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A case study on the use of a conceptual modeling framework for construction simulation

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Abstract
Construction simulation has been an active area of research in the last six decades. Nevertheless, there has been a gap between academia and industry in realizing the capabilities of simulation to support decision-making in construction. One of the well-recognized reasons is the difficulty of undertaking comprehensive simulation studies by construction practitioners, who usually lack sufficient knowledge and skills to adequately build simulation models. Efforts to bridge this gap have been focused on simplifying the computer coding and model implementation stages of construction simulation studies with limited research on the early stage of defining the model and abstracting the system, i.e., conceptual modeling. The conceptual modeling stage is known to be one of the most difficult tasks in a simulation study. Thus, several frameworks to support building conceptual models have been proposed in simulation literature. This study contributes to the research efforts to promote simulation in the construction industry through the adoption of a conceptual modeling framework. It demonstrates the application of the proposed conceptual modeling framework in a case study of piling operations. The findings of this paper reinforced the significance of conceptual modeling by confirming the role of the conceptual model as a communication link between stakeholders. Moreover, the conceptual model was used as a specification document for developing a flexible model that can be replicated in other settings. The use of a documented conceptual model assisted in managing the overall simulation study efficiently, which, in turn, lead to reductions in time and effort for different modeling activities.

Keywords
Construction simulation, piling, conceptual modeling

1. Introduction

Construction systems are typically complex and challenging to model. This complexity is due to the dynamic nature of construction projects where several resources with different roles need to interact within a limited space to develop the final construction product. Computer simulation is well suited for modeling complex and dynamic systems. Consequently, the use of computer simulation to model construction systems has attracted researchers over the last six decades.[1,2] However, there has been limited industrial recognition for simulation-based solutions in the construction industry.[3] Recent studies, such as Leite et al.[4] and Abdelmegid et al.,[5] investigated the barriers leading to this limited recognition. Among the identified barriers is the notion that construction practitioners find it challenging to develop simulation models for sophisticated construction systems. Conducting a construction simulation study requires deep knowledge of several domains in addition to construction, such as mathematical modeling, computer programming, statistics, and system engineering.[6–8] In addition, the process of developing a complete simulation model can be expensive and time-consuming. When compounded with the temporary and unique nature of

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construction projects, simulation studies can be perceived as non-feasible by construction decision-makers who might find it more sensible to follow a non-scientific intuitive approach to solve problems as they arise.[9]

In contrast to other fields that successfully adopted simulation in their standard practices (e.g., defense, healthcare, and manufacturing), construction simulation studies lack an adequate conceptualization of construction systems.[3,10,11] Therefore, a conceptual modeling framework that can assist in handling the complexity of construction systems may provide a solution for the lack of adoption of simulation in construction.[10]

A conceptual model provides unambiguous documentation of the structure and components of the final simulation model. The lack of a valid conceptual model for a simulation study may jeopardize the validity and credibility of the model.[12] Therefore, the process of building a conceptual model is acknowledged as one of the most critical tasks for carrying out a typical simulation study.[13] There has been an increasing interest in developing conceptual modeling frameworks for several operations research domains in the last couple of decades. Robinson[14] proposed a flexible framework, which consists of several steps for building the conceptual model as well as supporting steps for data collection and model assessment. This framework has been utilized by different studies that have extended its application to suit specific domains such as healthcare and manufacturing. Among the extensions of Robinson's framework is Hierarchical Control Conceptual Modeling (HCCM) by Furian et al.,[15] which aimed at explicitly modeling the hierarchy of decision-making in complex systems using logical components that are separate from, although linked to, the structural and behavioral components of the model.

This paper aims at demonstrating the applicability of an extended version of the HCCM framework—introduced in Abdelmegid et al.:[10] to develop a simulation model for the planning and control of cast-in-place reinforced concrete piling operations in a construction project. The extended HCCM framework for construction was motivated to cater to the needs of construction practitioners, who lack proper simulation knowledge and require simple approaches to capture their understanding of construction systems.[9] Piling operations present a good example of a complex system in construction sites due to the variety of equipment needed and the relatively small area where operations should take place to construct each pile.[16] The aim of this paper is achieved as follows: first, the extended version of HCCM is followed to develop a conceptual model of piling operations in a real-world construction project; then, the resultant conceptual model is implemented as a computer simulation using open-source simulation software (JaamSim); this model is then both calibrated and validated; finally, the efficacy of the conceptual model and resultant implementation are discussed. It is important to indicate that the focus of this paper is to understand the dynamics and dependencies of construction processes through Discrete Event Simulation (DES), which models the behavior of operating systems at separate points in time. Even though other static based simulation methods, such as Finite Element, have been extensively used in construction research, they are primarily concerned with the behavior of structural elements not construction operations.[17] Therefore, such static simulation methods are excluded from the scope of this paper.

In the next section, we provide background information on construction simulation research, piling operations, and conceptual modeling for simulation. Section 3 focuses on explaining the main components of the HCCM, which drove the development of the case study simulation model. Then, in Section 4, we present the conceptual model of the piling case study that resulted from applying HCCM. Section 5 describes both the variety and nature of data collected for this simulation study. Section 6 provides an explanation of how the conceptual model was implemented in JaamSim, followed by a discussion on model validation and calibration. A detailed discussion about the results of the model and their implication on the piling operations is provided in Section 7. The lessons learned from this simulation study are presented in Section 8. Finally, Section 9 provides concluding remarks about this research.

2. Background

This section contains summaries of the relevant literature for construction simulation, piling operations, and conceptual modeling in Sections 2.1, 2.2, and 2.3, respectively.

2.1. Construction simulation

The term ''Construction Simulation'' has been coined in academia to refer to the field of developing computer simulation models to experiment virtually with construction systems in order to understand their complexity and improve their performance.[18] As explained in the introduction of this paper, simulation modeling lend itself to construction problems due to the complex and dynamic nature of construction systems. Construction simulation research presented examples of the different applications for simulation to support the management of construction projects. For instance, simulation models can be used to improve construction plans, optimize resource allocation, and minimize construction cost and duration.[18] In addition, simulation models can help to understand the complex behavior of construction projects by virtually examining decisions before the expensive and risky real-life implementation.[19] From another perspective, Martinez[20] indicated the value of the modeling process itself to facilitate critical thinking and problem-solving even before building a computer model.

Alarcón et al.[21] reported two main directions for construction simulation research. The first research direction focuses on using simulation tools to test different applications of construction projects such as construction machinery selection,[22] supply-chain strategies,[23] and construction planning methods.[24] The second research direction is concerned with the development of simulation methods and languages to facilitate building construction-friendly simulation models. We envisage this paper as part of the second research direction. Thus, the following paragraph presents a historical overview of research efforts on developing construction-specific simulation methods and languages.

Advancements in construction simulation methods/languages have coincided with the rapid developments in computer programming languages.[18] Halpin[25] introduced CYCLONE, which employs activity cycle diagrams to conceptualize construction operations. CYCLONE was the basis of other construction simulation tools during the 1980s such as RESQUE,[26] INSIGHT,[27] UM-CYCLONE,[28] and COOPS.[29] Martinez[30] introduced Stroboscope, which was driven by the emergence of object-oriented programming languages.[18] Stroboscope was designed as a simulation language to model complex construction systems.[30] Simphony was first proposed by Hajjar and AbouRizk[31] to assist in building construction simulation models based on a graphical user interface instead of the traditional code writing technique that had been followed since the emergence of construction simulation research. Simphony enabled the development of several Special Purpose Simulation (SPS) tools such as AP2-Earth to simulate earthmoving operations,[32] CSD to simulate site dewatering operations,[33] and CRUISER to simulate aggregate production.[34] Recently, construction simulation studies are more focused on providing applicable means to support and improve the implementation of simulation studies in the construction industry. For instance, Lu and Olofsson[35] proposed an integrated framework to support the development of construction simulation models utilizing the advanced capabilities of Building Information Modeling (BIM) systems. A more advanced example is presented in Niyonkuru and Wainer,[36] which introduced an environment that can integrate simulation modeling with BIM visualization capabilities to develop real-time executable simulation models. Peña-Mora et al.[37] suggested the use of hybrid modeling of DES and System Dynamics (SD) to abstract different levels of management in constructions systems. The development of data-driven simulation models is another area of improvement proposed by Akhavian and Behzadan.[38] Virtual and Augmented Reality (VR/AR) technologies were utilized by Kamat et al.[39] to provide better means of communication for construction simulation models.

There is a common understanding that the construction industry is one of the least digitized sectors[40] and, consequently, industry practitioners still prefer to make decisions intuitively, that is, solely based on their experience.[41] As a result, the extensive research effort to develop simulation-based decision support tools has been met with consistent skepticism from the industry with respect to the feasibility of such tools in construction projects.[4,10] Recently, construction simulation research has paid more attention to overcoming the gap between academia and industry regarding the usefulness of simulation tools for construction. The Visualization, Information Modeling, and Simulation (VIMS) committee, under the umbrella of the American Society of Civil Engineers (ASCE), initiated a task force to investigate this gap and propose future research directions.[42] Six grand challenges were identified through this task force, including (1) Integration into school curricula to educate future engineers, (2) Limited multidisciplinary skills and research cooperation, (3) Verification and validation of simulation output, (4) Incorporation of human/occupant behavior into simulation models, (5) Credibility and adoption by industry practitioners for decision-making, and (6) Generating models that adapt to real-world changes. This paper will directly address Grand Challenge 5 but, as will be discussed in Section 6.8, Grand Challenges 3 and 4 are also relevant in this research.

2.2. Piling operations

In this paper, piling operations refer to the process of constructing deep cast-in-place reinforced concrete foundations under or around building bases to deliver loads safely to the ground and to support underground levels from surrounding loads. Traditionally, piling operations require the use of several types of equipment with different configurations and sizes, including drilling rigs, service cranes, loaders, and concrete trucks to complete the task.[16] Moreover, a sufficient supply of materials and consistent discharge of extracted spoil is required to avoid any disruptions to the piling process. This mixture of equipment and materials characterizes piling operations as more complex compared to other construction operations, especially when constrained within limited working space (a typical concrete pile diameter may range from 300 to 1800 mm[43]). Figure 1 illustrates a typical piling operation, which shows the variety of equipment and materials required for the construction of each pile.

Piling operations have received minimal attention in the construction simulation research compared to other construction operations such as earthmoving and tunneling. Zayed[44] developed simulation models to assess productivity and cost of continuous flight auger (CFA) piles. The results of the models were synthesized in several

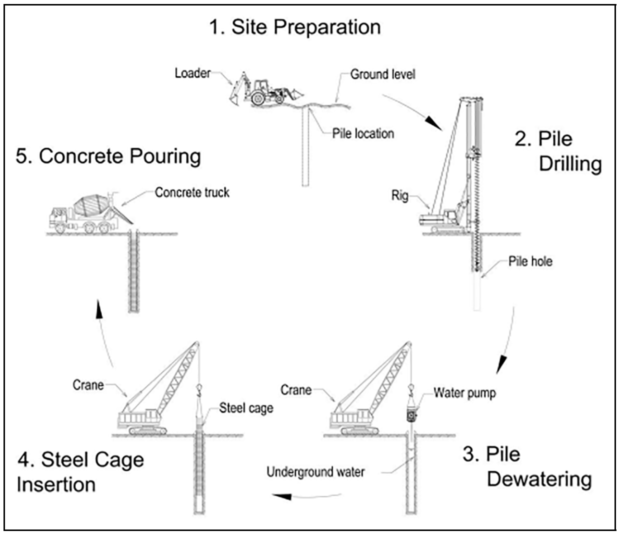


Figure 1. Piling main activities.

charts to assist in estimating the cost of a single pile based on its diameter and depth. Marzouk and Ali[16] utilized agent-based modeling (ABM) to develop a simulation model to evaluate the effect of several aspects on piling operations, such as safety consideration and site constraints. The model was limited to two instances of piling equipment: the piling rig and the crane. Moreover, the selection of piling sequence was performed autonomously by the simulation agents based on space and safety considerations. Even though the (limited number of) previous studies have provided effective methodologies to model piling operations, further research is required to address other aspects of piling such as instream flow of material, temporal and spatial effects on piling productivity, and incorporation of real-time project data into simulation models.

2.3. *Conceptual modeling for simulation*

Among the most challenging tasks in a simulation study are the early stage of model definition and system abstraction, which can be referred to as the conceptual modeling stage.[45,46] Conceptual modeling facilitates capturing essential information for the simulation model and guides a collaborative approach in developing the model.[47,48] It is an essential stage that takes place in any simulation study, whether explicitly through a documented approach, or implicitly within the mind of the modeler.[49,50]

Conceptual modeling has not received the same research attention as other stages within simulation studies, predominantly due to a general notion that conceptual modeling is more of an art than a science.[45,51] Akpan and Shanker[52] conducted a literature review on the use of two-dimensional (2D) over three-dimensional (3D) visualization techniques across different stages in simulation studies and found that out of 162 studies, only three investigated the use of 2D/3D visual aids to support conceptual modeling. In their survey on the different approaches followed by simulation practitioners, Brooks and Wang[53] concluded that the defense sector paid more attention to conceptual modeling compared to other simulation domains. One of the reasons is the complex and large-scale nature of their simulation models, which typically cost millions of dollars and include a vast number of stakeholders with different objectives and requirements.

There is no widely adopted definition for a conceptual model across the simulation community. Most of the definitions in the literature are vague and interpreted in varying ways.[54] The notion of a conceptual model varies from being an implicit model inside the mind of the modeler[49] to a fully documented process.[54] Simulation studies tend to define the conceptual model depending on the type and size of the problem within their specific domain. Lacy et al.[55] states that the conceptual model is an overloaded term that caused a great deal of confusion among the simulation community.

By reviewing the reported definitions in the literature, it is clear that there are some common elements among these definitions. The following are the three most prevalent commonalities:

- The conceptual model must be independent of any simulation language or software solution.[15,47,51]
- The process of conceptual modeling starts in the early stages of simulation studies.[47,56]
- Conceptual modeling is an iterative process. Hence, the conceptual model progressively changes throughout the lifecycle of DES studies.[53,57]

A conceptual model can be used to inspire and guide the design of the simulation model.[58] It can also provide a platform for designing multiple simulation models for a single problem.[50] A conceptual model assists in organizing modeling data and making sure that no input data is missing.[46,47] It also helps in generating new requirements for the model.[45,50] Most importantly, the complexity of designing a large-scale simulation model can be overcome when using a proper conceptual model.[50,59]

Building a conceptual model requires a great deal of creativity.[60] 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.[53] Therefore, different approaches are proposed in the literature to guide the process of conceptualizing systems to capture the necessary components and logic required to build simulation models. In the remainder of this section, we present an overview of two main approaches: ontological representation and conceptual modeling frameworks. Within the presentation of the two approaches, we discuss their suitability to support conceptual modeling in construction simulation studies with a focus on user-friendliness to construction practitioners, who traditionally lack experience in simulation modeling.

2.3.1. Ontological representations. Ontological representation is reported in simulation literature as a link between model abstraction and model implementation. From an information system perspective, an ontological representation is defined as ''an explicit specification of a conceptualization.''[61] Turnitsa et al.[62] argued that a conceptualization of an operating system can vary depending on the modeler's worldview and intent. They elaborated with the notion that a near-infinite number of conceptualizations can be developed for a single system, and even for each conceptualization, a similar infinite number of possible representations can be found. Accordingly, they proposed the use of ontological representation as the foundation of a formal shared understanding of operating systems. They reinforced their argument by concluding that ontological representation should be considered as the conceptual model in a simulation study. From another perspective, Silver et al.[63] investigated the role of ontological representations to bridge the gap between the understanding of the modeler and the domain experts about the operating system. Silver et al.[63] proposed the use of an ontology-driven simulation approach to support building simulation models based on domain-specific ontologies. Therefore, ontological representations can facilitate communication between different parties. In addition, they can accelerate model building by utilizing the knowledge available in the domain ontology. Hofmann et al.[64] confirmed the role of ontologies in improving interoperability and composability of simulation models by supporting interconnections between the conceptual representation of the model and its specification. They investigated the need to balance between two classes of ontologies, methodological and referential ontologies. The former term defines ''how'' simulation models are developed while the later defines ''what'' aspects of the real system should be modeled, which represents the role of conceptual modeling as adopted in this paper.

An example of the use of ontological representation to support simulation studies can be found in Djitog et al.,[65] which presented a holistic approach to model healthcare systems. In this approach, an ontology of healthcare systems formed the basis of building an abstraction of the system, which can then be implemented on computer as a multi-paradigm simulation model. A further development of ontological representation is the approach by Tolk et al.,[66] which focused on the transformation from ontologies into mathematical models that can then form the foundation of the computer model. This approach adopts definitions from ISO/IEC 11179 standard for metadata registry to formally capture information exchange. Silver et al.[67] presented a general-purpose ontology for DES (DeMO), which integrates the knowledge in domain and modeling ontologies to support building executable DES models. A more construction-relevant example is the approach by Saba and Mohamed[68] to support building construction simulation models. This approach adopted ontological concepts from the manufacturing domain (e.g., Manufacturing Semantics Ontology (MASON)[69]), integrated with the Process Interaction Modeling Ontology for Discrete Event Simulations (PIMODES),[70] to develop an Industrial construction ontology (InCon-Ont). They utilized the proposed ontology to enable model reusability and interoperability in distributed construction simulation systems.

Even though ontological representations can form the basis of a holistic approach for construction simulation, they can form a complicated technical language that does not necessarily cater to the end-user requirements. For example, El-Diraby[71] presented a domain ontology for construction knowledge. However, it is only targeting experts in the field of construction information systems. Similar to other concepts that are borrowed from information technology, more simplifications are needed to support a user-friendly approach to facilitate communication between the stakeholders of construction simulation studies. The following section discusses the use of conceptual modeling frameworks to overcome the complexity of ontological-based approaches for non-simulation experts.

2.3.2. Conceptual modeling frameworks. As noted by Van der Zee et al.,[46] frameworks provide a procedural approach that is based on industry guidelines, methods, and best practices to support building conceptual models in simulation studies. The development of conceptual modeling frameworks has been gaining more interest in the last decade with a focus on addressing specific applications withing different simulation domains.[72] One of the main motivations to the development of these frameworks is to promote professionalism in simulation domains through the explicit documentation of conceptual models.[53]

As reported in the introduction of this section, the defense sector has led the research efforts in conceptual modeling promotion. Among their early efforts is the presentation of a conceptual modeling framework by Pace.[45] This framework included four main steps that start with collecting simulation contextual information, identifying modeling entities and processes, developing simulation elements, and finally defining the logical relationships between these elements. Another framework in the defense sector was proposed by Balci and Ormsby,[50] which included eight processes for problem formulation, system investigation, high-level design, low-level design, integration, specification, use, and redefinition. Balci and

Ormsby[50] also stressed the importance of integrating model validation and verification into the complete life-cycle of the conceptual model.

From a broader perspective, a stream of recent research in conceptual modeling was initiated by the framework in Robinson.[14] This framework gained acceptance in the simulation research community due to its broad scope and applicability within different simulation domains.[73] It consists of a five-step procedure for conceptual modeling combined with two parallel steps for data collection and model assessment. Because of the flexibility of this framework, many extensions are proposed in the literature that focus on narrowing its scope to a specific domain or enriching its processes with more advanced techniques to improve its application. Examples of these extensions include the study by Van der Zee[73] for an integrated conceptual modeling/system engineering framework, Chwif et al.[47] for proposing better techniques for conceptual modeling documentation, Montevechi and Friend[48] for integrating Soft System Methodology with conceptual modeling, Ahmed et al.[74] for integrating Structured Analysis and Design Technique from software engineering with conceptual modeling, Kotiadis et al.[75] for a facilitative conceptual modeling framework, and Furian et al.[15] for the introduction of the HCCM framework. This paper is part of the research efforts to implement the HCCM in different simulation domains. Thus, the following section presents this framework in more details.

3. The HCCM framework

HCCM was developed to overcome the limitations of traditional queueing structures in abstracting sophisticated systems that can have complex dispatching rules, and where optimization algorithms can be required.[15] It adopts a concept presented in Arbez and Birta[76] to separate structural and behavioral components in conceptual models. In complex systems, it is observed that entities can have dynamically changing priorities, making it cumbersome to assign them to specific queues for different activities at the same time.[15] Therefore, HCCM pays more attention to governing entity flows within a system through the use of control units, control behavior, control hierarchy, and different categorizations for activities and entities. HCCM was motivated by the healthcare sector, but it has been employed to model several systems such as port operations management,[15] hospital patient transport,[77] doors and windows construction logistics,[78] tunnel construction,[10] earthmoving logistics,[79,80] and Cytology lab task allocation.[81]

Abdelmegid et al.[10] proposed an extension of the HCCM framework to suit the nature of construction systems by including more collaborative modeling tasks and different forms that present construction activities in a way that is more aligned to standard industry practice. The extended version of the HCCM framework consists of seven steps, which are summarized in Table 1.

The following section explains the outcome of applying the framework in a case study to model piling operations in a construction site.

4. Simulation conceptual model for piling operations

This paper adopted a case study approach to achieve the aim of demonstrating the applicability of the HCCM framework in complex construction operations. The case study was obtained from a construction project of a new educational building in Auckland, New Zealand. This building is located in an area of 19,500 m^2 and consists of four floors in addition to two underground levels. The building was estimated to cost US$81 million, and it was designed to be used for students' teaching activities, staff offices, and laboratories. The focus of the case study was on the piling operations, which included the construction of 158 piles at the outer parameter of the building in addition to 21 piles to support internal foundations and four piles to support a tower crane base. Several stakeholders were involved in this case study, such as the general contractor, the piling sub-contractor, and the research team. From the general contractor side, a commercial manager was representing the client of the simulation study. In addition, the construction manager, site engineers, and site supervisors were involved at different stages of the case study. The sub-contractor was engaged in the study through the operations manager and site superintendent. The research team comprised a variety of expertise such as construction management, simulation modeling, and statistics.

4.1. Simulation study initiation

In the first meeting with the client, it was clear that he was not very familiar with simulation modeling and how it could help to improve the project performance. Therefore, a simulation study proposal was developed, which included: a brief explanation of simulation modeling; a description of simulation team members; the amount and type of data required; the level of involvement required from the construction company; a preliminary timeline; the study constraints; and possible outcomes. This step is essential in any simulation modeling study to manage stakeholders' expectations and justify the need for simulation to solve the problem. Some parts of the proposal, such as the timeline, constraints, and outcomes, were updated in the later stages of the study.

Table 1. Extended HCCM for construction simulation.

Conceptual modeling step	Processes	Documents of the conceptual model
Simulation study initiation	- Form modeling team. - Hold general meetings with the client to understand the problem and identify key stakeholders. - Assess the suitability of simulation modeling to the problem.	1. Stakeholder list. 2. Simulation study proposal: - Feasibility study - Preliminary objectives - Simulation study timeline - Project constraints (Time, Cost, Resources)
Problem formulation	- Problem structuring methods (e.g., SSM). - Facilitation techniques (meetings—brainstorming—mind mapping).	3. Detailed problem description. 4. Assumptions list. 5. Simplifications list 6. A Sketch of the system. 7. List of data requirements.
Defining model objectives	- Facilitation techniques.	8. Modeling objectives. 9. General objectives.
Determining Model Inputs and Outputs	- Analysis of the system and the documents. - Facilitation techniques.	10. Input and Output list.
Designing model structure	- Reassessment of the need for simulation modeling for the defined problem. - Deep analysis of the system to determine what should be done to transfer the defined inputs into the outputs. - Prototyping.	11. Entity list. 12. Overall structural view of the system.
Designing model individual 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.	13. Entity individual behavior. 14. Decision register. 15. Activity tables.
Designing model control	- Analysis of the system to define control units and their relationships.	16. Individual control units' definition. 17. Tree structure of the control units. 18. Rule sets (textual form, pseudo-code, diagram).

4.2. Problem description

The problem description for the case study was first formulated during the early meetings (after initiation) with the client, and then, it was reinforced by the first author when attending weekly construction site meetings. In addition, he spent one full working day in the construction site to observe the piling operations and interview site engineers, supervisors, and workers. The identified problem had two major parties, the general contractor (the simulation study client) and the piling subcontractor. The general contractor wanted to make sure that the plan proposed by the piling subcontractor was realistic and conforms to the site conditions. There were several other subcontractors working on the site, such as earthmoving and reinforced concrete contractors, that were significantly affected by the performance of the piling contractor. Therefore, the primary concern of the general contractor was to guarantee that the flow of downstream work is not disrupted by any delays or unexpected situations imposed by the upstream work of the piling subcontractor.

The site location of the construction project was one source of the factors that contributed to the complexity of piling operations. These factors are summarized as follows. It was in a busy area of the city, which may affect time-sensitive materials delivery such as fresh concrete. There were several adjacent old buildings, and their stability could be highly affected by site operations. Soil investigations indicated different soil properties across the construction site. The site plan was an irregular shape, adding complexity to site layout planning to ensure safe routes for machinery and materials. Piling operations on this site were prone to other unexpected risk factors such as severe weather, groundwater level, preserved Pōhutukawa tree roots, and redundant underground utilities such as old utility holes and stormwater pipes. All of these (site location) factors added uncertainties to the piling operations and thus imposed high schedule risk on the piling subcontractor. Figure 2 summarizes the main aspects of the problem description of the piling case study.

4.3. Simulation study objectives

According to Robinson,[14] simulation studies' objectives can be categorized into two types: modeling objectives and general project objectives. Modeling objectives represent the main reason for developing the model, while general

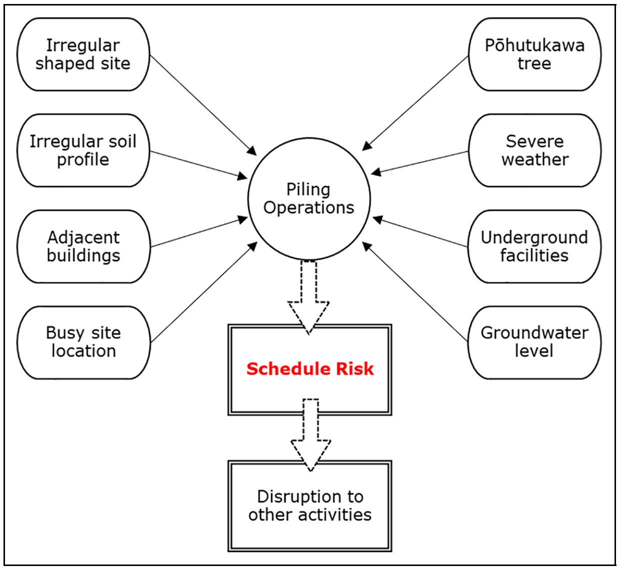


Figure 2. Summary of the problem description.

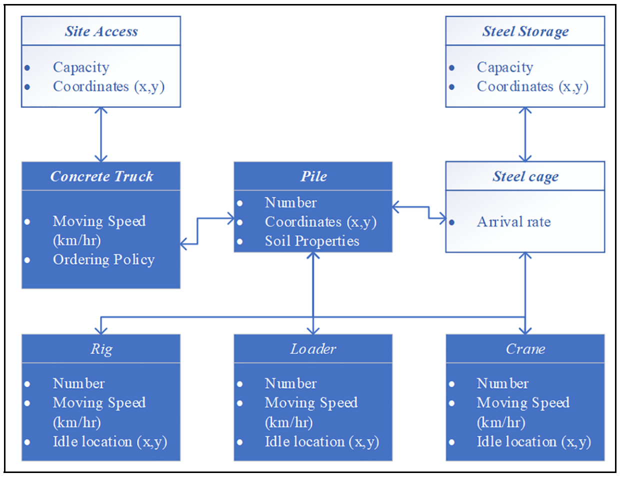


Figure 3. Entity structure.

objectives are made to describe the project management aspects of the simulation study, such as duration, resources, and client requirements. Based on the problem description in Section 4.2, piling is a risky, uncertain operation that can be affected by many factors. However, the primary decision that the general contractor or the piling subcontractor can make is the sequence in which the piling will be performed. Therefore, the modeling objective was set to assess the effect of piling sequence on the schedule certainty by calculating total piling time for several sequencing scenarios. General project objectives were initially set in the proposal presented at the initiation of the simulation study. These objectives were updated after having a deeper understanding of the problem and setting the modeling objective. Table 2 summarizes both the modeling and general objectives of this study.

4.4. Model inputs and outputs

The modeling objective defined in Section 4.3 is the basis for the model inputs (i.e., experimental factors), and these were set to be: the piling sequence; and the number and schedule of each type of equipment. Since the main attention of this project was the piling schedule, we focused on measuring the total project time as the main output (i.e., response) of the model.

4.5. Model structure

The first step in defining the model structure is to list all entities, their types, and attributes. Afterward, a map that depicts the relationships between the defined entities is developed. Eight entities were defined for the piling project, as depicted in Figure 3. The figure shows the structural view of the system where highlighted entities are the active entities, which are associated with individual behavior, and the other entities are passive entities that do not have an associated behavior. The behavior of entities will be explained in Section 4.6.

4.6. Individual entities' behavior

As explained in Abdelmegid et al.,[10] Business Process Model and Notation (BPMN) is found to be a suitable

Table 2. Modeling and general project objectives.

Modeling objectives	
Calculate total execution time for piling given different sets of sequencing scenarios	
General project objectives	
Study duration	3 months
Workload	2 Modelers
Visualization	A representation of the site layout that includes the locations of resources and piles
Flexibility and Reusability	The model should be flexible to allow for several site layouts to be modeled, different arrangements for machines, or extra details to be added, such as the supply chain of materials.
Documentation	Detailed conceptual model documentation and user-friendly computer model interface are required to promote better understanding and communication between stakeholders.

diagramming technique to represent individual entities' behavior because BPMN diagrams can fit the dynamic spatial nature of construction activities by representing the location where each activity takes place. Figure 4 shows the individual behavior of each active entity. It is important to note that decisions are not recorded in these diagrams as they will be defined next in Section 4.7. Gateways under the name of "Control Unit" are added to the BPMN diagrams to represent decisions that require the incorporation of the logic from entities' individual behavior. The activities in the diagrams are then analyzed in Table 3 to define their attributes such as participating entities, start and end types, state changes, predecessor activities, and control units. This conceptual model classifies the start and end of activities into three types: sequential (starts when another activity completes), requested (by a control unit), and scheduled (starts or finishes at a certain point in time).

4.7. System behavior

The most important feature of the HCCM is its ability to explicitly capture system logic through control units instead of embedding the logic within queue policies.[81] The first step in defining system behavior is to generate a tree structure that represents the hierarchy of control units and their relevant activities in the system. Afterward, governing rules of control units can be represented by logical flow diagrams. As depicted in Figure 5, three control units were defined for the piling case study: Piling control, Borehole control, and Machine control. The governing rules of each machine in the piling case study are explained in Figure 6. Based on the findings from the site observation and personnel interviews, it was found that the priority of the loader is to prepare a piling area first to allow other machines to operate on the pile before cleaning the site of another finished pile. The priority of the Crane was set to serve the tremie pour activity first so that concrete trucks are not held waiting for the crane to finish another activity. The second priority was to deliver cages to piles that are entirely drilled and dewatered. The last priority of the crane is serving piles that are drilled and waiting for dewatering. The concrete truck was designated to serve tremie pour piles first to release the crane from holding the tremie tube. If no tremie pour piles are required, a concrete truck can go to the first available pile for dry pour.

4.8. Assumptions and simplifications

Building a simulation model requires a creative effort in abstracting the system to a certain level of detail,[13] which requires using reasonable assumptions and simplifications.[51] Assumptions are made to fill any limited knowledge about the real system while simplifications are made aiming at reducing model complexity to accelerate computer implementation and to improve model transparency.[51] Assumptions and simplifications should be recorded throughout the life cycle of the whole simulation study, not only the conceptual model, as their definitions, level of confidence, and impact on the model can change based on the insight that is gained through the process of modeling.[82] In the case study, the assumptions and simplifications lists were represented in a tabulated form as in the framework by Robinson[51] (see Tables 4 and 5). They went through several iterations and were finalized during the validation stage. The level of confidence in each assumption or simplification provides justification for the decision of using them. The impact represents the implication of making each assumption or simplification on the overall accuracy of the model as perceived by the modeler.

5. Data collection

According to Pidd,[84] data requirements can be divided into three categories: contextual data, data for model realization, and data for model validation. The following section explains the data collected for each category.

5.1. Contextual data

Contextual data are qualitative and quantitative data that help the modeler to understand the problem and build the conceptual model.[85] As mentioned in 4.1, the initiation of the simulation study included meetings with the client. The deliverables of these meetings, the preliminary site drawings, and construction plans helped the modeler form a general understanding of the problem during the early phase of conceptual modeling. Attendance at the weekly work meetings of the construction site by the first author supported by two site visits reinforced the problem understanding and led to the completion and validation of the conceptual model.

5.2. Data for model realization

These types of data are required for developing the computer model.[85] For the case study, these data were mainly collected in the second site visit, where the first author interviewed the construction manager, site supervisors, and machine operators to collect and record the timing of different piling activities. These data were used to build the computer model and present preliminary results to the client. Based on interviews and analysis of documents, it was discovered that average durations were considered by the subcontractor in the plan of piling operations with no account for variability. Therefore, we were only able to collect the most likely, minimum, and maximum values of durations and confirm these data with samples of activity

Table 3. Activity definition.

No.	Activity	Entities	Start Type	End Type	Start State Change	End State Change	Predecessor Activity	Control Unit
1	Wait for preparation request	Loader	Seq.	Req.	Loader state is “AtWait”	Loader state is “GoingToPile”	2 or 12	Machine control
2	Prepare pile	Loader Pile	Req.	Sch.	Loader state is “AtPile” Pile state is “PrepArea”	Loader state is “GoingToWait” Pile state is “Waiting for PileDrilling”	N.A.	Borehole control
3	Wait for drilling request	Rig	Seq.	Req.	Rig state is “AtWait”	Rig state is “GoingToPile”	4	Machine control
4	Drill pile	Rig Pile	Req.	Sch.	Rig state is “AtPile” Pile state is “PileDrilling”	Rig state is “GoingToWait” Pile state is “Waiting for Dewatering”	N.A.	Borehole control
5	Wait for dewater/ loading request	Crane	Seq.	Req.	Crane state is “AtWait”	Crane state is “GoingToPile”	6, 8, or 9	Machine control
6	Dewater pile	Crane Pile	Req.	Sch.	Crane state is “AtPile” Pile state is “Dewatering”	Crane state is “GoingToWait” Pile state is “Waiting for Get_Cage”	N.A.	Borehole control
7	Load steel cage	Crane Steel Cage	Req.	Sch.	Crane state is “GoingToPile”	Crane state is “GoingToPile”	N.A.	Borehole control
8	Insert steel cage	Crane Pile Steel cage	Seq.	Sch.	Crane state is “AtPile” Pile state is “Get_Cage”	Crane state is “GoingToWait” Pile state is “Waiting for Concrete”	7	N.A.
9	Load tremie tube	Crane Pile	Req.	Sch.	Crane state is “AtPile”	Crane state is “GoingToWait”	N.A.	Borehole control
10	Dry pour	ConcTruck Pile	Req.	Sch.	Concrete truck state is “AtPile” Pile state is “Dry_Pour”	Concrete truck state is “Leaving” Pile state is “Waiting for Clean_Site”	N.A.	Piling control
11	Tremie pour	ConcTruck Pile Crane	Req.	Sch.	Concrete truck state is “AtPile” Crane state is “AtPile” Pile state is “Tremie_Pour”	Concrete truck state is “Leaving” Crane state is “GoingToWait” Pile state is “Waiting for Clean_Site”	N.A.	Piling control
12	Clear site	Loader Pile	Req.	Sch.	Loader state is “AtPile” Pile state is “Clean_Site”	Loader state is “GoingToWait” Pile state is “Complete”	N.A.	Borehole control

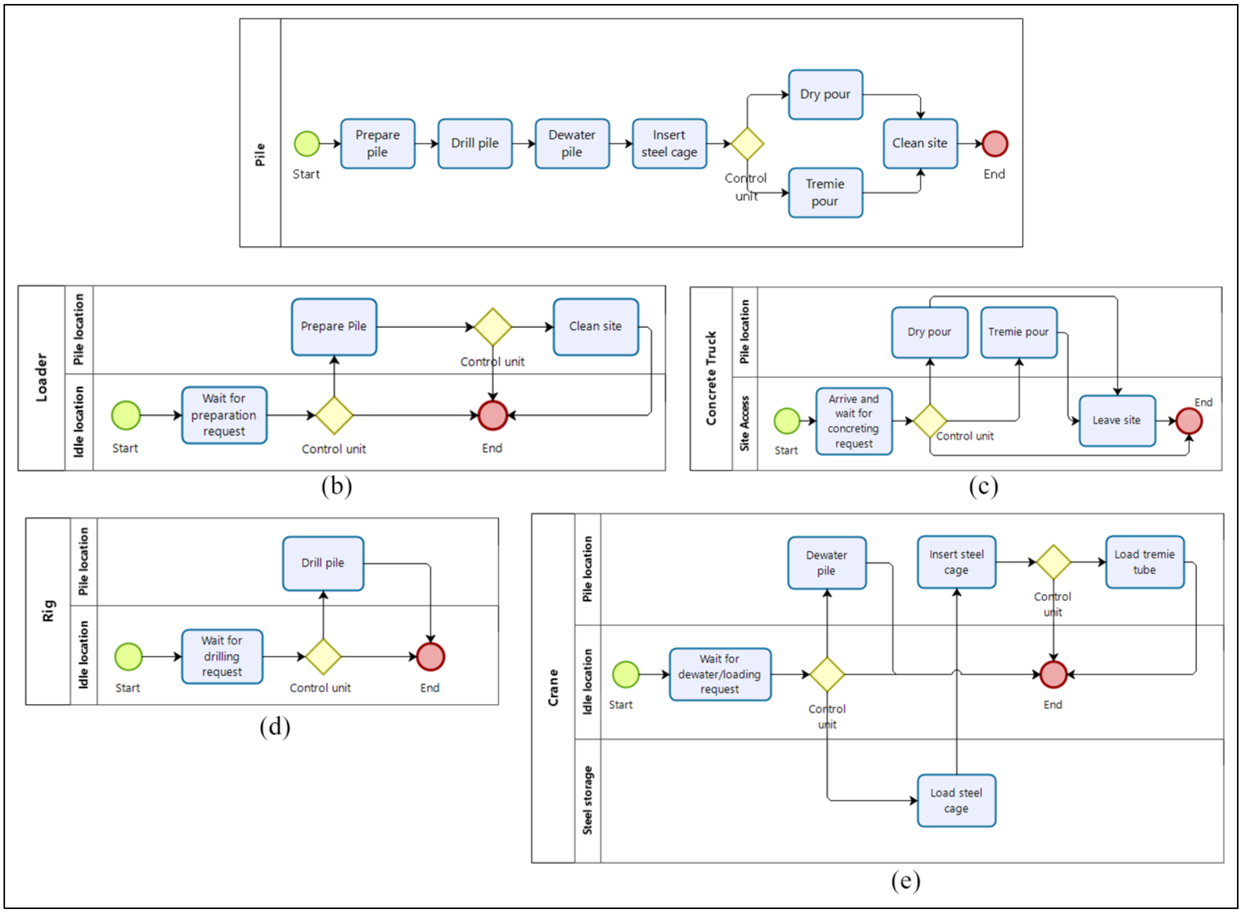


Figure 4. Entities' individual behavior (a) Pile individual behavior, (b) Loader individual behavior, (c) Concrete Truck individual behavior, (d) Rig individual behavior and (e) Crane individual behavior.

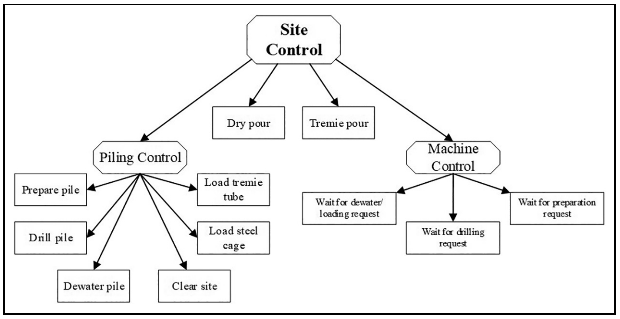


Figure 5. Hierarchy of control units.

timings recorded on site. Durations of different piling activities are further explained in Section 6.6.

5.3. *Data for model validation*

In order to validate the model, real production data should be collected to compare the results of the model with the real system. The construction company keeps a record of production data for each pile, such as the start and finish time of piling activities, types of machines used, and soil profile. The records were compiled manually on paper-based forms by the site engineers. In order to facilitate data analysis for the validation of the model, relevant piling data were transferred from paper-based forms into excel sheets that allowed accurate analysis of activity durations and piling sequencing.

6. Simulation modeling of piling operations

After finalizing and validating the conceptual model of the piling project by the first author, he collaborated with the second author, an expert simulation modeler, to build the computer model. Several options of simulation software were available for implementation. It was found that over-the-shelf simulation software could force the modeler to tweak the conceptual model to fit the software capabilities. However, JaamSim[86]—an open-source simulation software based on the Java programming language—can allow the modeler to create customized objects that are able to represent the behavioral aspects of system entities

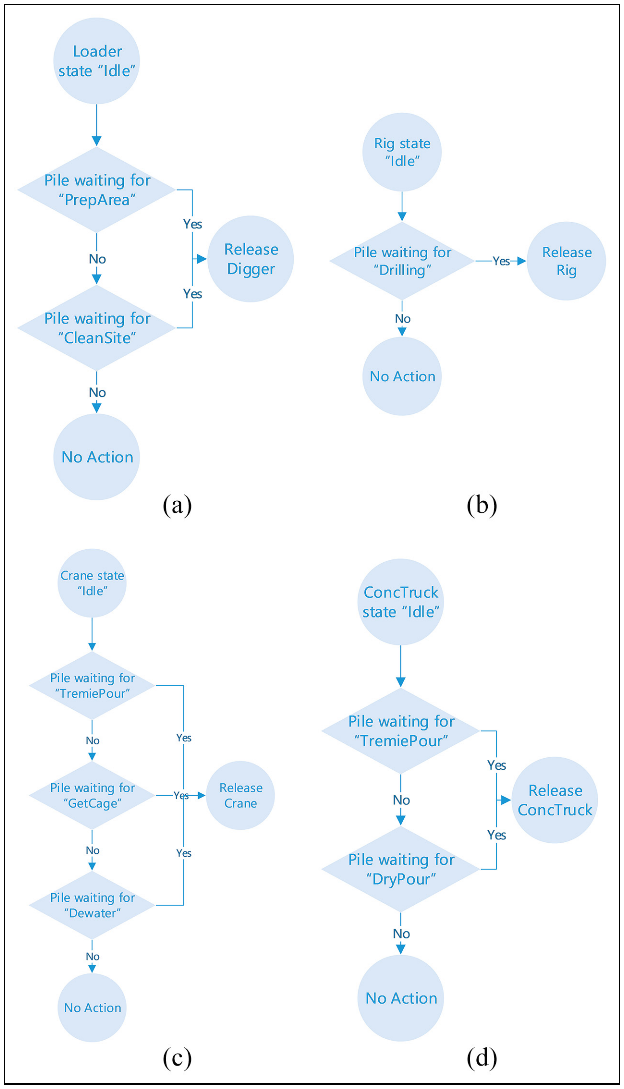


Figure 6. Control policies of Loader (a), Rig (b), Crane (c), and ConcTruck (d).

realistically. Therefore, a decision was made to utilize the flexibility of JaamSim to accurately represent the distinct features of the HCCM model without the need to make any unrealistic assumptions that might be required to improve the implementability of the conceptual model in over-the-shelf simulation software. The following sections explain in detail the process of building and validating the computer model for piling operations.

6.1. Building customized objects on JaamSim for piling operations

JaamSim includes pre-set modeling objects that can be used to represent the logic of different operations. However, the flexibility of JaamSim as an open-source simulation platform allowed the researchers to build objects that are accustomed to piling operations, thus imitating the real behavior of piling entities. This section explains the process of building the customized objects for piling operations. These customized objects are then used to build the logic of the computer model.

6.1.1. Piling controller. In order to incorporate the sequence of piling and to control the operations on site, a customized object was created as an extension of *UserController*, a more generic extension to JaamSim from other HCCM-based models. The Piling Controller object obtains the piling sequence from a spreadsheet then lists piles in the correct order as shown in Figure 7. It also manages the piling operations for each pile by receiving signals from piles based on their states and then requesting relevant machines to process the next step for the relevant pile. Also, this customized object controls the overall behavior of machines and sets dispatching rules based on both pile and machine states. Thus, it incorporates not only piling control unit but also the borehole control unit and the machine control unit as depicted in the conceptual model.

6.1.2. User signal. In order to allow the Piling Controller to make decisions on dispatching machines to piles, two customized objects were created based on JaamSim's *LinkedComponent* object. To implement the sequence and dispatch rules in the Piling Controller, *UserSignalAfter* objects were designed to signal the state changes of machines while *UserSignalBefore* objects were designed to signal pile's state changes. The roles of these two user signal objects are explained in Sections 6.3 and 6.4.

Table 4. Model assumptions.

Assumptions	Confidence	Impact
There will be no shortage of steel cages or concrete supply	High	Medium
Variability in piles length and soil conditions is modeled as a range in drilling time	Medium	High
Breakdowns durations vary from 45 min to 3 days	Medium	Medium
Concrete trucks arrive in the site based on an ordering policy and go to the nearest available pile regardless of piling order	Medium	Low

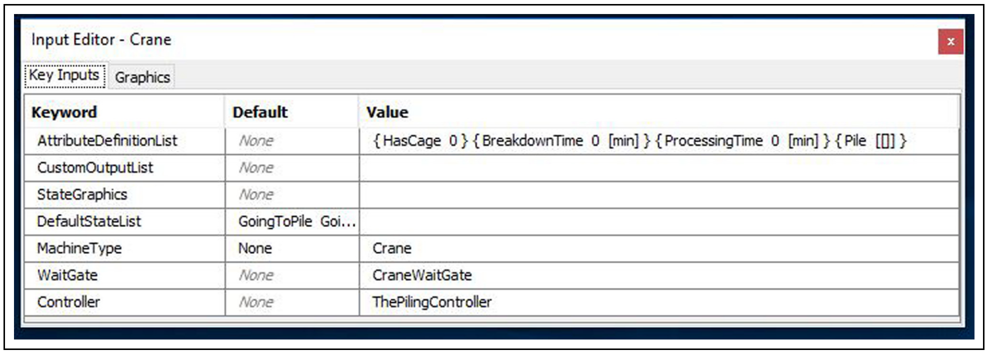
Table 5. Model simplifications.

Simplifications	Confidence	Impact
Times to travel between zones are calculated based on the average speed of each machine	High	Low
Each machine is located at a central point in the site, and it starts its activities for each pile from this point.	Medium	Low
Learning curves for machines' drivers follow the straight-line model[83]	Low	Medium
Breakdowns occur only at machines' waiting zones (during Idle state)	Low	Low
Delays due to severe weather are modeled as machine breakdowns	High	Low
Fueling of machines is not modeled	Medium	Low


Input Editor - ThePilingController

Keyword	Default	Value
AttributeDefinitionList	None	
CustomOutputList	None	
PileSequence	None	Pile23 Pile31 Pile27 Pile25 Pile39 Pile35 Pile40 Pile16 Pile18 Pile20 Pile8 Pile17 Pile33 ...

Figure 7. Piling controller.

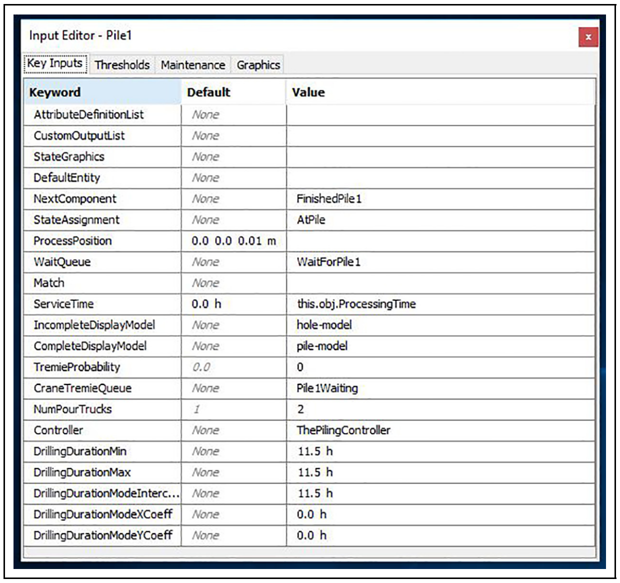

Input Editor - Crane

Keyword	Default	Value
AttributeDefinitionList	None	{ HasCage 0 } { BreakdownTime 0 [min] } { ProcessingTime 0 [min] } { Pile [[]] }
CustomOutputList	None	
StateGraphics	None	
DefaultStateList	GoingToPile Goi...	
MachineType	None	Crane
WaitGate	None	CraneWaitGate
Controller	None	ThePilingController

Figure 8. Crane customized object.

6.1.3. Machine object. As explained in 4.2 (when describing the conceptual model), piling operations depend on several non-stationary machines, which behave differently depending on the requests processed by the machine control unit (implemented as part of the Piling Controller). Therefore, a customized object was created in JaamSim to model machines' individual behavior. This customized object was based on the *SimEntity* object with attribute extensions to specify the Machine type, Wait gate (where the machine goes when not working on a pile), and the Piling controller which dispatches the machine to piles following the dispatching rules (see Section 4.7). Figure 8 shows the input editor of the Crane object as displayed in JaamSim.

6.1.4. Pile object. Each pile in the 183 piles considered in the case study was modeled in JaamSim as a customized object, which is an extension of the *Server* object. Similar to the Machine object, additional attributes were added to this customized object to include the Display model for complete and incomplete piles (so completed piles can be observed during simulation), Tremie probability (to simulate whether a pile needs a Tremie pour or not), Crane queue (in the case of a pile that requires a crane for a Tremie pour), Number of concrete trucks (required for the pile), Piling controller (that dispatches machines to the pile), and Drilling durations (explained in Section 6.5). The input editor of the Pile customized object is illustrated in Figure 9.



Keyword	Default	Value
AttributeDefinitionList	None	
CustomOutputList	None	
StateGraphics	None	
DefaultEntity	None	
NextComponent	None	FinishedPile1
StateAssignment	None	AtPile
ProcessPosition	0.0 0.0 0.01 m	
WaitQueue	None	WaitForPile1
Match	None	
ServiceTime	0.0 h	this.obj.ProcessingTime
IncompleteDisplayModel	None	hole-model
CompleteDisplayModel	None	pile-model
TremieProbability	0.0	0
CraneTremieQueue	None	Pile1Waiting
NumPourTrucks	1	2
Controller	None	ThePilingController
DrillingDurationMin	None	11.5 h
DrillingDurationMax	None	11.5 h
DrillingDurationModeInterc...	None	11.5 h
DrillingDurationModeXCoeff	None	0.0 h
DrillingDurationModeYCoeff	None	0.0 h

Figure 9. Pile customized object.

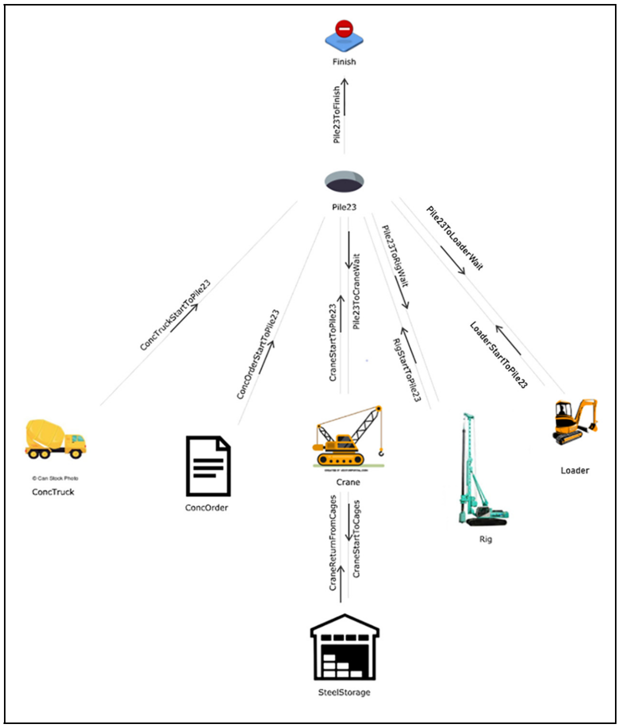


Figure 10. Single-pile operations.

6.2. *The logic of single-pile operations*

As shown in the conceptual model individual behavior (Figure 4(a)), in order to process one pile, six activities should be performed by site machines. Figure 10 shows a simplified view of the simulation model for a single pile, including the main entities and their routes. As depicted in Figure 10, the primary machines involved in piling operations stay in the system by having two ways routes between the piling zone and waiting zone while the concrete trucks and concrete orders (explained in Section 6.5) leave the system through the sink after processing each pile. A detailed explanation of the behavior of each machine at different zones is explained in the rest of this section.

6.3. *Machines behavior at waiting zones*

In order for the customized objects of machines to operate, several supporting JaamSim objects needed to be used in specific configurations to represent the logic of the model in regard to machines' activities. In this section, we explain the logic and supporting objects of each of the four machines at their waiting zones. For simplicity, we will present machines' logic with the first three requested piles in the case study (Piles 23, 27, and 31).

6.3.1. Loader and Rig at waiting zone. As indicated in the individual behavior section of the conceptual model, the behavior of both the Loader and Rig follow a simple logic of waiting for a job request then moving to perform a designated activity at the pile being processed (see Figure 4(b) and (d)). Therefore, they follow the same logic in the computer model. As shown in Figure 11, the Loader and Rig go through different JaamSim objects before being dispatched to the pile. The following steps explain the processes of generating and dispatching the Machine (Loader or Rig) object:

1. EntityGenerator (LoaderStart, RigStart): generates Machine objects.
2. UserSignal (LoaderEnterWait, RigEnterWait): signals the Machine state to the Piling Controller.
3. EntityGate (LoaderWaitGate, RigWaitGate): holds Machine until dispatched by the Piling Controller.
4. Assign (SendLoaderToPile, SendRigToPile): assigns a state to Machine.
5. Branch (AtLoaderWait, AtRigWait): dispatches the Machine to next requested Pile.
6. EntityConveyor (LoaderStartToPile, RigStart ToPile): moves the Machine to next requested Pile location.
7. EntityConveyor (PileToLoaderWait, PileToRig Wait): returns Machine (after it has performed the necessary process at the Pile) from processed Pile.
8. Branch (SetLoaderBreakdown, SetRigBreak down): in case of a breakdown, directs Machine

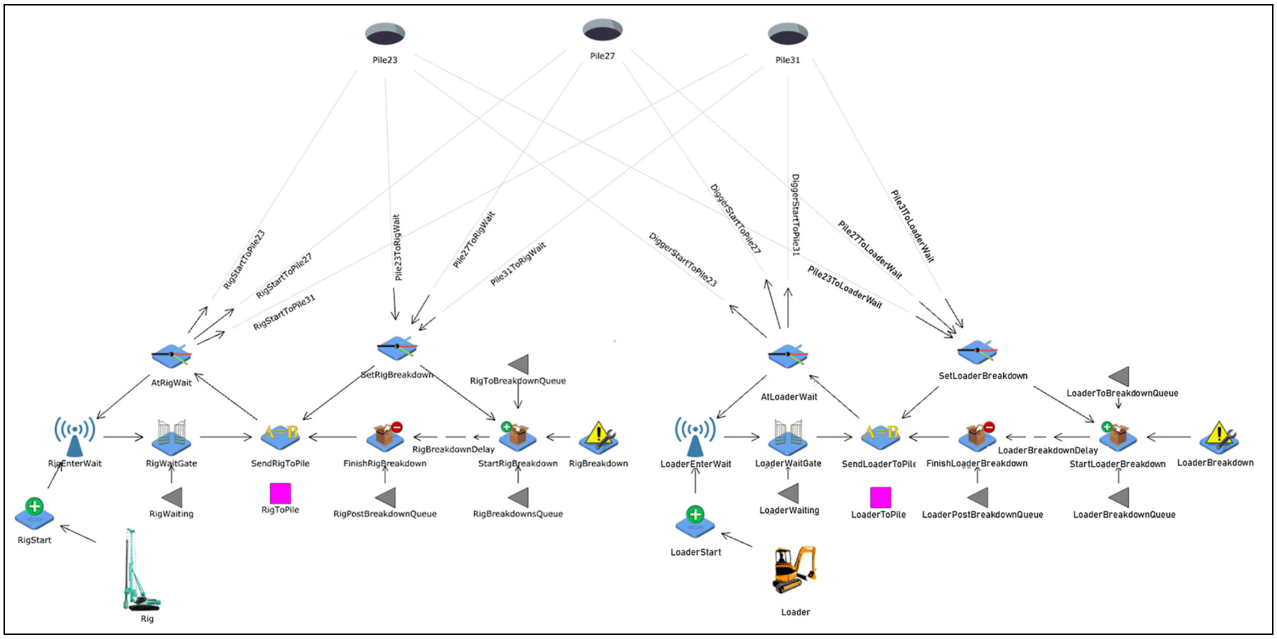


Figure 11. Loader and Rig waiting zones.

to breakdown objects (step 9), otherwise directs Machine to be ready to process other piles (step 12).

9. AddTo (StartLoaderBreakdown, StartRigBreakdown): pairs Machine with the Breakdown entity (the breakdown mechanism is explained in Section 6.7).
10. EntityDelay (LoaderBreakdownDelay, RigBreakdownDelay): delays Machine for breakdown period.
11. RemoveFrom (FinishLoaderBreakdown, FinishRigBreakdown): detaches Machine from Breakdown entity.
12. Repeat step 4.

It is important to note that the EntityGate requires a Queue object (*LoaderWaiting, RigWaiting*) and an ExpressionThreshold (*LoaderToPile, RigToPile*). Similarly, AddTo and RemoveFrom require Queue objects (*LoaderBreakdownsQueue, LoaderPostBreakdownQueue*, etc.). Therefore, all Queue and ExpressionThreshold objects are not included in the description of previous steps, but they are still necessary parts of the logic. This applies to all EntityGates, AddTo, and RemoveFrom used in this model.

6.3.2. Crane at waiting zone.

As can be found in the individual behavior of the Crane in the conceptual model (see Figure 4(e)), the behavior of the crane is the most complex among the various machines modeled in the simulation model due to its necessity to perform several activities between different site zones. Therefore, its logic in the computer model includes additional steps compared to other machines to control its routing behavior between its waiting zone, a pile's zone, and the cage storage zone. Figure 12 depicts the logic of Crane in the computer model, which acts according to the following steps:

1. EntityGenerator (CraneStart): generates Crane objects.
2. UserSignal (CraneEnterWait): signals the Crane state to the Piling Controller.
3. EntityGate (CraneWaitGate): holds Crane until dispatched by the Piling Controller.
4. Branch (CraneRouting): directs Crane to Pile (step 5) or Cages (step 15).
5. Assign (SendCraneToPile): assigns a state to Crane.
6. Branch (AtCraneWait): directs Crane to the next requested Pile (step 7) or to be back to wait (step 2).
7. EntityConveyor (CraneStartToPile): moves Crane to the next requested Pile location.
8. EntityConveyor (PileToCraneWait): returns Crane from processed Pile.
9. Branch (SetCraneBreakdown): in case of breakdown, directs Crane to breakdown objects (step 10), otherwise, directs Crane to process other piles (step 14)

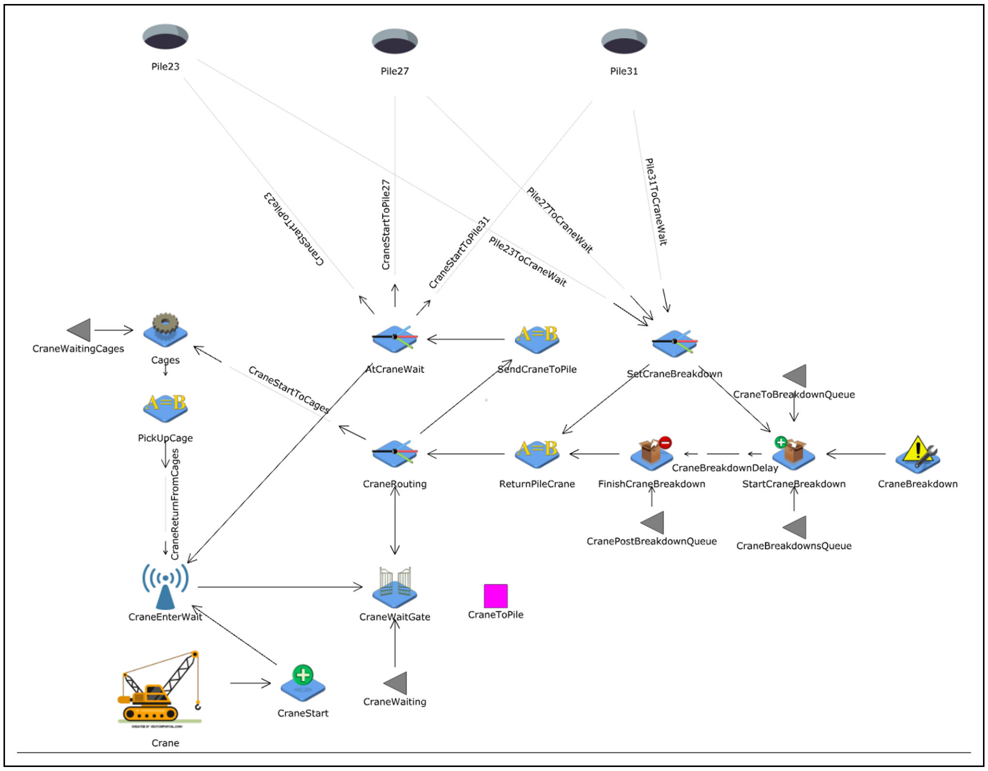


Figure 12. Crane waiting zone.

10. AddTo (StartCraneBreakdown): pair Crane with the Breakdown entity.
11. EntityDelay (CraneBreakdownDelay): delays Crane for breakdown period.
12. RemoveFrom (FinishCraneBreakdown): detach Crane from Breakdown entity.
13. Assign (ReturnPileCrane): assigns a new state to Crane.
14. Repeat step 3.
15. EntityConveyor (CraneStartToCages): delivers Crane to Cages.
16. Server (Cages): process Crane to pick up cage.
17. Assign (PickUpCage): assigns a new state to Crane.
18. Repeat step 2.

6.3.3. Concrete truck at waiting zone. The concrete truck follows a different logic compared to other machines as it has to follow a certain supply-chain policy where trucks arrive with fresh concrete, pour concrete into piles, and then leave the site (see individual behavior of concrete truck in the conceptual model (Figure 4(c))). Therefore, no EntityConveyors are used to return trucks back to the waiting zone. The logic of leaving the site is explained in the Pile individual logic in Section 6.4. Also, as concrete trucks can process any available pile with no specific preference, no user signal is used in the logic for simplicity. In addition, no breakdowns are assigned to concrete trucks as their breakdowns are incorporated in the concrete policy (as explained in Section 6.5). The following steps explain the ConcTruck logic (see Figure 13):

1. EntityGenerator (ConcTruck Start): generates ConcTruck objects.
2. EntityGate (ConcTruck WaitGate): holds ConcTruck until dispatched by the Piling Controller.
3. Assign (SendConcTruckToPile): assigns state to ConcTruck.
4. Branch (AtConcTruckWait): dispatch ConcTruck to next available Pile.
5. EntityConveyor (ConcTruckStartToPile): moves ConcTruck to next available Pile location.

6.4. *Piles individual logic*

As stated earlier, each pile should go through different activities, which are performed by different machines. Once a machine is dispatched from its waiting zone to the next requested pile, it goes through a series of steps to process the pile and either return back to the waiting zone or

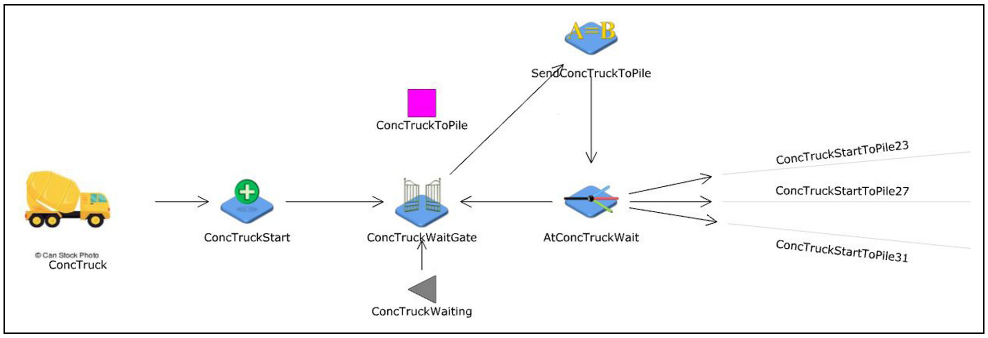


Figure 13. Concrete truck waiting zone.

leave the system. Figure 14 illustrates the piling zone and all objects. The following is an explanation of the behavior of each machine at piling zones.

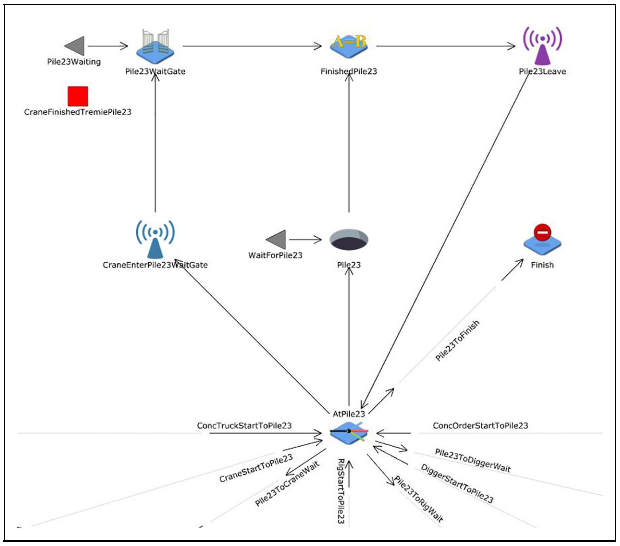


Figure 14. Piling zone.

6.4.1. Loader and Rig at pile. The logic of operations of the Loader and Rig at a piling zone from the event of their arrival can be explained in the following steps:

1. Branch (AtPile): dispatch Machine to Pile.
2. Customized Object (Pile): processes arrived Machine, that is, machine completes process at pile.
3. Assign (FinishedPile): assigns a state to Machine.
4. UserSignal (PileLeave): signals Machine state to the Piling Controller.
5. Branch (AtPile): sends Machine back to its waiting zone.

6.4.2. Crane at pile. Since the Crane is responsible for dewatering, inserting a cage, and holding the tremie tube if a tremie pour is required, it has a different logic compared to other machines. In the case of Crane performing dewatering or inserting cage, it follows the same steps as the Loader and Rig. However, in the case of tremie pour, the crane is responsible for lifting a tremie tube during the pouring duration, that is, while concrete is poured. Therefore, an EntityGate is added to the process to hold the Crane as described below:

1. Branch (AtPile): dispatch Crane to CraneEnter PileWaitGate.
2. UserSignal (CraneEnterPileWaitGate): signals Crane state to the Piling Controller.
3. EntityGate (PileWaitGate): holds Crane until tremie pour is completed, that is, concrete trucks have visited pile and the pouring process has been completed.
4. Assign (FinishedPile): assigns a state to Machine.
5. UserSignal (PileLeave): signals Machine state to the Piling Controller.
6. Branch (AtPile): sends Machine back to its waiting zone.

6.4.3. ConcTrucks at pile. As explained in Section 6.3.3, Concrete Trucks leave the system after being processed at a Pile. Therefore, a sink was added to the piling zone to receive all leaving Concrete Trucks. The logic of Concrete truck operations at piling zone is explained in the following steps. Note that there is no difference in the logic of Concrete Trucks in the case of Tremie pour. However, longer durations for waiting and pouring are used in the case of Tremie Pour.

1. Branch (AtPile): dispatch ConcTruck to Pile.
2. Customized Object (Pile): process arrived Conc Truck.
3. Assign (FinishedPile): assigns a state to Conc Truck.

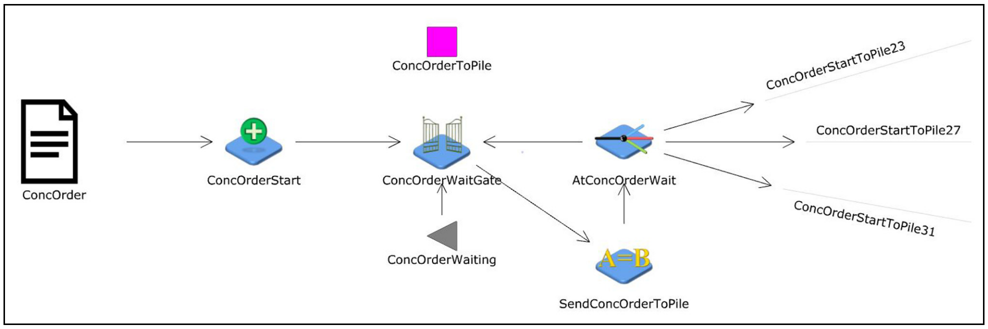


Figure 15. ConcOrder waiting zone.

4. UserSignal (PileLeave): signals ConcTruck state to the Piling Controller.
5. Branch (AtPile): sends ConcTruck to Finish.
6. Sink (Finish): receives leaving ConcTruck.

6.5. Modeling concrete orders

Concrete is a very time-sensitive material. Any delays in concrete delivery could lead to failing quality tests, thus rejecting the whole truck from pouring concrete and sending it back to the production yard. Therefore, concrete orders should follow a strict policy to ensure concrete delivery in the least possible time between production and pour. The lead time of concrete was modeled by adding a new ‘‘dummy’’ machine that follows the same logic as concrete trucks. This addition was not initially included in the conceptual model as it was assumed to be incorporated in the arrival rate of concrete trucks (see conceptual model assumptions in Table 4). However, the computer modeler found that the addition of this dummy machine can improve the model’s flexibility by allowing the end-user to change the concrete ordering policy depending on the situation on-site. The duration of processing this dummy machine is set based on historical data. Figure 15 illustrates the logic of ConcOrder, which is a customized Machine object, at the corresponding waiting zone. A ConcOrder is dispatched to a Pile when the drilling is completed; then, it waits at the pile to block the ConcTruck from being dispatched until the processing time of ConcOrder (lead time) is passed. Thus, it represents the lag in time between the completion of drilling activity and the start of concrete pour.

6.6. Activity timings

This section presents the timings of all piling activities and machinery. Data for timings were either obtained from the construction planning documents or directly collected from site observations. The following explains how timings were incorporated into the computer model.

6.6.1. Durations of piling activities. As explained in Section 5.2, only the most likely, minimum, and maximum values of activity durations were available during data collection for the model realization phase. Hence, activity durations are assumed to follow a triangular distribution, as explained in Table 6.

6.6.2. Travel time. As stated in the simplifications list in Section 4.8, the average speed is used to calculate the travel time of each machine on-site. In the JaamSim model, each EntityConveyor was set to calculate the travel time based on its length and machine average speed (Table 7). Thus, the site plan was represented in the model in scale to allow accurate calculation of travel times. Average speeds were obtained from Machines’ data sheets and were confirmed by the time recordings from site visits.

6.7. Breakdowns

In order to model breakdowns, historical data were analyzed to identify the types of breakdowns that can occur during piling operations, their durations, and frequency. The following is an explanation of the results of the breakdown data analysis and the method of incorporating breakdowns in the simulation model.

6.7.1. Breakdown events. Based on the data collected from the site, five types of breakdown events were identified, and 13 breakdown events were recorded in total. Also, it was found that concrete trucks were not included in any breakdown records, which can be reasonable considering that any breakdowns to concrete trucks are the supplier’s responsibility, and these breakdowns can be incorporated into the variability of concrete trucks arrivals (see Section 6.5). Table 8 lists breakdown events and frequencies based on the site records analysis. As indicated in the conceptual model simplification list (Table 5), the weather is modeled as a machine breakdown as there was a case in which all machines were stopped from work due to severe weather

Table 6. Activity durations.

Activity	Duration (min)
Prepare pile	TriangularDist(120,180,150)
Drill pile	TriangularDist(180,300,240)
Dewater pile	TriangularDist(30,60,45)
Load steel cage	TriangularDist(10,20,15)
Insert steel cage	TriangularDist(20,30,25)
Dry pour	TriangularDist(10,15,12)
Tremie pour	TriangularDist(20,40,30)
Clear site	TriangularDist(10,15,12)

Table 7. Machine average speeds.

Machine	Average Speed
Rig	1.9 km/h
Crane	1.4 km/h
Loader	3.75 km/h
Concrete Trucks	5 km/h

conditions. It can be concluded that rigs were the machine most prone to breakdowns as there were five cases where one rig was down and two cases where all rigs got broken. The frequency of breakdowns was modeled using a discrete distribution. The probability values of the discrete distribution for breakdown types are listed in Table 8.

6.7.2. Breakdown durations. It was not possible to obtain accurate details on breakdown durations from site data as most of the breakdowns were only recorded as incidents in daily records. It was found that nine breakdowns were recorded for 1 day while there were two cases for a 2-day breakdown and two other cases where breakdowns extended for 3 days. It is important to indicate that the average working time for this site was 10.3 h/day. Based on that, another discrete distribution was used to assign durations of breakdowns with the probability values as listed in Table 9.

As the total project duration was 59 days, the duration between breakdowns was modeled using an exponential distribution with a mean of 4 days (40 h), which is approximately equal to the total project duration divided by the number of breakdowns.

6.7.3. Modeling breakdowns. The logic of modeling breakdowns includes three main stages: (1) creating breakdowns, (2) assigning breakdowns to machines, and (3) discarding breakdowns. First, an *EntityGenerator* object creates a Breakdown Entity, then its type and duration are set using "Assign" objects that are linked to the Discrete Distributions as explained in Sections 6.7.1 and 6.7.2. Second, the Breakdown Entity is combined with the machine it is assigned to using an "AddTo" object until the breakdown duration elapses. Then, the Breakdown Entity gets dispatched from the machine using a "RemoveFrom" object and proceeds to a "Sink" object to leave the system. Afterward, machines can resume their activities as usual. The entities used to assign breakdowns to machines can be found in their logic description in Figures 11 and 12.

Table 8. Breakdown types and frequencies.

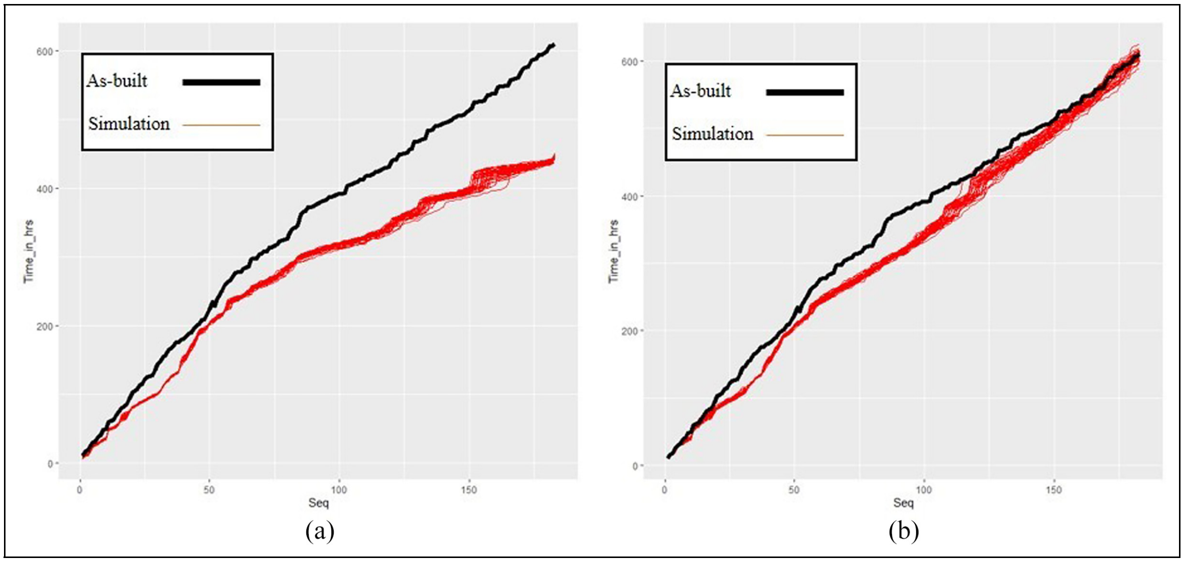
Breakdown type	Frequency	Probability
Rig breakdown	5	0.385
Crane breakdown	3	0.230
Loader breakdown	2	0.154
All rigs breakdown	2	0.154
All machines breakdown	1	0.077

Table 9. Breakdown durations.

Breakdown duration	Frequency	Probability
10 h	9	0.692
20 h	2	0.154
30 h	2	0.154

6.8. Model validation and calibration

The stage of model validation and calibration was completed collaboratively by the research team, which includes experts in construction management, computer simulation, and statistical analysis in order to achieve a high level of validity for the simulation model. The results of the simulation model were compared to real production data to validate and calibrate the model. However, the only accurate data available from the site were the durations of the rigs and concrete trucks. Accurate timings of the loader and crane activities were not available. Consequently, two steps were taken to validate and calibrate the model. First, as-built durations of rigs and concrete trucks were deliberately added to the model (instead of the durations in Table 6) to validate the logic by comparing simulation time with as-built total time. Second, a detailed comparison was conducted on the completion time of each pile to calibrate the durations of unrecorded machines. In both of the previous steps, the sequence of piling in the model was set to follow the as-built sequence to assure the most realistic results are obtained from the simulation model. The following is an explanation of each step of model validation and calibration.



(a) (b)

Figure 16. As-built versus simulation piling productivity.

6.8.1. Adjusting loader and crane timing. By running the model with as-built durations of rigs and concrete trucks, the average total simulation time was found to be 87% of the as-built time, which indicates that the estimated durations of loader and crane activities should be adjusted to match reality. By multiplying loader and crane durations by 1.14, the model provided a total average simulation time that matches the real finish time. Figure 16 shows a comparison between the as-built productivity rate (thick black line) and the simulation rate (thin red lines) for two cases: (a) preliminary timings and (b) adjusted timings. As shown on the right side of the figure, even when the simulation model provides a similar finish time, the pace of piling is not matching reality. By analyzing as-built data, it was found that the throughput of piles increased when progressing in time, which was interpreted to be the effect of a learning curve. The next section will explain how a learning curve was incorporated in the simulation model to achieve similar throughput by calibrating the loader and crane durations.

6.8.2. Incorporating learning curve in the simulation model. Several studies investigated the learning curve effect on construction activities, and several models were proposed, such as the Straight-line model, Stanford "B" model, Cubic power model, and Exponential model.[83,87–89] For simplification, this study adopted the Straight-line model by assuming a linear relationship between machine productivity and the simulation time. In the simulation model, all loader and crane durations were multiplied by a variable X, which is calculated as in Equation (1):

$$X = A1 + (A2 - A1)^*(T - S)/T \qquad (1)$$

where $A1$ = Adjust factor 1, $A2$ = Adjust factor 2, T = total simulation time (set to be 1000 h), and S = simulation time at the moment of starting the activity.

Table 10 lists the experiments conducted to define the best Adjust factor combination that imitates the real learning curve on site. Figure 17 provides four examples of the productivity comparison between simulation and real outputs by displaying the 95% confidence band of simulation results (yellow area), real outputs (black dotted line), and mean of simulation replications (blue dashed line). Through visual inspection of all scenarios, using adjust factors (0.0,1.65) provides the best fitting results (see Figure 17(a)), which indicates that the loader and crane used to operate at 60% of their assumed productivity at the beginning of the project, then reached the assumed productivity after 400 h, then operated at 150% of assumed productivity at the end of the project. This finding can be confirmed by the fact that site engineers were providing average timings based on what they have observed from similar projects.

7. Experimentations and results

As this simulation study is triggered to assist the general contractor in assessing the reliability of future plans proposed by piling subcontractors, we aimed at demonstrating the usefulness of the model by testing several scenarios for the piling sequence. In the project under study, the subcontractor provided a piling schedule of 72 days (744 h) while in reality, they finished in 59 days (610 h), which put the general contractor in a critical situation to adjust their plans to fit the 14 days difference. This included adjusting the start date of other sub-contractors and the

Table 10. Adjust factors for the learning curve.

A1	*A2*	*X*				Mean simulation time in hours (actual = 610)
		S = 0	*S* = 200	*S* = 400	*S* = 600	
0.0	1.7	1.7	1.36	1.02	0.68	619.2217469
0.0	1.65	1.65	1.32	0.99	0.66	607.3328308
0.1	1.8	1.8	1.46	1.12	0.78	636.9266832
0.1	1.6	1.6	1.3	1	0.7	617.5790284
0.2	1.7	1.7	1.4	1.1	0.8	631.0150757
0.2	1.6	1.6	1.32	1.04	0.76	619.290268
0.2	1.55	1.55	1.28	1.01	0.74	608.5886618
0.3	1.5	1.5	1.26	1.02	0.78	607.856343
0.3	1.6	1.6	1.34	1.08	0.82	625.7512172
0.4	1.5	1.5	1.28	1.06	0.84	619.0079039
0.4	1.45	1.45	1.24	1.03	0.82	607.8221739
0.4	1.4	1.4	1.2	1	0.8	592.472851
0.5	1.5	1.5	1.3	1.1	0.9	626.3450111
0.9	1.2	1.2	1.14	1.08	1.02	598.6291942
1.14	1.14	1.14	1.14	1.14	1.14	609.1415629

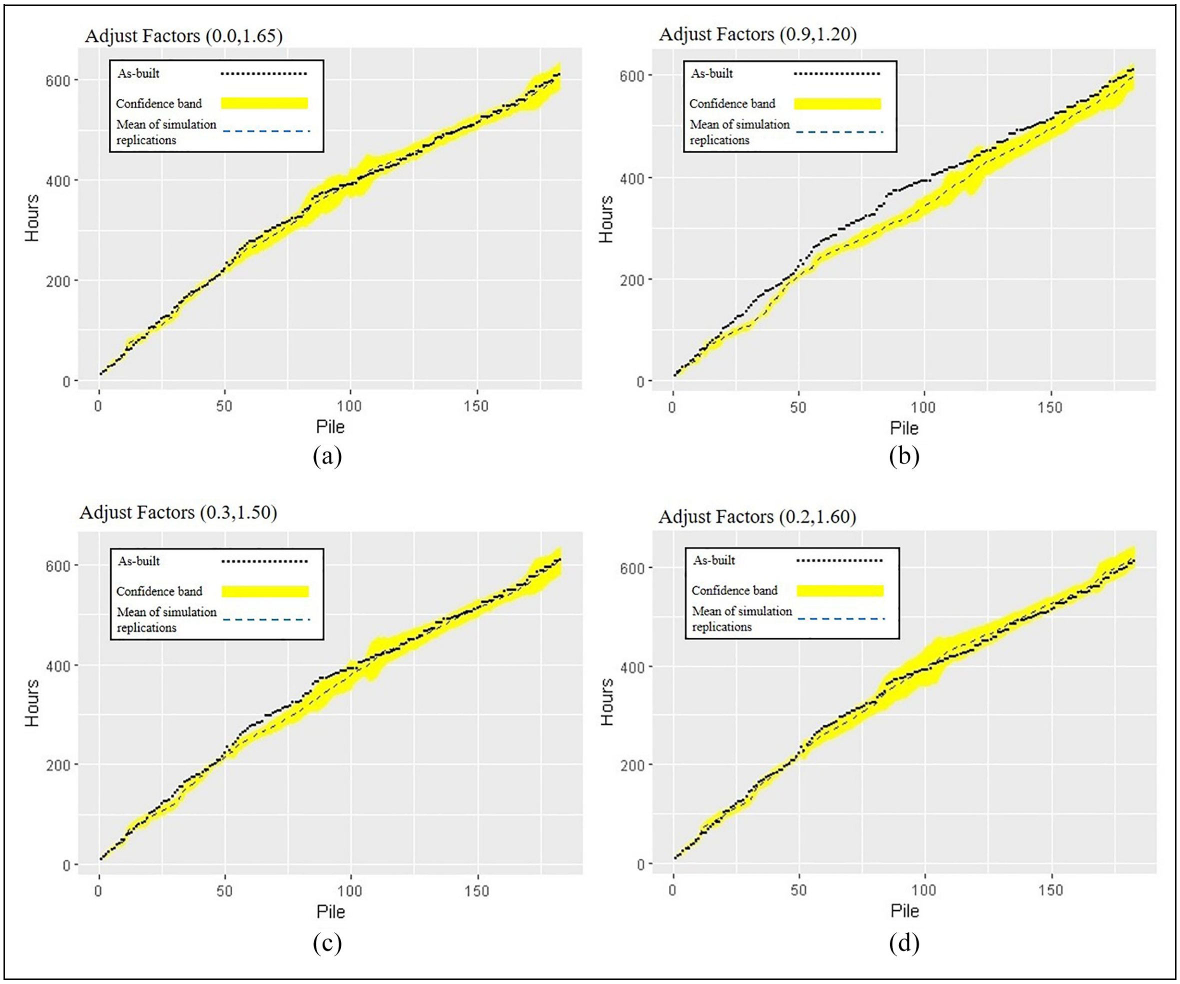


Figure 17. Effect of different adjust factors on piling productivity (a) Adjust Factors (0.00, 1.65), (b) Adjust Factors (0.90, 1.20), (c) Adjust Factors (0.30, 1.50) and (d) Adjust Factors (0.20, 1.60).

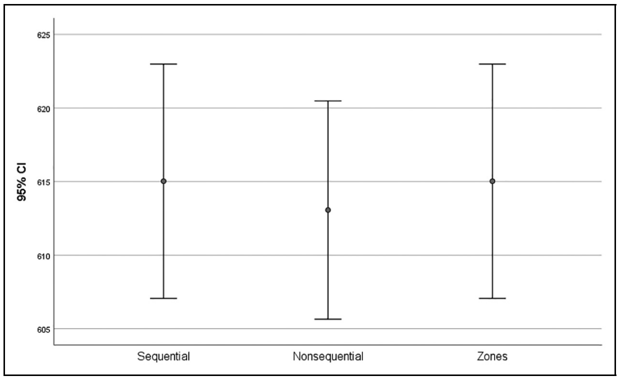


Figure 18. Results of using the model as a planning tool.

delivery of essential resources for the following construction phases. The piling sub-contractor justified the difference between planned and real finish time by relating to the uncertainty of piling operations, especially underground conditions such as soil properties and water level. As expressed by the piling subcontractor, packing a time contingency for piling operations is a common practice in the industry (20% in the case study). However, as will be explained in this section, having a valid simulation model for the process can provide better insight on a more realistic finish time that accounts for risks without the need for such extended schedule contingencies.

7.1. Using the model as a planning-support tool

One of the interests of the general contractor was to understand the effect of piling sequence on the overall performance of the project. In one scenario, a sequence that follows an ascending order can minimize material and machine movement around the site as all of the resources will be focused on the same piling area. It is important to indicate that the practices of piling construction require that two adjacent piles should not be drilled in parallel to avoid soil failure. Therefore, a staggering piling sequence should be followed in this scenario. However, this sequencing scenario can increase the risk of not having insight into the nature of the soil at different areas of the site. Another proposed scenario is to execute piles at different zones to act as an extra sampling process of the site then move forward from each finished pile in a similar order until all piles are completed. This sequence scenario will incur excessive material and machine movement as all resources should be relocated for each pile. However, it can provide better insight by reducing the risk, thus increasing finish time certainty. A third sequencing scenario is a mix of the previous two scenarios by dividing the site into different zones and finishing one zone at a time, but not necessarily in ascending order. This way, all resources will need to relocate between site zones only once at a time. Moreover, this sequencing style can allow next construction activities, such as pile capping and earthmoving, to take place concurrently without clashing with piling operations. Figure 18 shows the 95% confidence interval of the simulation results of the three proposed scenarios as generated by running the model 39 times for each scenario. The number of replications was determined as 39 to ensure that the error factor in the total piling duration is less than 0.5%. It can be found that the first and third scenarios yield nearly similar results, while the second scenario provides a mean value of total duration time that is nearer to reality (613 h). In addition, all scenarios resulted in a confidence interval that contained the actual project duration with a similar width among the three scenarios.

7.2. Using the model as a control tool

In addition to the models generated for the planning of piling operations, the client needed to use the model as a control tool by including live data from the site into the model and forecast finish times at 10-pile intervals. By analyzing site data, it was found that the activity most affected by uncertainty in piling operations is the drilling as soil layer properties can change from one location to another. Hence, drilling time varies depending on the location of each pile. To account for the location effect on drilling time, the simulation model was designed to anticipate future drilling durations using a regression model that examines site data by analyzing the relationship between drilling times and pile coordinates. Figures 19–21 show the results of experimenting with the model as a control tool for the three proposed scenarios in 95% confidence interval graphs. The horizontal axis represents the models created at 10-piles intervals, and the vertical axis represents the finish time. In addition, two boundary lines are added to the graphs for the planned and actual finish times. As the experiments were conducted at a 10-piles interval, 19 models were generated for each scenario with 39 runs for each model.

7.3. Interpretation of simulation results

It can be concluded that based on the results of the simulation model, it was possible to show that the piling schedule of the subcontractor lacked accuracy due to the traditional use of a Gantt chart to plan the project. Using a simulation model during the planning stage can provide better estimations that account for different uncertainties while considering the complexity and variability of piling operations. In general, the three scenarios provided highly accurate results that are very near to reality.

However, the results of using the model as a control tool demonstrate that incorporating live data from the site can significantly affect the total time estimates in all scenarios. In the first scenario, the simulation results showed

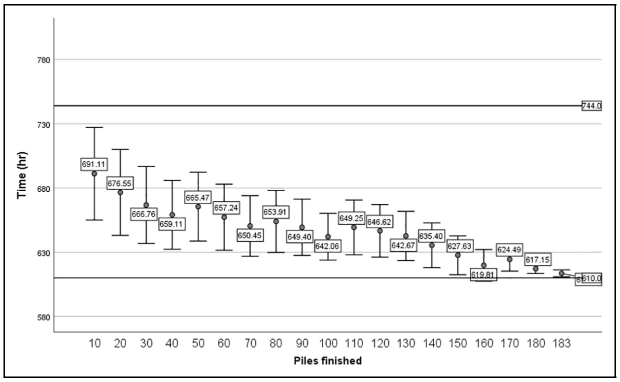


Figure 19. Results of running the model as a control tool (Sequential order).

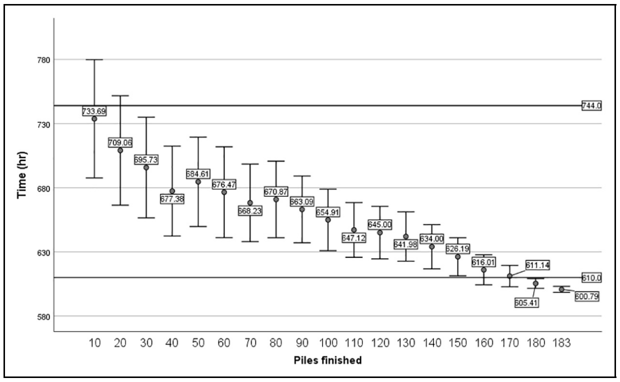


Figure 20. Results of running the model as a control tool (Nonsequential order).

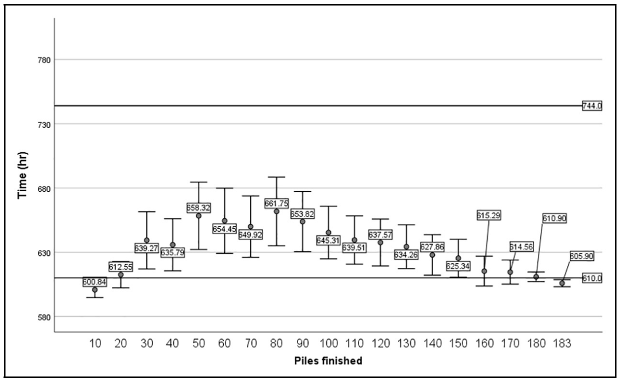


Figure 21. Results of running the model as a control tool (Order by Zones).

a decrease in the mean values throughout the project duration (from 691.11 to 613.59 h). The confidence interval was consistently decreasing by time as well. This indicates that following a sequential-staggered order can provide reasonable certainty by time as both the mean and standard deviation were decreasing with the progress of the project. The second scenario showed similar behavior to the first scenario but with a higher difference in the mean values (from 733.69 to 600.79 h). Also, the confidence interval showed a steeper decrease over time. The very high mean value after 10 piles can be attributed to the excessive movement of resources at each piling cycle. However, good insight can be achieved by following the non-sequential piling order due to the spread of piling data around the site, which provides a better understanding of the overall site geology.

Finally, the third (actual) scenario showed some irregularity in the mean value ranging between 600.84 h initially, peaking to 661.75 h after 80 piles finished, then decreasing to 605.9 h at the end. However, the confidence interval was kept minimal compared to the previous two scenarios. Even though the mean and confidence interval of the third scenario were nearer to the actual project duration, they show inconsistency in trends. For example, as shown in Figure 21, the results for 10 to 50 piles show an upward trend that can mislead the results by indicating that the project will finish later than expected. Then the curve starts going toward the real finish time after finishing 80 piles. The inconsistency in the third scenario can be due to the effect of sudden changes in geology between different zones. However, one advantage of this scenario is that it provides better site layout coordination as it considers allowing other trades to commence their work onsite before finishing all piles.

8. Discussion and lessons learned

In this section, we first discuss the usefulness of having a structured approach for developing and documenting a conceptual model. Then, we explain how the final simulation model can be used to plan similar piling operations in the future.

8.1. Conceptual model as a communication link between construction planner and simulation modeler

In simulation research, it is highly evident that one of the most integral roles of the conceptual model is to facilitate communications and collaboration between different simulation study stakeholders.[12,53,72,75,82,90] In order to address different stakeholders' backgrounds, expectations, and use of ''technical'' language, the conceptual model was framed in a generally acceptable way for both construction managers, who traditionally lack simulation knowledge, and simulation modelers, who usually seek more technical and advanced representation methods. The usefulness of framing the conceptual model in such a way was proven by facilitating the engagement of the major stakeholders in the development of the conceptual model. In this sense, stakeholders attended all invited meetings, and they provided all information and data required by the simulation team. In addition, the conceptual model can act as the specification of the computer model. Using the conceptual model as a specification document led to reducing simulation study time and effort as it was used to retain the required information by the computer modeler without the need to consult the client. Accordingly, building the computer model required 45 h in total, including 30 h for coding and 15 h for validation and calibration.

8.2. Using the simulation model as a decision support tool for piling operations

As reported in the conceptual model, one of the simulation study's objectives was to build a flexible simulation model that can allow modeling different site layouts, equipment settings, and piling sequences (see Table 2). Therefore, the implemented model was divided into two elements: (1) User input-data sheets and (2) JaamSim model generator. The input-data sheets are user-friendly excel sheets that allow the construction manager to enter specific production data such as piles coordinates, types and numbers of machines, and piling sequence. The model generator is a Python code script that imports site data from the input-data sheets and generates all JaamSim objects and constructs; then exports them into a JaamSim operable file that includes the code of the model. The results of the simulation model can then be analyzed in statistical analysis tools such as RStudio. Figure 22 describes the mechanism of the implemented piling simulation model. Figure 23 is a screenshot of the final model generated for the piling case study.

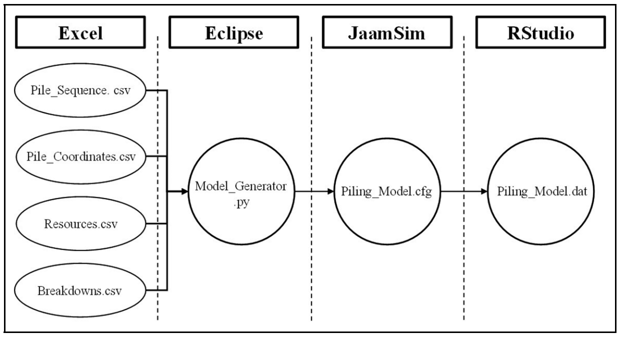


Figure 22. Model implementation steps.

9. Conclusion

Since the 1960s, extensive research effort has been undertaken to illustrate the powerful capabilities of simulation modeling to support the management of dynamic operations in construction projects. However, simulation application has been very limited in construction. Among the reasons for the limited simulation uptake in construction is the difficulty in implementing the available simulation solutions by construction managers, who usually lack the technical skills to understand and build simulation models. This paper contributes to the efforts to overcome the current limitations by presenting a construction-specific conceptual modeling framework to facilitate communications between construction managers and modelers in construction simulation studies. The proposed framework extends the HCCM, which is a conceptual modeling framework originally developed to support healthcare simulation. In this paper, we reported the process of building a simulation model for construction piling operations, from the conceptual modeling phase to the model experimentation phase. The piling case study provided a good opportunity to test the capabilities of HCCM in comparison to traditional queuing structures, as the project included complex entity relationships, with machines being moved between piles out of order to optimize schedule performance. By adopting the control aspects of HCCM, the researchers were able to represent a more realistic view of the decision-making mechanisms in the case study by explicitly capturing the relationships between entities and activities in a hierarchical structure. In addition, Presenting the conceptual model in an understandable form for construction managers and the simulation modeler helped reach mutual understanding and improved model credibility. Therefore, the findings of the case study demonstrated how the proposed framework can overcome some of the limitations in current construction simulation practices.

The computer model was implemented in JaamSim, which provided higher flexibility to model the control aspects of HCCM rather than forcing the modeler to make any assumptions to be able to use over-the-shelve software. Customized objects were added to JaamSim to account for the model logic and control aspects. In addition, the model was designed to accept input data from excel sheets that are accessible to construction managers. Python code was created to generate a JaamSim file for any set of inputs. This separation between model implementation steps allows any user with no knowledge in simulation modeling to easily manipulate input data to test the effect of different decisions, such as piling sequence and machine selection, on the system performance.

Several recommendations can be derived from the lessons learned of this case study. First, a domain-specific conceptual modeling framework is necessary to improve the utilization of simulation in the construction industry. This domain-specific framework can be developed by integrating the process of conceptual modeling within the current practices of construction management. Second, electronic means of data collection are very valuable to assist rapid and accurate representation of simulation input

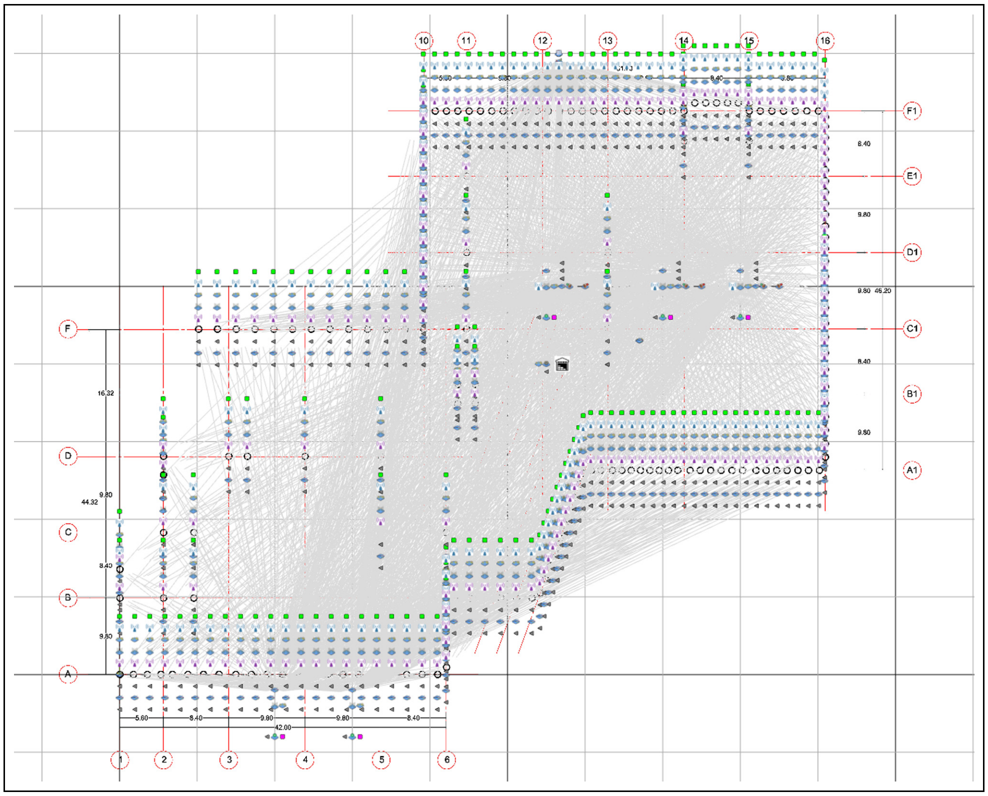


Figure 23. Screenshot of the JaamSim model for the case study.

data without the need for error-prone manual data entry methods. Considerable time was consumed in this study to transfer and validate the data from hand-filled forms into electronic data forms, especially with a muddy construction operation such as piling. Third, more research is required in the area of modeling site geology during piling operations. The method used in Werner et al.[91] to model the geology during tunneling construction operations using Bayesian updating and Hidden Markov chains can provide insight for simulating piling operations. The use of a similar method in modeling site geology can be presented as future research of this study. Fourth, due to the dynamic and risky environment of construction systems, it is necessary to design construction simulation models to be flexible to avoid tweaking the model to fit the predefined modeling objects in most of the available simulation software, which was fundamentally developed for other domains such as manufacturing and production systems.

The findings of this paper add to the growing body of knowledge in the field of construction simulation as it provides a detailed description of modeling piling operations supported with a case study from a complex construction project. In addition, it contributes to the general simulation research by demonstrating how the extended version of HCCM framework was followed to develop a conceptual model and how this conceptual model was then implemented in computer using open-source simulation software.

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