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TOWARDS A CONCEPTUAL MODELING FRAMEWORK FOR CONSTRUCTION SIMULATION

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ABSTRACT

Discrete event simulation (DES) has been used in academia to solve complex construction management problems for decades. However, it has not gained widespread adoption within the industry. A considerable effort to increase the acceptance of DES in construction has been carried out. However, it has been heavily focused on implementing DES models, neglecting both a detailed conceptualization of the real system and an understanding of stakeholders' requirements. Conceptual modeling (CM) is a fundamental step in DES which helps build stakeholders' trust in the resulting model. We argue, then, that it is vital to develop a CM framework for the construction domain to improve the acceptance of DES in the industry. We propose a domain-specific CM framework for construction application. This framework will be formulated to suit the complex environment of construction projects.

1 INTRODUCTION

Construction projects involve complex operations and high levels of risk and uncertainty (AbouRizk et al. 2011). These characteristics, among others, are responsible for the notion that it is difficult to manage construction projects efficiently (Peña-Mora et al. 2008). Construction companies nowadays are striving to maintain high standards of performance. Therefore, there is a need to develop supportive tools for decision makers in the construction industry in order to achieve better project productivity performance. These decision support tools should enable the evaluation of management decisions without the need to interfere with the actual operations. DES is an excellent technique that enables experimentation with different scenarios in a virtual environment and evaluates the outcome by understanding the system behavior (Behzadan et al. 2015).

DES has been adopted by most construction simulation studies (Martinez 2010). DES models can represent: the overall logic of a construction system; the resources involved to execute different activities; and the surrounding environment such as weather, ground conditions or economic issues (AbouRizk 2010). In the past four decades, there has been significant research activity aimed at developing DES-based solutions to improve performance in different stages of a construction project. Despite these research efforts, DES has not been widely adopted in the construction industry (AbouRizk 2010; AbouRizk et al. 2011; Lee et al. 2013; Leite et al. 2016).

Researchers have been trying to determine approaches to promote the use of DES in construction. The Technical Council on Computing and Information Technology of the American Society of Civil Engineering (ASCE) investigated the major challenges that construction practitioners face in applying computer simulation (Lee et al. 2013; Leite et al. 2016). The lack of engagement by the stakeholders in simulation studies was among the identified challenges. This challenge can be resolved by the use of appropriate CM frameworks. CM is considered the most important task to be carried out in a DES study and plays a major role in finding a common agreement among stakeholders (Balci 2012). CM helps in building model credibility by unambiguously documenting the model structure and components (Robinson et al. 2015). However, CM is also considered to be a very difficult task and hard to understand in general (Law 1991). Therefore, there is a growing interest in CM within the general DES community. Several DES studies proposed the use of a framework to help in building conceptual models in a systematic and stepwise manner. A review of the current literature for construction DES modeling indicates that, surprisingly, CM has received little interest by the construction DES community. However, it has been thoroughly studied in other domains such as healthcare, manufacturing, military and business (Balci 2012).

Some recent construction DES research tackled the area of CM by indicating the importance of problem definition and model abstraction while building DES models (AbouRizk 2010; Martinez 2010; Saba 2012; Behzadan et al. 2015; Poshdar et al. 2016). On the other hand, several CM frameworks are motivated by the specific domain they represent, such as healthcare, military, business and manufacturing (Balci 2012; Robinson et al. 2015). Therefore, a dedicated effort needs to be made to develop a specific CM framework for the construction domain. It will use the insights from frameworks already developed for other domains such as healthcare and manufacturing in order to suit the construction project environment. The proposed framework is planned to be aligned with common industry practice by integrating its processes with a standard construction planning technique. The step of construction project planning produces significant resources that could be integrated with a CM framework. Thus, the burden of producing a conceptual model for construction systems could be significantly reduced by adopting the integrated CM/Planning framework.

This paper is a part of an ongoing research program aimed at developing a multi-scale simulation system to manage production complexity in construction projects at various production levels. In section 2, we review the literature on the application of DES in construction in order to investigate the gap in using CM frameworks for DES in the construction compared to other domains. Further, we review the CM literature in order to justify the use of a CM framework to remove/reduce the identified gap. This review will include a brief description of the former frameworks that have formed the basis of the proposed CM framework for construction. Then in section 3, we describe the proposed framework by providing a detailed discussion of each related methodological step, illustrated by examples from a real case study involving a major infrastructure project. Lastly, we provide conclusions and further research.

2 LITERATURE REVIEW

In order to identify the gap for CM in construction DES compared to other domains, we review the literature on CM for DES in construction (in section 2.1) and the literature on CM for DES in general (in section 2.2).

2.1 DES in Construction

In a survey conducted by Leite et al. (2016) to identify and investigate the challenges of using computer technology in the construction industry, simulation was described as a value-adding research direction by 88% of the respondents. One reason given for this is the high capability of simulation in building models that assist in exploring different construction scenarios even before setting foot on site. Martinez (2010) reported that DES is one of the most common approaches for simulation modeling to improve construction project operations.

AbouRizk (2010) argues that DES tools developed for construction have not been adopted successfully in the industry. He identified a gap between the academia, where researchers can see the benefits of using DES in construction, and the industry practitioners who are still skeptical about the value of using such technique in their projects. Usually, construction managers prefer to solve their problems intuitively in an ad-hoc manner (Koskela 2000; González and Alarcón 2010).

Several of the reported studies to improve construction DES modeling pointed implicitly to the importance of CM by stressing the need to pay more attention to the early stages of DES studies. Martinez (2010) mentioned that significant effort has to be dedicated to understanding the purpose of the model and the system that will be represented. Then, the scope of the model, the level of detail, the elements that will be used to represent the real system and the logic should all be decided before developing the computer model. In the same manner, AbouRizk (2010) listed four stages involved in building a DES model, the first two are dedicated to generating the product abstraction that specifies the product to be built and the process abstraction where processes, resources and the environment required to build the product are abstracted and implemented as models. Lee et al. (2013) stated that computer tools represent only one factor for the success of construction simulation models and that more focus must be placed on the development process. Poshdar et al. (2016) suggested the use of CM as the first step of lean construction simulation to improve the simulation model by explicitly considering management interventions and decision links.

Another aspect of CM that has been mentioned in construction DES research is the need to include construction stakeholders in the modeling process to facilitate their agreement on the model components and operations. Leite et al. (2016) point out that construction stakeholders are usually not familiar with DES. Hence, they argue that the inclusion of the main stakeholders in simulation studies will help to build a user-oriented model that satisfies the requirements of both the modeler and the end-user without the need for spending time and resources in extensive training or special education. Behzadan et al. (2015) maintain that the decision-makers should be aware of the entities of the model and how they interact according to the logical rules of the model. It is also asserted by Lee et al. (2013) that it is important to educate the stakeholders about the processes of a DES study, not only the final model and its output analysis.

2.2 CM for DES

CM is one of the early steps in the development of a DES model (Chwif et al. 2013). Any DES modeler must go through the process of CM either in his/her mind or by using a fully documented approach (Nance 1994; Balci and Ormsby 2007). In fact, according to Pace (2000), most of the challenges that modelers may face in DES studies are related to the initial phases while later phases seem to be less of an issue.

There is no widely adopted definition of CM across the DES community. Most of the definitions in the literature are vague and interpreted in varying ways (Robinson et al. 2010). DES studies tend to define the conceptual model depending on the type and size of the problem within the specific domain. Lacy et al. (2001) state that CM is an overloaded term that caused a great deal of confusion among the DES community. However, most of the descriptions in the literature agreed that CM must start as early as possible and then progressively updated throughout the DES lifecycle (Brooks and Wang 2015; Robinson 2015). Moreover, there is common agreement that the CM process must be independent of any simulation language or software solution (Robinson 2008a; Chwif et al. 2013; Furian et al. 2015).

Law (1991) found that CM was the most difficult aspect of simulation studies. One reason for that is the notion that CM was considered more as an art than as science (Pace 2000; Robinson 2008a). Van der Zee et al. (2010) argue that CM combines multiple disciplines such as operations research, statistics, engineering, and computer science. Moreover, building a conceptual model requires a great deal of creativity (Van der Zee 2007). However, creativity alone is not enough and even the most experienced modeler would need to follow some guidelines in order to build a valid conceptual model (Brooks and Wang 2015). Much effort has been made to bring a systematic approach to CM. Robinson (2008b) proposed a framework that consists of five main steps for building the conceptual model in addition to two steps for data collection and model assessment. Van der Zee et al. (2010) state that Robinson's framework is flexible and can be undertaken in different ways to produce the required output. Hence, it has been used as a cornerstone by many CM studies that suggested some improvements and additions in order to extend its application. Participatory Simulation (PartiSim) was introduced by Tako et al. (2010) as an extension of the CM framework in Robinson (2008b) for the healthcare domain. The framework utilizes the facilitated mode to build DES models instead of the traditional expert mode which depends only on the modeler to do much of the simulation effort (Robinson et al. 2014). PartiSim consists of six stages for building a facilitated DES model (Tako and Kotiadis 2015). Our proposed framework will adopt the techniques used for the first 3 stages that are concerned with the initiation and CM of a DES study.

Hierarchical Control Conceptual Modeling (HCCM) (Furian et al. 2015) is a CM framework that includes the main steps of the framework by Robinson (2008b) as well as separation of the structural and behavioral components as in ABCmod (Arbez and Birta 2011). The main contribution of HCCM is the substitution of queuing structures with control units that represent the rules governing entity flows in the system. Furian et al. (2015) argue that some entities may switch between being resources or consumers in the same model. Therefore these entities cannot specifically be linked to queues for certain tasks. Furthermore, the use of traditional queuing structures can become very cumbersome when modeling a complex and dynamic system, with sophisticated dispatching strategies such as optimization routines (Furian et al. 2015).

3 PROPOSED FRAMEWORK AND CASE STUDY

The proposed framework can be considered as an extension of the framework presented in Robinson (2014). It includes the control part of HCCM with insights from PartiSim, especially in regards to the engagement of project stakeholders and the facilitation techniques. The framework consists of 7 consecutive steps. Figure 1 provides an overview of the proposed framework and a brief description of its steps. The remainder of this section is a detailed description of each step of the proposed framework accompanied with an explanation of a real case study that has been employed to test the applicability of the framework.

The case study is a tunneling project in Auckland, New Zealand, using a pipe-jacking machine to install a storm water pipe. The tunnel is executed using a micro tunnel-boring machine (MTBM). The jacking machine is fixed in a launching shaft and the MTBM will penetrate the ground starting at the jacking machine until it reaches the reception shaft. The pipe jacking process starts by transporting the pipe from a delivery truck into the jacking machine using a gantry crane, then pushing the pipe into the tunnel. During the jacking process, the front of the MTBM penetrates the ground and the extracted soil is filled in a muck skip. The muck skip travels inside the tunnel over rails using a locomotive. After filling the muck skip the jacking process should stop and the locomotive will drag the skip into the shaft where the crane hook is waiting to carry the skip into a muck pit on the surface. The final step is loading the dirt into a hauling truck using an excavator.

3.1 DES Study Initiation

This step is undertaken to start a new DES study. It includes developing the initial plan of the study and identifying the stakeholders who will be engaged to guide its outcome. Within this step, the modeling team meets with the problem owner (client) to understand the problem and to collect any available information about the system. Then, a proposal for the DES study is developed that includes a feasibility study of the project, preliminary objectives, and a timeline. It is important to identify all relevant project constraints to provide a reasonable plan. Further, a stakeholder list that includes information about all identified stakeholders must be generated as an output from this step.

In the case study, meetings with the operations manager of the construction company were held to understand the project and any problems at the managerial level and to identify the main stakeholders. A proposal was then prepared by the research team to provide information about the importance of DES to solve the current problems and a schedule of the study taking into account any identified constraints.

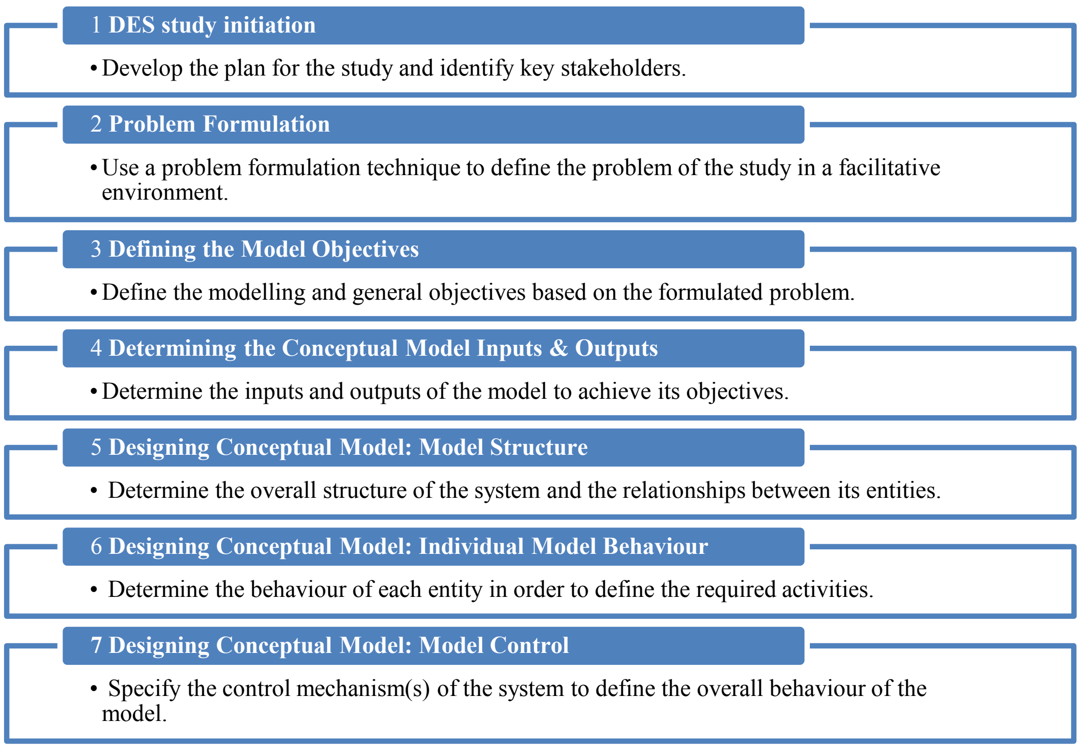

Figure 1: Overview of the Proposed Framework.

3.2 Problem Formulation

This step is performed to develop the initial understanding of the problem into a formal representation using a problem structuring method such as the Soft System Methodology (SSM) or a textual description of the problem situation depending on the complexity of the problem. It is important to realize that not all information may be available at this stage and some assumptions need to be made to overcome any knowledge limitations about the system. These assumptions should be identified and recorded in a log called 'Assumption list'.

The problem definition of the case study was created in collaboration with the construction manager and site engineers by holding several meetings to understand the problems at the operational level. The problem definition was then presented in a textual form in addition to a general layout of the site that was used to identify all the system entities at a later stage (see section 3.5).

3.3 Defining the Model Objectives

The aim of this step is to extend the preliminary objectives defined in the initiation step. Hence, this step must be conducted in a fully facilitated mode in order to manage the stakeholders' expectations after gaining their consensus on the problem definition. Robinson and Pidd (1998) reported that unfulfilled expectations are one of the main sources of stakeholders' dissatisfaction in DES studies. The defined objectives will be categorized into general and modeling objectives as in Robinson (2014). Two modeling objectives were defined by the stakeholders of the case study, minimizing the total execution time and improving the efficiency of resources. General objectives included the visualization, reusability and documentation requirements of the model.

3.4 Determining the Conceptual Model Inputs & Outputs

The conceptual model inputs are the data that can be altered, before running the model, to experiment with different scenarios. It is important to note that inputs can be in the form of quantitative factors (e.g. number or speed) or qualitative factors (e.g. changes to rules) (Robinson 2014). For the case study, the following input variables were selected: (1) the number of pipes per each jacking cycle, (2) the number of muck skips, (3) the number of cranes, and (4) the number of trucks. On the other hand, model outputs are used to check whether the objectives have been accomplished and to indicate the reasons if they have not (Robinson 2008b). The required method for reporting the results of the model should be reflected in the definition of model outputs (e.g., numerical data or graphical data) (Robinson 2014). Project total time, the efficiency of equipment and wasted time were defined as the outputs of the model for the case study.

3.5 Designing Conceptual Model: Model Structure

After defining the objectives, inputs, and outputs, the modeler might find that the problem can be easily solved without using DES. Hence, it is advised to reassess the need for DES at this point before proceeding with the expensive and time-consuming DES study (Robinson 2014). The CM process can be stopped at this stage if it is determined that a DES model is not required.

The step of designing the model structure starts by defining the entities of the system, as they are the core elements of the model structure. The proposed framework follows the concept of HCCM in defining entities by their active/passive state. This definition will eliminate the need to distinguish between resources and consumers which can lead to complexity in describing construction entities that may act as resources and consumers in the same model (a machine that accomplishes a task and needs to be filled by fuel). Furthermore, no queues or entity groups will be included, as they will be replaced by control units to explicitly account for decision-making units as explained later in subsection 3.7. All information regarding the defined entities should be included in a tabular form. Furthermore, the structure of the system can be captured using an informal graphical technique to draw an overall picture of the model (Furian et al. 2015). Figure 2 depicts the structural view of the system in the case study. Pipes and Soil are the key (active) entities and flow through the system. Other active entities are localized, such as the Jacking Machine (J. Machine) and Locomotive in the Shaft (a passive entity), and the Muck Skip that moves between the Shaft and the Muck pit (another passive entity).

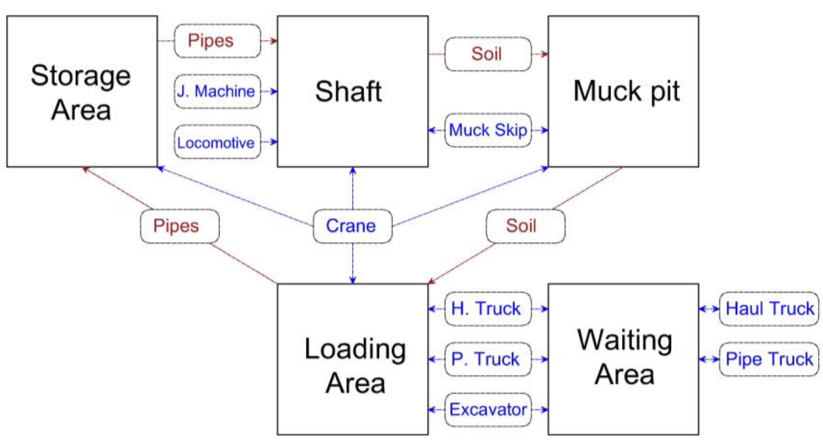

Figure 2: The Structural View of the Pipe-jacking Project.

3.6 Designing Conceptual Model: Individual Model Behavior

All identified entities from the Model Structure (see 3.5) will be analyzed to decide what to include/exclude and to define the attributes of these entities. All assumptions about inclusion/exclusion should be recorded in the assumption list. Similarly, any simplifications needed to define the attributes of the entities should be included in the simplification list. These assumptions and simplifications will define the model scope and level of detail as expressed in Robinson (2008b). It is important to note that the behavioral representation of the entities should be free from any decision points as they will be represented later in the control units. However, the modeler may need to record any decisions that are related to the entities in a special register in order to use it later on when defining the control units. Figure 3 shows an example of the behavioral view of the muck skip in the case study, using a Business Process Model and Notation (BPMN) diagram. The definition of the model activities can be conducted at this stage. A tabular form should be presented including the activities and their details such as attributes, participating entities, state changes and the specification of requests made for that activity.

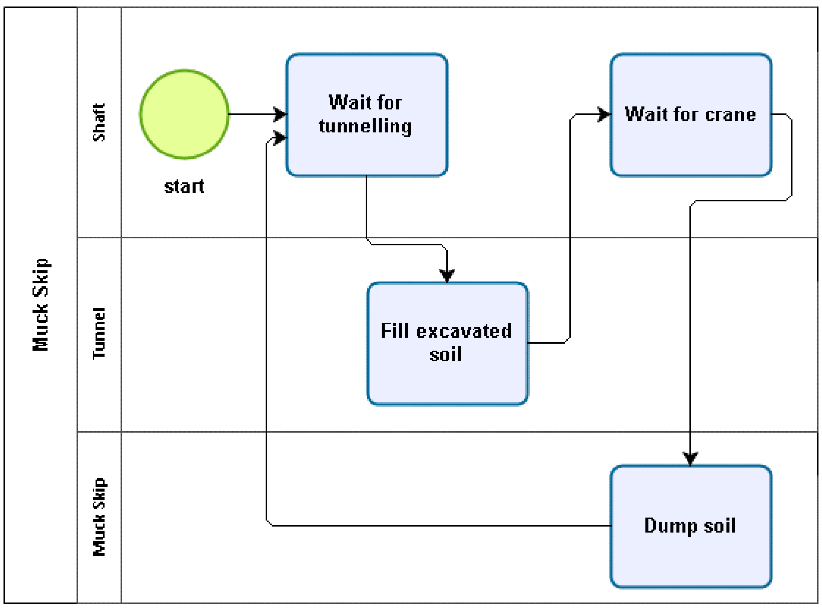

Figure 3: Behavioral View of the Muck Skip.

3.7 Designing Conceptual Model: Model Control

The last step in the CM framework is to capture the behavior of the system by specifying the control mechanism of the model. This step is the key feature of the HCCM framework (Furian et al. 2015). Control units represent different levels of decision making within the system. They utilize a defined set of rules to manage requests for activities that are generated by entities. These rules control the conditional behavior of the model by determining what requests can be dispatched, how requests should be dispatched and what requests are obsolete (Furian et al. 2015). The definition of control units includes determining the set of rules and their relations. Three conceptual model components are produced as the outputs of this step:

1. A tabular form for control units including the engaged entities and the control units' attributes such as the state variables and the level of responsibility of each control unit.
2. A tree structure that represents the control view of the model. This tree structure includes the control units represented by internal nodes (i.e., Site Control, Operation Area Control, and Site Access Control) and the activities represented by leaves (See Figure 4).

3. Rule sets for control units that can be represented in textual form, pseudo-code, or a diagrammatic form such as a logical flow diagram. Figure 5 is a logical flow diagram that depicts the control policies for the Operation Area Control unit in the case study.

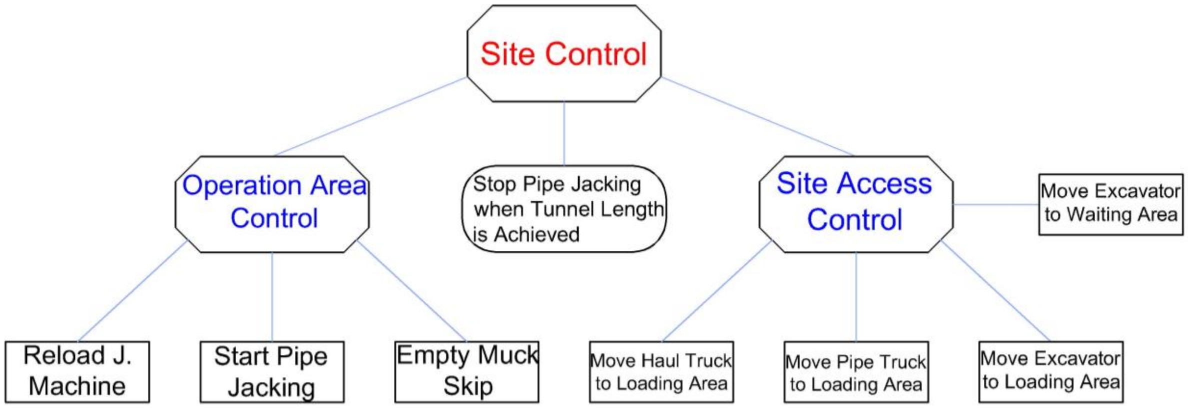

Figure 4: Control View of the Pipe-jacking Project.

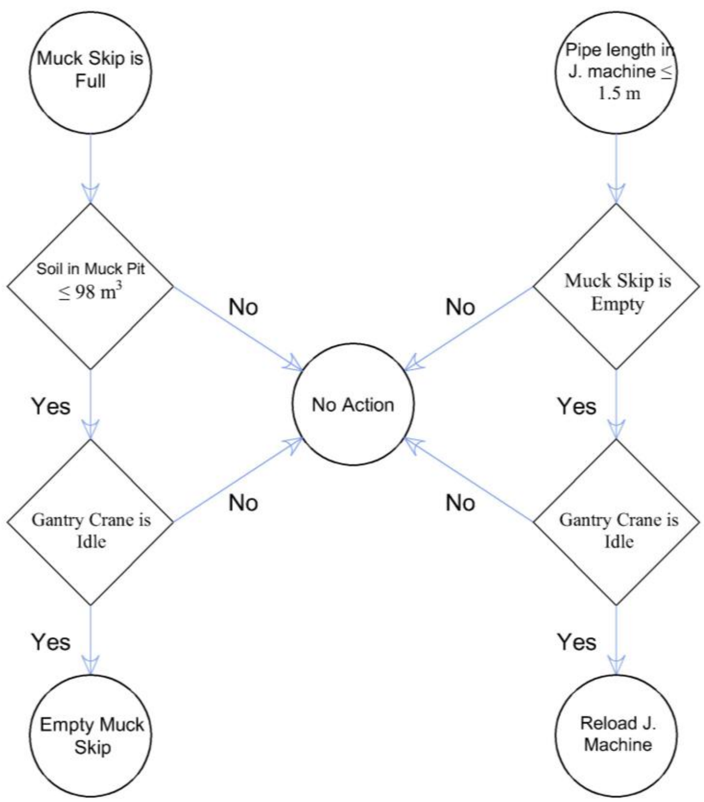

Figure 5: Control Policies for the Operation Area Control Unit.

3.8 Summary

Table 1 summarizes the steps of the framework, the tasks required for each step and the outputs.

Table 1: The Proposed Framework.

CM step	Tasks	Documents of the Conceptual Model
1. DES study initiation	• Formmodeling team. • Hold general meetings with the client to understand the problem and identify key stakeholders. • Assess the suitability of DES to the problem.	1. Stakeholder list. 2. Simulation study proposal: a. Feasibility study b. Preliminary objectives c. Simulation study timeline d. Project constraints i. Time ii. Cost iii. Resources
2. Problem Formulation	• Problem structuring methods (e.g., SSM). • Facilitation techniques (meetings - brainstorming - mind mapping).	1. Updated Stakeholder list. 2. Detailed problem description. 3. Assumption list. 4. A Sketch of the system. 5. List of data requirements.
3. Defining the Model Objectives	• Facilitation techniques.	1. Modeling objectives. 2. General objectives.
4. Determining the Conceptual Model Inputs & Outputs	• Analysis of the system and the documents. • Facilitation techniques.	1. Input & Output list.
5. Designing Conceptual Model: Model Structure	• Reassessment of the need of using DES for the defined problem using facilitation techniques. • Deep analysis of the system to determine what should be done to transfer the defined inputs into the outputs. • Prototyping.	1. *Updated* Assumption list. 2. Entity list. 3. Overall structural view of the system. 4. Simplification list.
6. Designing Conceptual Model: Individual Model Behavior	• Individual entity analysis to define all attributes and include them in the entity list. • Visual representation of the behavior of entities. • Definition of all activities and their attributes.	1. *Updated* Assumption list. 2. *Updated* Entity list. 3. *Updated* Simplification list. 4. Entity individual behavior. 5. Decision register. 6. Activity Tables.
7. Designing Conceptual Model: Model Control	• Analysis of the system to define control units and their relationships.	1. *Updated* Assumption list. 2. *Updated* Simplification list. 3. *Updated* Activity Tables. 4. Individual control units definition. 5. Tree structure of the control units. 6. Rule sets (textual form, pseudo-code, diagram).

4 CONCLUSION

This paper is part of an ongoing research effort looking at the development of a multi-scale simulation system to support decision making in the construction industry. The proposed framework is the first step in building the planned simulation system. The objective of this framework is to overcome two limitations in construction DES research. Firstly, it promotes the engagement of construction stakeholders in the modeling process through the use of facilitation techniques adopted from the PartiSim framework. Secondly, it assists in capturing the complexity of construction systems using the advanced capability of the HCCM framework. Future improvements for the proposed framework will include adding a validation sub-stage for each step and incorporating a construction planning technique into the framework in order to develop an integrated CM/planning framework for construction operations.

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