A. (2016). Overview of Fuzzy simulation techniques in construction engineering and management. In Ceberio, M., & Kreinovich, V. (eds.) *2016 Annual Conference of the North American Fuzzy Information Processing Society (NAFIPS)*. IEEE, El Paso, TX, USA, pp. 1-6.

Robinson Fayek, A., & Oduba, A. (2005). Predicting industrial construction labor productivity using Fuzzy expert systems. *Journal of Construction Engineering and Management*, *131*(8), pp. 938-941.

Sargent, R. G. (2015). An introductory tutorial on verification and validation of simulation models. In: Yilmaz, L., Chan, W. K. V., Moon, I., Roeder, T. M. K., Macal, C., & Rossetti, M. D. (eds.) *Proceedings of the 2015 Winter Simulation Conference*. IEEE, Huntington Beach, CA, USA, pp. 1729-1740.

Sawhney, A., Bashford, H., Walsh, K., & Mulky, A. R. (2003). Agent-based modeling and simulation in construction. In: Chick, S., Sánchez, P. J., Ferrin, D., & Morrice, D. J. (eds.) *Proceedings of the 2003 Winter Simulation Conference*. IEEE, New Orleans, LA, USA, pp. 1541-1547.

Shaheen, A. A., Robinson Fayek, A., & AbouRizk, S. M. (2009). Methodology for integrating fuzzy expert systems and discrete event simulation in construction engineering. *Canadian Journal of Civil Engineering*, *36*(9), pp. 1478-1490.

Siebers, P. O., MacAl, C. M., Garnett, J., Buxton, D., & Pidd, M. (2010). Discrete-event simulation is dead, long live agent-based simulation! *Journal of Simulation*, *4*(3), pp. 204-210.

Son, J. W., Rojas, E. M., & Shin, S.-W. (2015). Application of agent-based modeling and simulation to understanding complex management problems in CEM research. *Journal of Civil Engineering and Management*, *21*(8), pp. 998-1013.

Swinerd, C., & McNaught, K. R. (2012). Design classes for hybrid simulations involving agent-based and system dynamics models. *Simulation Modelling Practice and Theory*, *25*, pp. 118-133.

Thomas, H. R., Završki, I. (1999). Construction baseline productivity: theory and practice. *Journal of Construction Engineering and Management*, *125*(5), pp. 295-303.

Watkins, M., Mukherjee, A., Onder, N., & Mattila, K. (2009). Using agent-based modeling to study construction labor productivity as an emergent property of individual and crew interactions. *Journal of Construction Engineering and Management*, *135*(7), pp. 657-667.

Zadeh, L. A. (1980). Fuzzy sets versus probability. *Proceedings of the IEEE*, *68*(3), p. 421.

Zhang, H., Tam, C. M., & Li, H. (2005). Modeling uncertain activity duration by fuzzy number and discrete-event simulation. *European Journal of Operational Research*, *164*, pp. 715-729.