Naraghi A.M., González V.A., O'Sullivan M.J., Walker C.G., Poshdar M., and Abdelmegid M.A (2017). "Implementation of hybrid simulation modelling framework in construction." In: *LC3 2017: Volume I – Proceedings of the Joint Conference on Computing in Construction (JC3)*, July 4-7, 2017, Heraklion, Greece, pp. 439-446. DOI: https://doi.org/10.24928/JC3-2017/0072.

IMPLEMENTATION OF HYBRID SIMULATION MODELLING FRAMEWORK IN CONSTRUCTION

Ashkan M. Naraghi [1], Vicente. A. González[2], Michael O'Sullivan[3], Cameron G. Walker[4], Mani Poshdar[5], M. Adel Abdelmegid[6]

Abstract: The goal of construction system modelling is to improve construction work performance by tracking the dynamic behaviour of construction systems. Discrete-Event Simulation (DES) has been suggested as a supporting tool for management decision-making in order to capture the dynamic complexity of construction projects. However, the limitations of DES in modelling influential factors such as the individual and emergent behaviour of system entities have led to the combined use of Agent-based Simulation (ABS) and DES. This paper provides an overview of DES and ABS applications in construction, and then discusses rationale for integrating DES and ABS from the conceptual stage onwards. Furthermore, a hybrid DES-ABS conceptual framework is introduced and the challenges of this type of hybrid simulation model are explained.

Keywords: Hybrid simulation, construction management, decision support system.

1 INTRODUCTION

Simulation models are used as supporting tools in many industries in order to deal with complexity and uncertainty in a timely and cost-effective manner (AbouRizk, 2010). Nevertheless, the application of simulation modelling in construction projects with complexity and uncertainty inherent in their processes is predominantly limited to academic research (Lee et al., 2006). Traditional tools such as Critical Path Method (CPM) and Program Evaluation and Review Technique (PERT) are still preferred by construction managers to plan and manage construction processes.

CPM is one of the most common and popular planning tools in the construction industry. Researchers, however, have pointed out several disadvantages of CPM including a lack of support for cyclic activities, an inefficient representation of constraints at the operational level, the difficulty in supporting time interval inputs, and the assumption that there are unlimited resources (Kim, 2007, Peña-Mora et al., 2008). More recently PERT was introduced to support the modelling of activities with stochastic nature and limited resource availability (Peña-Mora et al., 2008). Both CPM

[1] PhD Student, Department of Civil and Environmental Engineering, The University of Auckland, Auckland, New Zealand (corresponding author). E-mail address: amoh769@aucklanduni.ac.nz
[2] PhD, Senior Lecturer, Department of Civil and Environmental Engineering, The University of Auckland, Auckland, New Zealand. E-mail: v.gonzalez@auckland.ac.nz
[3] PhD, Senior Lecturer, Department of Engineering Science, The University of Auckland, Auckland, New Zealand. E-mail: michael.osullivan@auckland.ac.nz
[4] PhD, Associate Professor, Department of Engineering Science, The University of Auckland, Auckland, New Zealand. E-mail: cameron.walker@auckland.ac.nz
[5] PhD, Lecturer, Engineering, Department: Engineering, Computer & Mathematical Sciences, Auckland University of Technology, Auckland, New Zealand. E-mail: mani.poshdar@aut.ac.nz
[6] PhD Student, Department of Civil and Environmental Engineering, The University of Auckland, New Zealand E-mail address: mabd556@aucklanduni.ac.nz

and PERT do not account for the intrinsic dynamics on a project schedule since they do not provide a mechanism to explicitly represent feedback between performance and management actions, which is the main source of dynamic system behaviour. Arguably, in nearly all construction projects, the final CPM/PERT schedules significantly differ from the initial schedules and incorporate additional time or costs.

The development of Discrete-Event Simulation (DES) techniques in construction reflects the requirement for construction managers to easily and quickly analyze construction projects irrespective of their complexity or size (AbouRizk, 2010). A number of researchers have addressed the benefits of applying DES in construction such as planning improvement, analysis of productivity, and emissions quantification (AbouRizk, 2010, Ahn et al., 2010). However, DES models cannot reliably represent the production environment of construction due to the difficulty in simulating the free movement of entities and representing the decision patterns of individual entities at very small time increments (Watkins et al., 2009). These limitations have led researchers to study the integration of DES with other simulation techniques such as Agent-Based Simulation (ABS). ABS models simulate entities of a system as intelligent and autonomous objects which interact both with each other and their environment to achieve multiple targets. Therefore, this study investigates a hybrid modelling approach which is formed by integrating DES and ABS.

Section 2 contains a literature review of previous research efforts related to applying DES and ABS in construction and also highlights the features and limitations of these techniques. Then, in section 3, descriptions of the different forms of hybrid simulation modelling, are presented, followed by a proposed hybrid DES-ABS framework. Finally the main findings and conclusions are discussed.

2 Simulation Modelling Paradigms

Simulation modelling tools facilitate the study of complexity in construction projects at varying levels of abstraction (Rekapalli and Martinez, 2011). DES, SD and, more recently, ABS are the most common simulation modelling techniques in construction. According to Brailsford and Hilton (2001), each of the aforementioned techniques serves a specific range of abstraction levels. DES is mostly used to model a construction system at the operational and/or the tactical level. It is a quantitative approach with discrete changes to the system (events) and that captures details of the system. SD, on the other hand, supports decision-making at the strategic level by focusing on feedback processes. The SD approach, which is qualitative in nature and continuous in behaviour, traces causal relationships among system variables. The purpose of the SD approach is to present a holistic view of the project environment (Alzraiee et al., 2013). Alternatively, ABS is a bottom-up approach that models the behaviour of autonomous entities as well as the emergent behaviour of micro decisions (Siebers et al., 2010). Therefore, ABS can be used to model a system at an even more detailed level than DES. In this paper, modelling at the operational and tactical levels is considered, so SD is out of scope and not considered.

2.1 Discrete Event Simulation Modelling

DES tools have been applied to simulate and analyze construction processes in a wide range of construction contexts such as earthmoving, tunnelling, and erecting high-rise buildings. The most common DES strategy in construction is Activity Scanning (AS) where a system focuses on activities that are highly dependent on time schedules and preconditions (Rekapalli and Martinez, 2011). Three-phase and three-stage strategies, which are used by simulation tools such as CYCLONE, CIPROS, RESQUE, STROBOSCOPE and Simphony.Net, are modified forms of AS (Zhang et al., 2005).

Martin and Raffo (2001) argue that most commercial DES tools for studying construction use a process-oriented approach. Entities in this approach are not classified as individuals with their own characteristics, they are only data containers. Indeed, DES models focus mainly on the analysis of a construction process from a time, cost and resource utilization perspective (Peña-Mora et al., 2008).Therefore, DES models cannot fully represent and analyze all construction contexts.

2.2 Agent-based Simulation Modelling

ABS is a modelling approach that simulates a system through a set of agents that interact with each other and the system's context (Watkins et al., 2009). Even though, there is no general acceptance of the definition of "agent", some characteristics of agents have been commonly accepted and used. These characteristics include autonomy, understanding, learning, and cooperation (Turban et al., 2005). In addition, Each agent's goals may be different, but they follow very simple rules such as ''If-then'' (Marzouk and Ali, 2013). Therefore, it is easy to capture an agent's behaviour in complex systems such as construction processes, but it is very difficult to analyze the behaviour that arises from the interaction of agents, called "emergent behaviour" (Bonabeau, 2002).

Kim and Kim (2010) describe the following steps for building an agent-based model: 1- Define the agents and their attributes and characteristics along with their targets and goals; 2- Identify the boundaries of the context that the agents will live in and interact with; 3- Define the correlation of agents via communication protocols including classification of relationships and interactions among agents and with the environment. 4- Identify updating methods of agent attributes after interaction with and learning from other agents or their environment.

A number of researchers have applied ABS modelling to solve problems in different domains of the construction industry. Resource allocation and scheduling (Kim and Kim, 2010), safety and risk (Taillandier et al., 2015), and bidding environments (Awwad et al., 2015) are some of the investigated domains. In contrast to commercial DES software, development of an ABS model requires the heavy use of programming languages such as java (Siebers et al., 2010). Therefore, ABS modelling still remains in the domain of simulation modellers and academic researchers. According to Crooks et al. (2008), there is also some difficulty when validating ABS models at the macro-level, especially when there is a lack of adequate empirical data. He indicated that the emergent behaviour which arises from agents' interactions over time is not directly related to the individual agents' characteristics.

3 HYBRID SIMULATION MODELLING

Hybrid simulation modelling refers to the integration of two or more simulation approaches to facilitate the study of a complex system. Hybrid models represent the interaction between components of a system at different abstraction levels, in which the limitations of each simulation approach are mitigated by the other approach's capabilities (Lynch et al., 2015).

3.1 Hybrid Forms

Chahal (2010) proposes three types of hybrid forms: First, a hierarchical form, in which each paradigm is used for a specific abstraction level and interaction between models is either cyclic or parallel. Second, a process environment form, in which one simulation approach represents the process and the other represents environmental factors. The simulations are coupled in terms of time and space. Third, an integrated form that integrates all modelling approaches into one model, and there is no clear boundary between the approaches. Alvanchi et al. (2011) suggest two other types of hybrid classification. One is dominant modelling, in which one simulation technique builds up the main model and the direction of interactions is from a supportive simulation model to the dominant approach. The other is parallel hybrid modelling (that is similar to the hierarchical form summarised earlier in this section) and this structure has bidirectional interactions between modelling paradigms.

3.2 Hybrid DES-ABS Framework

Although DES and ABS are both useful simulation techniques, some aspects in complex systems are best represented by a DES model and others by an ABS model. A number of studies have been conducted on a framework for developing a hybrid DES-ABS model in healthcare, manufacturing, etc. (Wang et al., 2013, Lynch et al., 2015), but the study on the development of a hybrid DES-ABS model in construction is still in its infancy.

The first step to develop a hybrid DES-ABS model is to provide answers to the following questions: 1- What problems are going to be addressed by a hybrid DES-ABS model? 2- What kind of information is exchanged between DES and ABS? 3- How do these two types of simulation modelling interact with each other?

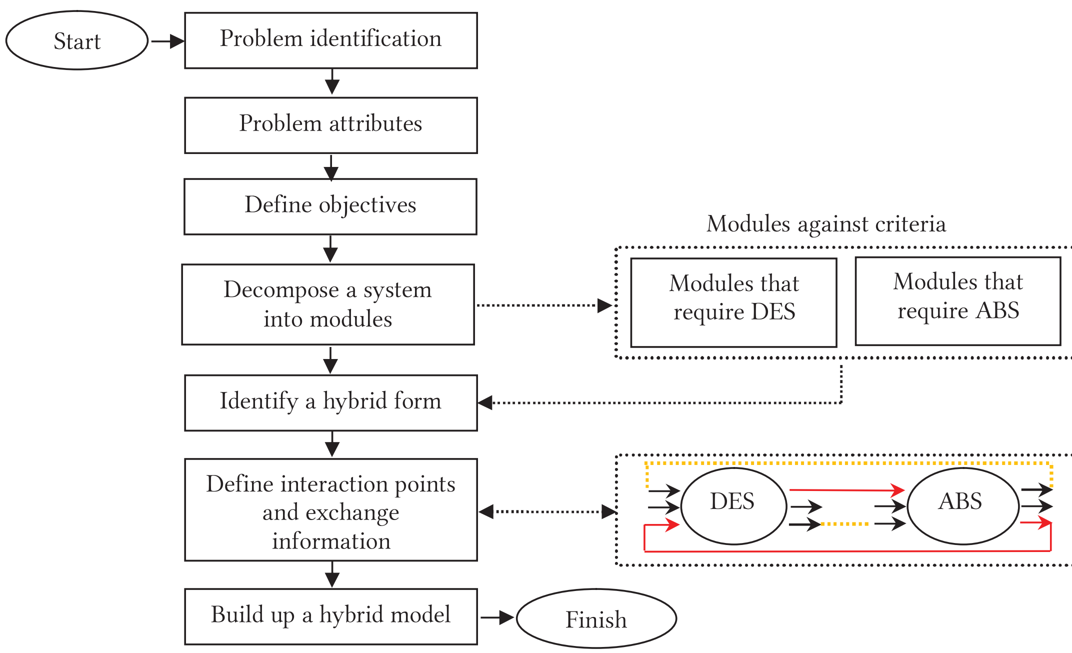

Figure 1Developing a hybrid DES-ABS model

Figure 1 depicts a framework for developing a hybrid DES-ABS model. After identification of a problem and its attributes (that include including constraints, assumptions and scope) the objectives of the simulation study are defined. On the basis of the defined objectives, a “modularization process” is applied to subdivide the system into several parts, called as ‘modules’ (Turban et al., 2005). The modules were then mapped to the appropriate simulation approach using criteria provided in table 1. Based on applicability of DES and ABS for modelling the elements of a problem, a type of hybrid DES-ABS form will be selected as discussed in section 3.1.

Identification of the hybrid form facilitates understanding of what information is exchanged and how it is exchanged between DES and ABS. The interaction between simulation models consists of two scenarios: 1- An output(s) of one model is used as an input(s) for the other model, or 2- An output(s) of one model is not replaced as an input of the other model, but can influence the value of its input. The next section will provide a brief summary of the application of the proposed framework to develop a hybrid DES-ABS model application in a real case study.

Table 1 Criteria for selection between DES and ABS

Criteria	DES	ABS
Purpose	Optimization, Prediction and Comparison of Alternatives	Optimization, Behaviours, Learning and Adapting, and Understanding of Emergent Phenomena/Situations
Problem Scope Level	Tactical - Operational	Strategic- Tactical - Operational
Randomness	High Importance	Low/High Importance
Level of Resolution	Detailed Level	Detailed Level and Aggregated Level
Interaction between Individual Objects	High	High
System View	Detailed View	Very Detailed and Holistic View
Complexity	Detail	Detail and Dynamic
Environment Interaction	No	Yes
Control Parameter	Holding (Queues)	Transaction Mechanisms
System Process	Discrete	Mostly Discrete

3.3 Empirical Evaluation of the Framework

A pipe-jacking project as a part of the City Rail Link (CRL) in Auckland - New Zealand has been chosen to evaluate the proposed framework as a case study. The main purpose of the simulation study is to complete the project on time, which is achieved by implementing the following objectives: 1- Minimizing total execution time; and 2- Improving the efficiency of resources. Thus, the system's processes are categorized and put into two modules: Production and Logistic.

The production module comprises a Micro Tunnel-Boring Machine (MTBM) loading a muck skip attached to a locomotive. The logistic module comprises the muck skip being transported to the main shaft, being raised by a gantry crane, emptied into a muck pit, then lowered back down to the locomotive. The MTBM consists of several components such as a cutting wheel, a jack machine and conveyors and therefore it has different failure modes. Hence, the failures have different severity level that cause from small to full replacements. Using the proposed framework, the production module was determined to be suitable for ABS it could model the MTBM behaviour, as well as to provide the MTBM characteristics e.g. failure rates. On other hand, the logistics module was determined to be suitable for DES to model the travelling of muck skip inside the tunnel and also when it is carried by a gantry crane to be emptied into the muck pit. The

AnyLogic simulation modelling environment has been used here as it supports hybrid models. Figure 2 gives screenshots of the hybrid model in AnyLogic.

DES is used as a supportive tool to enable the MTBM's behaviour to be controlled. When the muck skip is full, 'StopExcavation' message from 'pickup Soil' block of the DES model is sent to the MTBM agent that triggers a transition of the MTBM into the 'stInactive' state and stops the MTBM from excavating (as shown in figure 2). In addition, when the MTBM enters one the failure states, 'stBroken' or 'stScheduledService' the soil excavation will also be stopped. The status of MTBM changes to the 'stOperational' state when the empty muck skip returns to its initial position and is ready for loading by the MTBM. Soil amounts that are produced when the MTBM is in the "stExcavating" state are inserted as entities to the DES model.

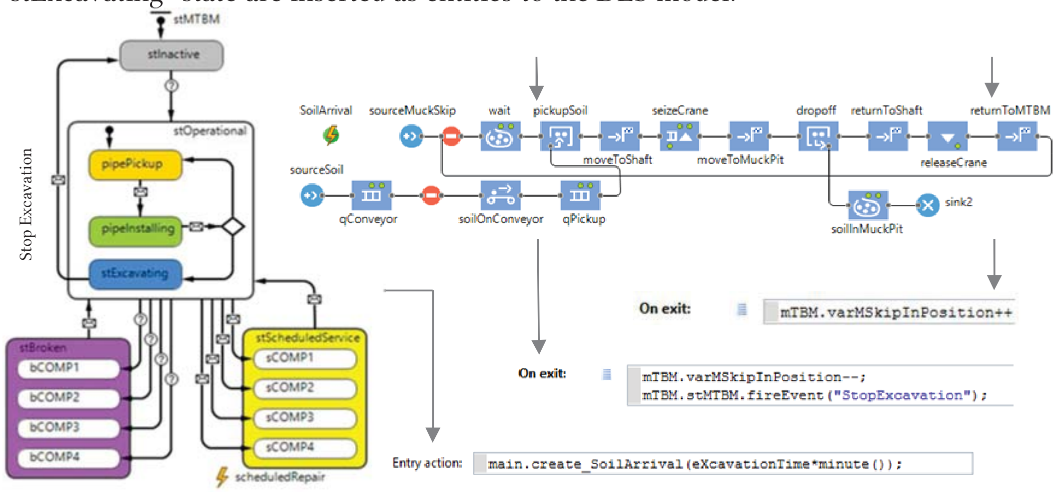

Figure 2 The left figure shows the ABS statechart of MTBM, and the right figure shows the DES model of muck skip

3.4 Hybrid DES-ABS Challenges

The components of a hybrid DES-ABS model follow the same structure that is based on individual entities (Furian et al., 2014). Therefore, this hybrid model doesn't suffer from some technical difficulties, such as time advancement, when compared to a hybrid DES-SD framework. The main difference between DES and ABS is the movement and behaviour of objects. Entities of DES models are managed through system-level rules, but agents in ABS models follow the rules that result from agent-agent and agent-environment interactions. It is not easy to model DES behaviour in software designed for ABS, and vice versa. For instance, when modelling an earthmoving operation in DES software, once a task is assigned to a truck it is difficult to interrupt and change the task based on changes in the system that happen after the task assignment. However, in an ABS model, the rules on interactions mean that, for example, changes to tasks are relatively straightforward to model.

DES and ABS approaches can interact with each other through a single integrated model with both DES and ABS attributes. AnyLogic is the only commercial software that supports ABS and DES in an integrated platform. Another approach to hybrid modelling is to use two different software packages. This approach is not without difficulties. For instance, it may be difficult to utilise an output of one model as an input to the other model without cumbersome file-based workarounds. In addition, it requires heavy computational effort to provide an iterative approach for updating both models when information is exchanged between the two.

4 CONCLUSIONS

In this study the authors have discussed the necessity for a simulation approach which can address the complexity of the construction environment. This paper identifies DES and ABS as two suitable approaches for operational and/or tactical level modelling and provides a comprehensive overview of DES and ABS modelling in construction as well as their drawbacks and limitations. DES is the most common simulation approach in construction, but faces challenges when it is required to model autonomous objects or very detailed decision patterns. In contrast, ABS can simulate intelligent objects that interact with each other and their environment to achieve some goals. However, the applicability of ABS to solely simulate construction systems is questionable. Therefore, the authors proposed the use of a hybrid DES-ABS model to overcome these limitations. Furthermore, the framework of the proposed hybrid model was explained. Validation output of a hybrid DES-ABS model could either come from actual results of a real-life construction project or the results obtained from a DES model with the same input data.

This hybrid framework can be further extended by including SD to address interactions between the elements of the model at different levels of abstraction. This study is the initial step of a continuous research effort to develop a hybrid simulation modelling framework for construction.

5 REFERENCES

AbouRizk, S. 2010. Role of Simulation in Construction Engineering and Management. *Journal of Construction Engineering and Management*,136,1140-1153.

Ahn, C., Ppan, W., Lee, S. & Peña-Mora, F. Enhanced estimation of air emissions from construction operations based on discrete-event simulation. *Proceedings of the International Conference on Computing in Civil and Building Engineering*, Nottingham, UK, 2010.

Alvanchi, A., Lee, S. & AbouRizk, S. 2011. Modeling Framework and Architecture of Hybrid System Dynamics and Discrete Event Simulation for Construction. C*omputer-Aided Civil and Infrastructure Engineering*, 26, 77-91.

Alzraiee, H., Moselhi, O. & Zayed, T. Dynamic planning of construction activities using hybrid simulation. ISARC 2013 - *30*th *International Symposium on Automation and Robotics in Construction and Mining* , 2013. 459-467.

Awwad, R., Asgari, S. & Kandil, A. 2015. Developing a Virtual Laboratory for Construction Bidding Environment Using Agent-Based Modeling. *Journal of Computing in Civil Engineering*, 29, 04014105.

Bonabeau, E. 2002. Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences of the United States of America*, 99, 7280-7287.

Brailsford, S. & Hilton, N. 2001. A comparison of discrete event simulation and system dynamics for modelling health care systems, In, Riley, J. (eds.) *Planning for the Future: Health Service Quality and Emergency Accessibility. Operational Research Applied to Health Services (ORAHS)* Glasgow Caledonian University

Chahal, K. 2010. *A generic framework for hybrid simulation in healthcare*. Brunel University School of Information Systems, Computing and Math PhD Theses.

Crooks, A., Castle, C. & Batty, M. 2008. Key challenges in agent-based modelling for geo-spatial simulation. Computers, *Environment and Urban Systems*, 32, 417-430.

Furian, N. N., D.; Vossner, S.; O'Sullivan, M. & Walker, C. 2014. Multi-Paradigm Modeling and Simulation in Health Care. Business Modeling and Simulation, 22-27.

Kim, J. 2007. An investigation of activity duration input modeling by duration variance ratio for simulation-based construction scheduling. Thesis.

Kim, K. J. & Kim, K. 2010. Case study on the evaluation of equipment flow at a construction site. *Journal of Computing in Civil Engineering*, 24, 570-575.

Lee, S. H., Peña-Mora, F. & Park, M. 2006. Dynamic planning and control methodology for strategic and operational construction project management. *Automation in Construction*, 15, 84-97.

Lynch, C., Padilla, J., Diallo, S., Sokolowski, J. & Banks, C. A multi-paradigm modeling framework for modeling and simulating problem situations. *Proceedings - Winter Simulation Conference*, 2015. 1688-1699.

Martin, R. & Raffo, D. 2001. Application of a hybrid process simulation model to a software development project. *Journal of Systems and Software*, 59, 237-246.

Marzouk, M. & Ali, H. 2013. Modeling safety considerations and space limitations in piling operations using agent based simulation. *Expert Systems with Applications*, 40, 4848-4857.

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, 701-710.

Rekapalli, P. V. & Martinez, J. C. 2011. Discrete-Event Simulation-Based Virtual Reality Environments for Construction Operations: Technology Introduction. *Journal of Construction Engineering & Management*, 137, 214-224.

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, 204-210.

Taillandier, F., Taillandier, P., Tepeli, E., Breysse, D., Mehdizadeh, R. & Khartabil, F. 2015. A multi-agent model to manage risks in construction project (SMACC). *Automation in Construction*, 58, 1-18.

Turban, E., Aronson, J. & Liang, T.-P. 2005. *Decision Support Systems and Intelligent Systems*, 7th Edition, Pearson Prentice Hall.

Wang, W., FU, W., Zhang, H. & Wang, Y. 2013. Hybrid modeling and simulation of automotive supply chain network. *Research Journal of Applied Sciences, Engineering and Technology*, 6, 1598-1605.

Watkins, M., Mukherjee, A., Onder, N. & Matilla, K. 2009. Using Agent-Based Modeling to Study Construction Labor Productivity as an Emergent Property of Individual and Crew Interactions. *Journal of Construction Engineering & Management*, 135, 657-667.

Zhang, H., Tam, C. M. & Li, H. 2005. Activity object-oriented simulation strategy for modeling construction operations. *Journal of Computing in Civil Engineering*, 19, 313-322.