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A SCENARIO-BASED SIMULATION FRAMEWORK OF ON- AND OFF-SITE CONSTRUCTION LOGISTICS

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ABSTRACT

Constructing a building is a very complex process including a vast number and variety of participants, tasks, materials and elements. Interdependencies between the on- and off-site logistics frequently lead to an error-prone and chaotic process. However, good communication can reduce the effects by enabling the different actors to react. Simulation is a classic approach to understand complex problems and has been widely applied in the construction field. Nevertheless, the existing construction simulation approaches still do not consider the entire construction logistics process. This paper proposes a concept to model and simulate on- and off-site construction logistics, to facilitate the understanding of the boundary-spanning dependencies of both on- and off-site domains. A framework is provided, including simulation fundamentals (i.e. logistic BIM model), simulation data preparation (i.e. process pattern definition) and implementation of a scenario-based simulation. Finally, a discussion of the possible benefits and improvements of the proposed approaches is provided.

1 INTRODUCTION

A significant number of major contemporary construction projects all over the world suffer from delay and its consequences. In Germany recently there have been several public projects which have surpassed by far their time and cost estimation e.g. Berlin airport, to name only one striking example. Those colossal transgressions of the estimated costs lead to general incomprehension in society. In 2013, the German Federal Ministry of Transport and Digital Infrastructure initiated the "Construction of Major Projects" Reform Commission, which consisted of different experts to minimize these negative consequences of huge construction projects in the future. The Commission proposed a plan of work and emphasized the fair collaboration of all project actors. To achieve this aim Building Information Modeling (BIM) is suggested as a method to enhance communication, transparency and collaboration. Furthermore aspects like a more complete design before the start of the construction project and a project risk management are considered as measures for a successful implementation of a construction process (BMVI 2015).

There are many diverse reasons for delay in construction projects (Assaf and Al-Hejji 2006), one of which is logistics. At the moment in practice, these logistic processes are frequently not planned well enough. This is due to the deficiency of current planning approach in facilitating a boundary-spanning information flow and the lack of a holistic software platform. In addition, the delivery of information from one project partner to the other is mostly not transparent. A supplier who cannot deliver a product due to the shortage of a raw material (RM) normally will not inform the construction manager instantly.

To the contrary, the supplier will try to fix the problem alone and hence hinders the construction manager to cooperate in the solution of the problem. To solve it, both the project participants´ attitude and the antagonistic contracting relationship should be changed in practice. For instance, a contractual penalty for a delay could be lower if the supplier proofs that all information was passed instantly to the construction manager. A win-win situation is created like this because the supplier pays less penalty or no penalty and the construction manager can react adequately and minimize the consequences due to his perception.

Reviewing the construction logistics research, on-site logistics planning has been well discussed and developed, e.g. Critical Path Method (CPM), Location-based Management for Construction (LBMS) and Advanced Work Packaging (AWP) (Kelley 1961; Kenley and Seppänen 2010; Ponticelli, O'Brien, and Leite 2015). Since the early 1990s, persistent efforts have been made to explore how manufacturing concepts can be transferred to the construction context. The importance of Supply Chain Management (SCM) for improving the performance of projects has also been recognized (e.g. Vrijhoef and Koskela 2000). Furthermore, the off-site planning and control for on-site construction has been gradually improved in the logistics sector. Although a series of approaches for modeling general construction supply chain or logistics have been proposed (e.g. Azambuja and O'Brien 2009), the boundary-spanning relationship and dependency between on- and off-site construction logistics remain overlooked areas of research (Arashpour et al. 2016).

To establish a robust link between on- and off-site construction logistics with predictive information, a reliable simulation is required. Construction simulation techniques are well-established and mature (Hajjar and AbouRizk 2002) and hence provide suitable tools to analyze complex circumstances and solve problems efficiently. For more than three decades event-based simulation has been utilized to outline construction operations (Martinez and Ioannou 1999). Though simulation is not frequently used in practice because the effort of creating suitable simulation models is very high (Szczesny and König 2015). Nevertheless, nowadays the creation of event-based simulation models can be simplified using 3D BIM models (Wu et al. 2010; Xu, AbouRizk, and Fraser 2003).

The approach of four-dimensional (4D) modeling (3 dimensions plus time) has been applied in the construction field to support management tasks (Hartmann, Gao, and Fischer 2008). As a concept manifestation, 4D BIM is worldwide fast developing based on the unified format of Industry Foundation Classes (IFC) in recent years (e.g. Han, Cline, and Golparvar-Fard 2015). It provides access for as-designed models to object's progress data, and creates an adjustable task-object relationship for automatic updates, which support the calculation of the rate of progress and color coding of the actual and planned progress (Hamledari et al. 2017a). However, the application of 4D BIM is capable but has not met its full potential to improve construction logistics planning and monitoring. Linking off-site with on-site logistics and considering the cascading effect have the potential to turn reactive 4D BIM into proactive. To promote and make full use of current 4D BIM in the logistics field, a simulation-based framework for the on- and off-site logistics is introduced in this paper.

2 PROBLEM STATEMENT

In this paper, the scope of logistics is limited to the planning and control of the material flow and related information flow between the point of origin (raw material) and the point of consumption (built construction components). To streamline the entire construction project a local optimization of processes is not always the best choice. Depending on the nature of on- and off-site production, this paper divides the construction logistics into two domains, as shown in Figure 1.

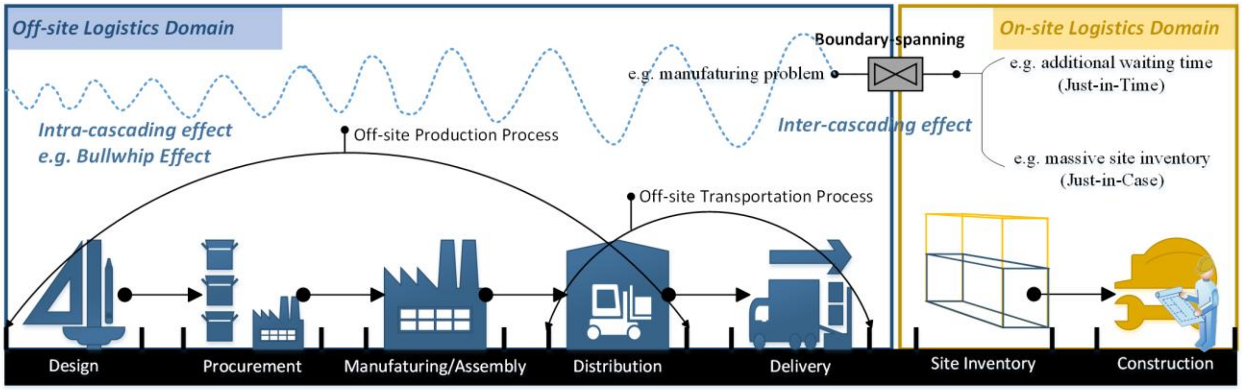

Figure 1: Domains and cascading effects of the on- and off-site construction logistics.

The off-site logistics domain includes possible processes of design, procurement, manufacturing or assembly, distribution and delivery from the planning and production of raw materials through to the delivery of the final products (e.g. prefabricated building elements). These processes can further be subdivided into off-site production and off-site transportation. The on-site logistics domain focuses on the processes and activities, which occur in the environment of construction site. The end of the off-site logistics (delivery of the final products) is the start of the on-site logistics (transfer the final products into building components). Actually, the on-site construction relies heavily on the off-site logistics due to the boundary-spanning relationship, which can be defined as the cascading connection (Arbulu and Tommelein 2002). The uncertainty in off-site production processes may cause e.g. risks of supply delay, error or cost raising, defects and additional completion cost. To avoid these transferred risks, it is necessary to understand the cascading effect caused by the off-site logistics. There are two types of the off-site cascading effect:

Intra-cascading effect: is the internal effect within the off-site logistics domain, which can be interpreted as the Bullwhip Effect and dictated by demand forecasting, production constraints, price fluctuation and storage capacity etc. It requires more specific requirements and higher Level of Information (LOI) from on-site sector to keep a positive result.

Inter-cascading effect: describes how off-site risks can transform to on-site risks, which depends on which boundary-spanning strategy is chosen. For example, if the Just-in-Time strategy is applied, once the delay occurs at one stage of the off-site logistics process, the additional waiting time for on-site construction will immediately increase. Alternatively, if the Just-in-Case strategy is applied, more site inventory may be planned.

As discussed above, a better understanding of the boundary-spanning relationship and dependencies of both domains is required. Based on it, an effective approach to predict events of off-site delay can be developed and used to avoid negative cascading effects caused by off-site delay events. This paper pays attention to both on- and off-site logistics domain, and tries to develop a simulation-based framework to reach the final goal as discussed. This paper first makes efforts to build up the fundamentals of logistic simulation i.e. a logistic Building Information Modeling model (logistic BIM model). Predicting an off-site delay event is important for the whole construction logistics, thus Customer Order Decoupling Point (CODP) classification is applied for the definition of production process. Meanwhile, the modularized transportation process and construction process are also integrated into the logistic BIM model. After a series of process patterns and their syntagmatic relation are identified, the boundary-spanning constraints are defined. With the complete concept of the logistic BIM model, a scenario-based simulation is introduced to find out countermeasures to avoid negative effects from off-site to on-site.

3 FRAMEWORK

A robust connection of the on- and off-site construction logistics needs sufficient product-process mixed information (Sacks 2016) and it is hard to achieve without a precise modular structure of processes. Consequently, it is useful to establish a custom BIM model as the fundamental of the on- and off-site logistics simulation to provide complete product (with an information enriched model) and process (in modularized pattern) information.

To be able to gain profit of the integrated logistics, it is necessary to procure, store and process information about the processes first. Further this research proposes to develop a logistic BIM model (see Figure 2), which will be used to link the logistic processes dynamically. When the links between the process patterns and the connection to the model are established, a simulation can be set up and performed. It provides information that is more useful to the decision-makers and enables them to choose measures, which limit the potential risk of delay.

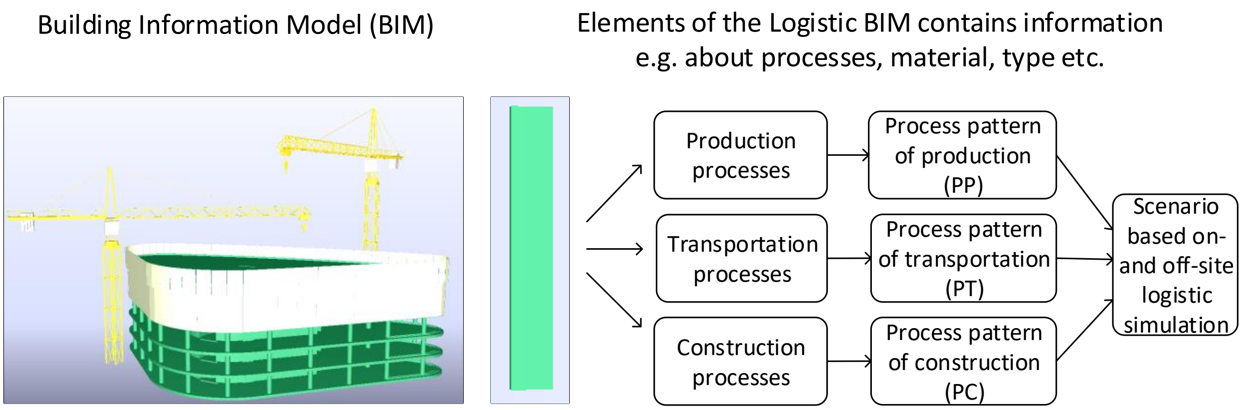

Figure 2: Overview of the simulation framework for the on- and off-site construction logistics with a logistic BIM model.

In the logistic BIM model, each construction element is linked to all the essential parameters of the construction processes, including type, dimension, material, location, productivity rate of construction and required resources etc. Additionally, information about production and transportation processes should be added into the logistic BIM to establish a connection between the on- and off-site logistic domains. If there is a problem with the production of a precast element, it is essential to know whether the following processes can be adjusted. For instance, the transportation method or even the construction sequence or method could be changed to recover the time loss. In conclusion, the project time is directly influenced by the three different process pattern types for production, transportation and construction.

In order to support the simulation of on- and off-site logistics, it is important to extract the process pattern from the real practice as: process patterns for production (PP), process patterns for transportation (PT) and process patterns for construction (PC). Among these process patterns, PC can be directly extracted from the basic 4D BIM (Hamledari et al. 2017b). PT and PP belong to the off-site process patterns, which need to be defined according to the existing principles in their respective fields.

3.1 Classification and Subdivision of Off-Site Process Patterns

Defining PP is not a simple task for the construction industry, because every construction project has a vast number and variety of construction components, which involve a series of corresponding off-site production processes. According to the practical experience, the complete material flow or workflow indeed can be defined with unique production features (e.g. concrete reinforcement, power distribution equipment etc.). However, this kind of detailed pattern of one specialized product is hard to apply to other types of construction components. If we conduct an on- and off-site logistics simulation based on this method, we need to define thousands of PP of various types.

This paper applies an extended typology of CODP from Wikner and Rudberg (2005) as the classification criteria to define PP. CODP is the most important point to turn planning-driven process (rely on forecasting information) to pull order-driven process (rely on real-time information). The basic typology of CODP includes four types, i.e. engineer-to-order (ETO), make-to-order (MTO), assemble-to-order (ATO), and make-to-stock (MTS) (Olhager, Rudberg, and Wikner 2001). The different CODP types have different features about lead-time float interval, stock control strength and specification/model LOD. For instance, ETO and MTO contain higher lead-time float possibility, while ATO and MTS usually hold a certain amount of site inventory. The extended CODP classification integrates the production dimension (subscript PD) and engineering dimension (subscript ED). In addition, engineer-to-stock (ETS_{ED}) and adapt-to-order (ATO_{ED}) have been added for design stage. It is possible to define PP according to an extended CODP classification criteria, in which every CODP type reflects a customizable process module.

For example, according to the basic CODP typology, every element can firstly be classified as a certain type e.g. ETO (see Figure 3). Then it will be subdivided (e.g. ETO = ATO_{ED} + MTO_{PD}) based on the extended CODP classification criteria. Finally, this specific PP can add detailed logistic information about off-site production and sstore real-time information in the logistic BIM model.

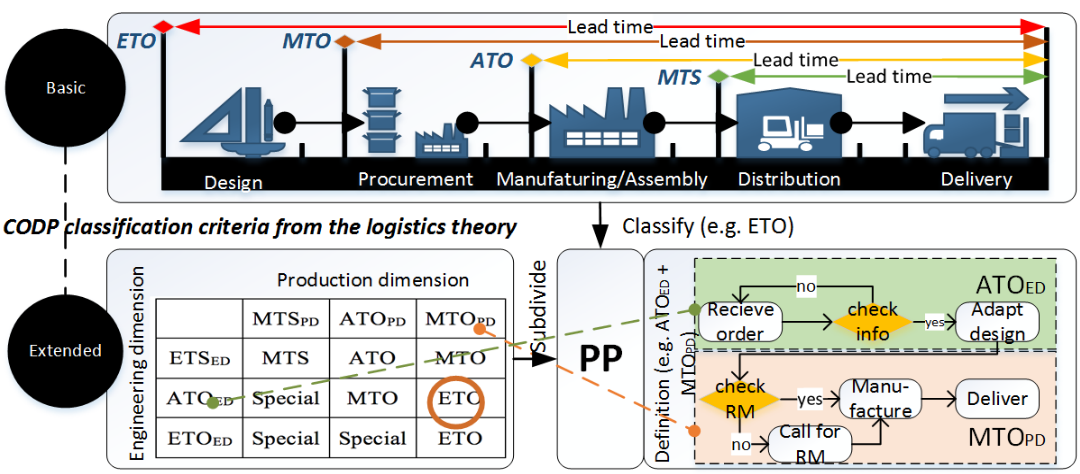

Figure 3: Definition of PP based on an extended CODP classification criteria.

This method defines a series of basic process patterns to build modularized production processes. It will not conflict with modelers/planers' own production process or custom-made production process, because the provided basic process patterns can be disassembled and adapted to the specific project. Even for an already existing custom-made production process, it is helpful to define checking points along the whole process according to the basic principle of CODP.

The benefits of classification and subdivision of PP according to extended CODP classification criteria are: (1) an expedient introduction of off-site production processes to support on-site construction management; (2) a higher extendibility and modularity for a computer simulation.

Transportation is the intermediate process between the off-site production process and on-site construction process (see Figure 4). A quick response to changes and a lower cost within due time are more important than the transportation flow itself. Therefore, PT should focus on adjusting itself according to a series of dynamic parameters (e.g. vehicle, batch size and route etc.), which may alter because of disruptions of the off-site production.

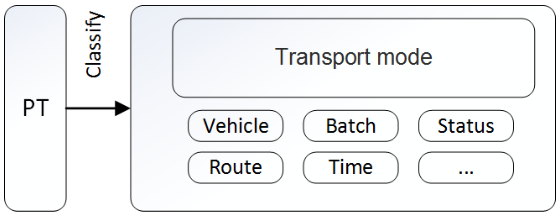

Figure 4: Definition of PT.

On-site construction processes are various and complex, however, there are already several approaches (e.g. CPM and AWP) to control and promote them. There is no need to redesign construction process patterns with 4D BIM, but it is essential for the on- and off-site logistics to build a robust connection among PP, PT and PC.

3.2 Integration of On- and Off-Site Process Patterns

As previously stated, PP and PT are the precursor of PC. A robust connection of the on- and off-site construction logistics, operationally means a good integration of PP, PT and PC. PC is well defined with current 4D BIM and it can provide basic information to PP through the same BIM element, as illustrated in Figure 5. The link of the modeled process information with the BIM element enables a generation of a construction schedule. With this construction schedule and further information like a delay, a simulation can be conducted. As a result, an alternative process configuration can be selected to avoid delay. Adding dynamic logistics information to 4D BIM leads to a faster adaption of the processes to an issue and hence to shorter project times.

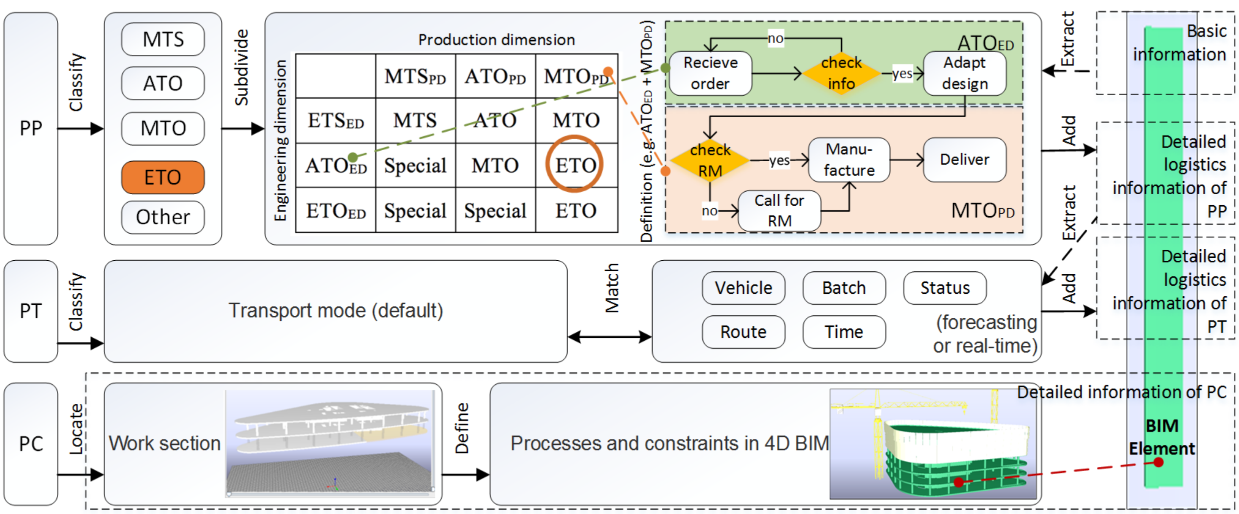

Figure 5: Overview of integration of PP, PT and PC.

After classifying and subdividing PP, this BIM element can get detailed logistics information of off-site production by selecting the corresponding PP. Then the transport method can be chosen according to updated logistics information, and all the related parameters can be calculated and added to the logistic BIM model. Finally, the complete logistic BIM model is capable to support the integrated functions, e.g.

collaborative decision-making for construction change. However, the logistic BIM model should be developed gradually. This paper takes a work section of bucket foundation and column as an example to explain how off-site logistics process can be integrated with on-site logistics process by applying above mentioned process patterns in the logistic BIM model.

Besides the definition of PP, PT and PC, another essential step is building a link among them. There is a possibility to create a link in the logistic BIM model through the IfcRelAssignsToResource relationship. Figure 6 shows an example about how to build a link between PP and PC/PP for the logistic BIM model:

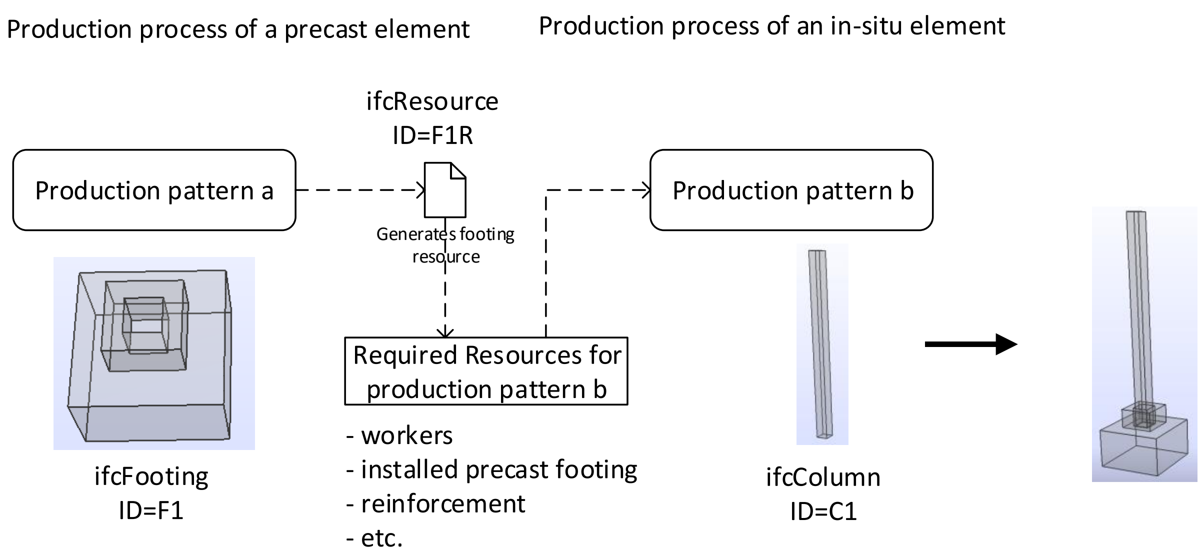

Figure 6: An example of bucket foundation and column to explain the linking concept with IFC.

It is just a general example of the concept of creating a link with IFC format. In this example, a precast bucket foundation can be treated as one of the resources of a cast-in-place column, and the production process pattern a (PPa) can be linked with construction process pattern b (PCb) by creating an ifcResource (ID: F1R).

From the perspective of simulation, it is also possible to create a series of constraints to specify this link. This research applies SiteSimEditor (Szczesny and König 2015) to provide a solution. As shown in Figure **7**, there are three types of constraints, which are necessary to be defined.

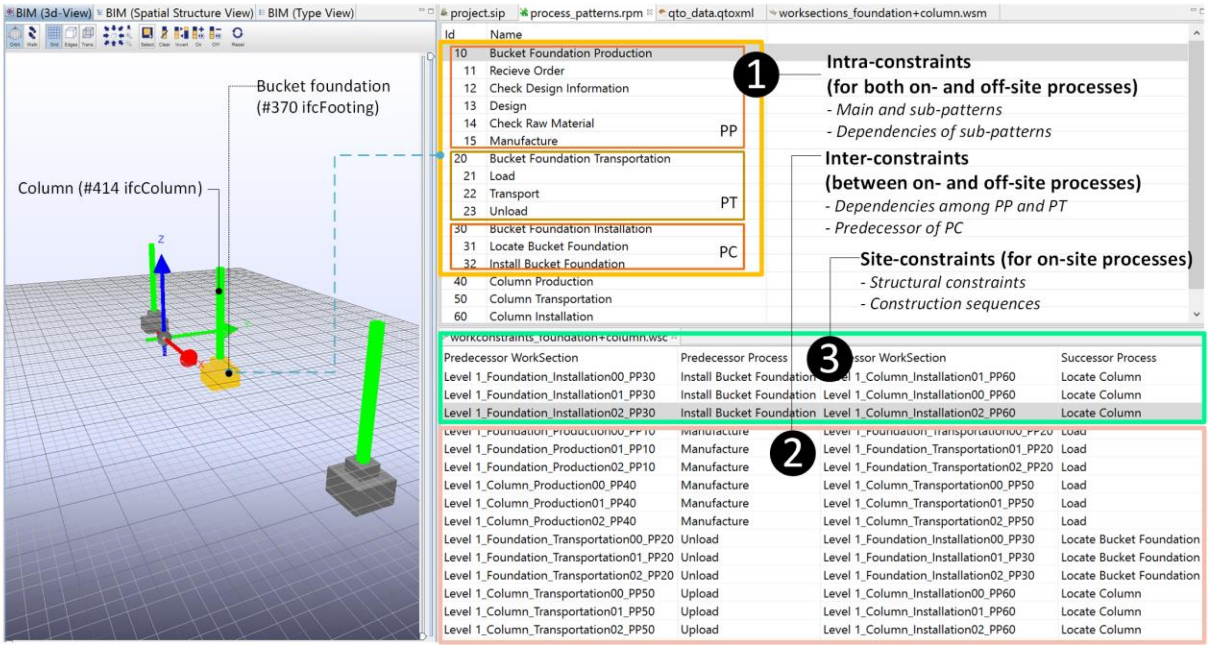

Figure 7: Link of PP, PT and PC defined by constrains in the SiteSimEditor.

Type 1 intra-constraints: are automatically defined when the process patterns are created. They describe the dependency among all the defined templates of process pattern, including both on- and off-site process templates. They are the most fundamental constraints.

Type 2 inter-constraints: are responsible for defining the boundary-spanning relationship, to prescribe the dependency between production process and transportation process and to determine the off-site predecessor of a construction task.

Type 3 site-constraints: focus on the on-site processes, which contain the structural constraints (e.g. column is supported by the bucket foundation) and construction sequences (e.g. sequences for different work sections).

The composition of these three types of constraints contributes to a strong linkage among different process patterns in the SiteSimEditor.

3.3 Scenario-Based Simulation

A problem can occur at any point along the process flow of on- and off-site construction logistics. The objectives of simulation is to: (1) first detect all the error-prone points with their probability of occurrence; (2) then search solutions for the detected problem and report a final risk value.

Based on a logistic BIM model with predefined process patterns, the first objective can be achieved by a mature stochastic simulation. However, to choose an appropriate solution is more complicated. It involves different supply strategies and adjustability of construction sequences. Therefore, a scenario-based simulation is suggested in this paper to compare various potential solutions. Figure 8 shows the basic steps of the simulation.

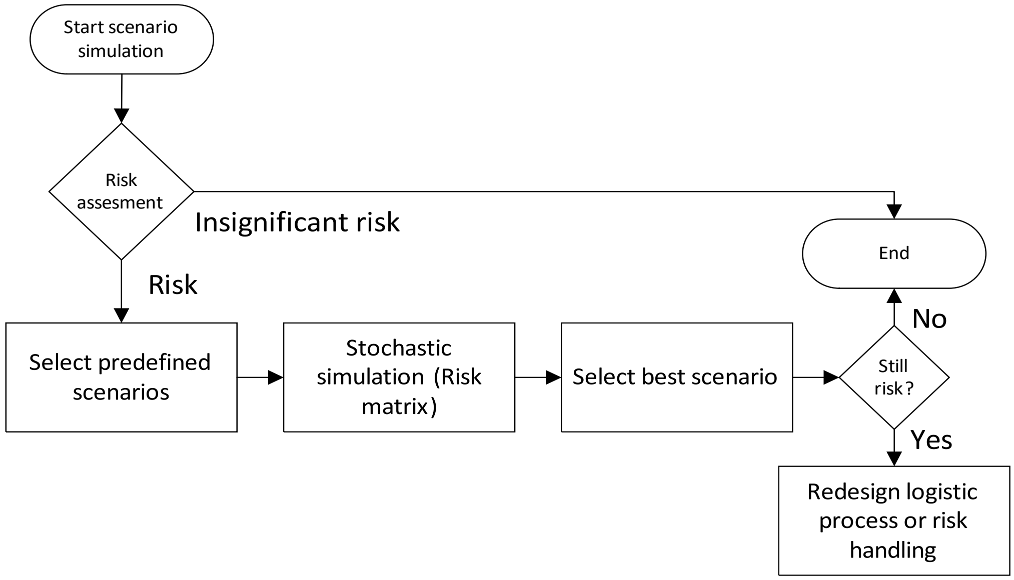

Figure 8: Workflow of the scenario-based simulation of an error-prone point.

The first step after initialization is a risk assessment of the entire construction logistics process. It aims to detect all the significant risk points according to a risk threshold. The risk threshold is defined by the probability of problem occurrence and the construction project stakeholders' risk attitude towards the off-site production.

In the following a special focus lies on the dynamic and modular connection between the processes. Therefore, a variety of pre-defined scenarios is calculated. A scenario is a combination of process patterns of the three logistic domains in construction logistics. If there is a high risk of delay in any of the processes, a rule-based selection of a successor process is conducted. For example, a risk of delay in a production process may be compensated by a transportation process that is more expensive but faster or more flexible than the standard transportation method. Nevertheless, in many cases the risk of delay cannot be compensated entirely by the transportation process. Is that the case, a change in the construction sequence or process may provide a reasonable means to further reduce the risk of delay of the production process. Subsequently, the best scenario is selected due to a weighted combination of costs of delay risks and costs of risk mitigation and hence considers the risk-cost trade-off.Once the best scenario is selected it has to be evaluated whether the remaining risk is acceptable according to the project risk management. If it is, the design of the logistic processes is determined, otherwise the risk management has to develop further strategies either to avoid processes with risks or to provide means for the containment of the potential consequences.

The example of bucket foundation and column construction is also taken to explain the scenario-based simulation workflow in SiteSimEditor, as shown in Figure 9.

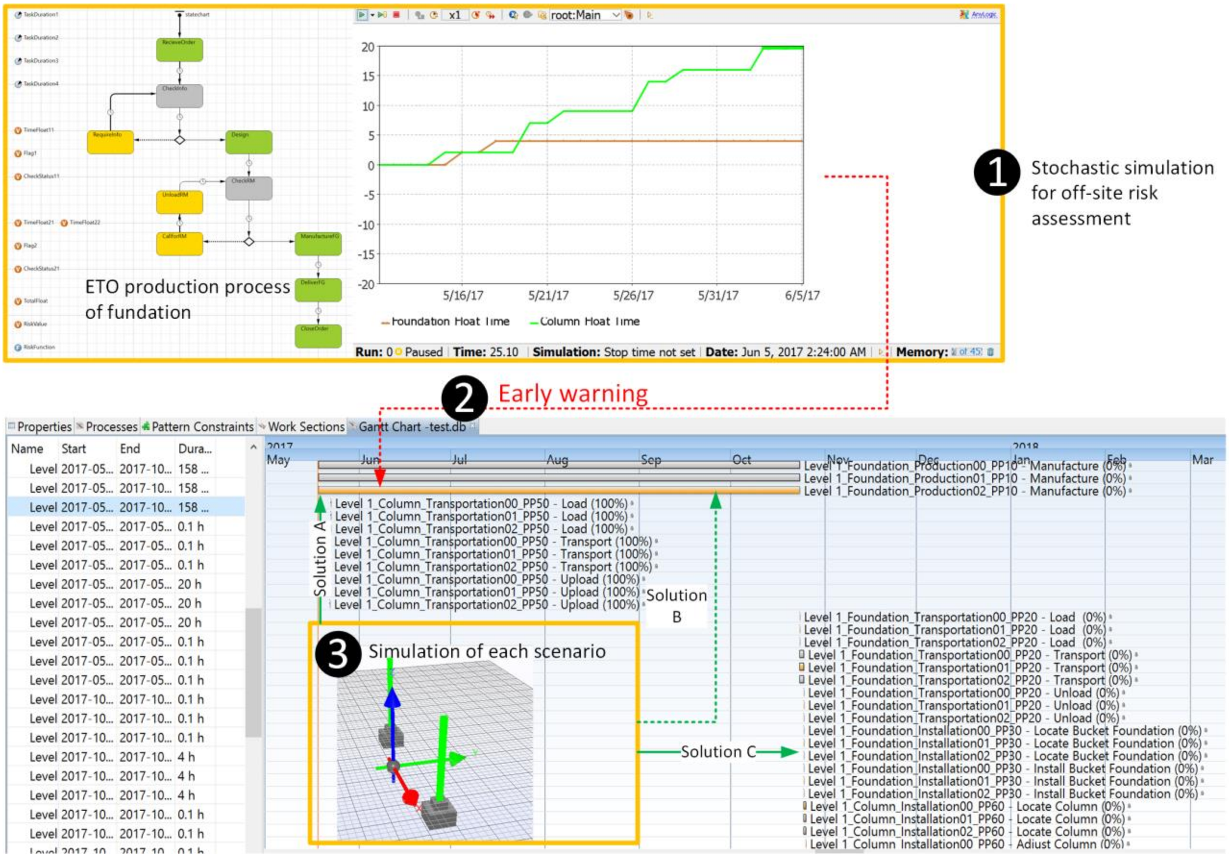

Figure 9: An on- and off-site logistics simulation example of bucket foundation and column.

In this example, an off-site risk of delay can be detected through the stochastic simulation in the early stage. Then an early warning is highlighted in the 4D logistic BIM model, which is a trigger to launch a scenario-based simulation. In this step, each possible predefined scenario (e.g. replace supplier or change on-site construction sequence) is simulated and related risk value and probability of occurrence are calculated and recorded in the risk matrix. Next, all the feasible solutions or ineradicable risks are reported, which may belong to different scenarios.

4 CONCLUSION AND OUTLOOK

The ICT-enabled construction logistics systems or tools (e.g. 4D BIM) have not met their full potential. One of the most important reasons is the lack of understanding of the boundary-spanning relationship and dependencies of both on- and off-site logistic domains. This paper made efforts to explain the concept of the on- and off-site construction logistics and proposed a framework, which involved 4D BIM (as the simulation fundamental), CODP classification (for data preparation) and a scenario-based simulation.

Although this scenario-based simulation framework is established, there is a series of follow-up research work to verify and to promote.

First, the stochastic simulation for off-site risk assessment needs to be improved, i.e. the process pattern needs to be defined with more details and the probability distribution of every bifurcation point needs to be investigated in practice.

Second, the integration of on- and off-site processes needs to be strengthened, while the constrains definition needs to be simplified and modularized.

Third, it is necessary to adapt current scheduling approach to the on- and off-site construction logistics. Current scheduling in SiteSimEditor for integrated logistics is hard to ensure the leading character of on-site construction. It is easier to find a major control object by setting the off-site logistic schedules as a reference of the on-site construction schedule. It means only when the risk (e.g. risk of delay) from off-site is detected, the off-site schedules should be unfolded and checked.

In the future, applications like real time web-based simulation of the entire logistic process could be developed. With such tools, all project partners would be immediately informed if a delay occurred. The delay could be either automatically recognized with the use of sensors or a responsible person could enter the delay in the web-application. An alternative schedule could be generated automatically and in case of more severe problems, a visual alert could highlight the urgency.

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