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A FRAMEWORK FOR AUGMENTING 4D VISUALIZATION OF CONSTRUCTION PROJECTS WITH SCHEDULING UNCERTAINTIES

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Abstract: Along with the advent of Building Information Modeling (BIM) came the rising popularity of visualizing not only the product of a project but also the underlying activities leading to such products. For this purpose, the schedule of a project is coupled with its 3D model to visualize how different components of a project are placed during the construction, creating what is known as a 4D model. Through enabling a detailed visualization of the construction processes, 4D models allow the scrutiny of a chosen construction method or schedule for the feasibility in view of the space required for the execution of different tasks. Nevertheless, while there exist several methods to generate a stochastic schedule of a construction project, the de facto practice in the generation and application of 4D models is based on the application of deterministic schedules. Accordingly, the current 4D models cannot represent the uncertainties associated with the start and end time of various construction activities. As a result, any decisions made about the constructability of a project on account of the existing 4D models ignores the risks of delays in the completion of activities and the ensued potential constructability conflicts. This research aims to develop a framework to effectively visualize the risk of constructability conflicts associated with the construction projects. In other words, using the stochastic scheduling paradigm, the proposed framework enables augmenting the existing 4D models with information about the probability of each elements being under construction at any given time. A case study is developed to integrate the stochastic schedules coming from the discrete-event simulation tool with the 3D model of the building and further visualize the scheduling uncertainty in the 4D visualization. It is shown that the proposed method has a strong potential to provide inputs for more precise constructability analysis.

Keywords: 4D Visualization, Scheduling Uncertainties, Building Information Modeling, Risk Visualization, Clash Probability

1 INTRODUCTION

Building Information Modeling (BIM) has had a significant impact on the way buildings and infrastructures are designed, built, managed, and maintained in the Architecture, Engineering, and Construction (AEC) industry in the past decade (Volk et al. 2014). One of the many applications of the BIM is the ability to integrate the scheduling of the construction work with the 3D model of the building to generate the 4D model. Next to offering the possibility for more precise coordination of activities and logistic planning, the 4D visualization allows for a comprehensive constructability analysis of the project. It can be used to avoid hard or soft conflicts between building components or between the construction workspaces (Ganah et al. 2005, Hartmann and Fischer, 2008, Wang and Leite 2016). Even further, researchers have suggested the integration of other layers of information (e.g., cost, safety, quality, etc.) with the 4D models to generate what is known as nD models (Ding et al. 2012, Ding et al. 2014).

The backbone of a reliable 4D model is an accurate schedule with a sufficient level of detail that matches the requirements of the expected spatial analysis. Given the predictive nature of schedules, it is important to highlight that every schedule comes with a degree of uncertainties associated with the expected start time and duration of various activities. However, while there exist several methods to capture these uncertainties using stochastic scheduling methods (Lee 2005, Lee and Arditi 2006, Lee et al. 2009), the current state of the practice in 4D modeling is based solely on deterministic schedules. As a result, even if the stochastic schedules are available, the managers and analysts need to generate deterministic schedules using most probable, optimistic, or pessimistic durations. Now, although the generated 4D models would essentially represent the degree of certainty embedded in its underlying deterministic schedules, the constructability analysis that ensues from these models would hardly carry the level of credibility expected of them. In other words, a slight modifications or deviation in the schedule can render a constructability conflict found in a 4D model invalid or vice versa. Therefore, it is important to incorporate the scheduling uncertainties into the 4D model so that more realistic perception of constructability conflicts can be obtained.

While the authors have previously presented a method to calculate the probability of scheduling conflicts using the integration of Discrete-Event Simulation (DES) and 3D models (Mawlana et al. 2015), the proposed method was presented as an addition to the mainstream 4D modeling practices. On this ground, the present research aims to develop a framework for the incorporation of scheduling uncertainties in the regular 4D modeling routines so that managers and analysts can observe the impact of variability in the duration of the activities on the potential areas of conflict.

The remaining of this paper is structured as follows: first, the proposed framework is elaborated. Then, the implementation and case study is discussed. Finally, the conclusions and future work of the authors are presented.

2 PROPOSED METHOD

Figure 1 represents the proposed framework. As shown in the figure, the process starts by generating the DES model of the pertinent construction processes. DES model can capture the interaction between various activities and how resources flow in between these activities. As an output, DES model can generate the distributions associated with the start and end time of various activities, as shown in Figure 2.

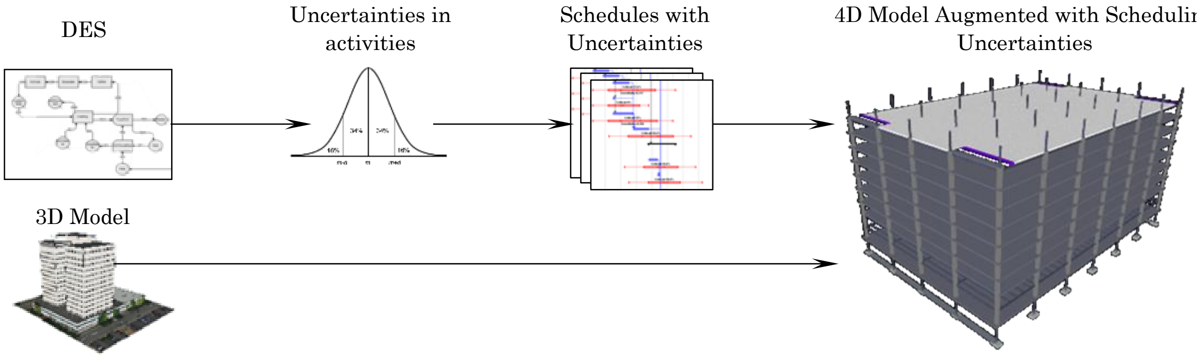


Figure 1: Overall framework for the augmenting the 4D models with scheduling uncertainties

As shown in this figure, it can easily be determined what is the start (or end) time associated with a certain level of confidence (e.g., 75%, etc.). It should be noted that the characteristics of these distributions depend on: (1) the distributions used in the modeling of the durations of various activities in the DES model, (2) the structure of the activity network and the resource flow between various activities, and (3) the number of simulation replications.

In the first step, as shown in Figure 3, the analyst decides on the resolution of the required uncertainty visualization. This can be done by setting an interval for the level of confidence (e.g., 10%, 20%, 30%, …, 100%) or defining a strategically designed set of confidence levels (e.g., 10%, 50%, 75%, 90%, 100%). In parallel, the simulation model that represents the operation is run for a certain number of replications. The simulation model results in a series of schedules that are created using the randomly generated durations of the activities. Each of these durations has its own probability, and it is not necessarily the same probability as the total project duration. That is, these schedules are not necessarily homogenous, in the sense that each of right-out-of-the simulation schedules can be based on the integration of activities with different levels of confidences. To be able to generate homogenous schedules later, the simulation-generated schedules are disassembled into activities and a pool of activities with different confidence levels for the start and end time is generated.

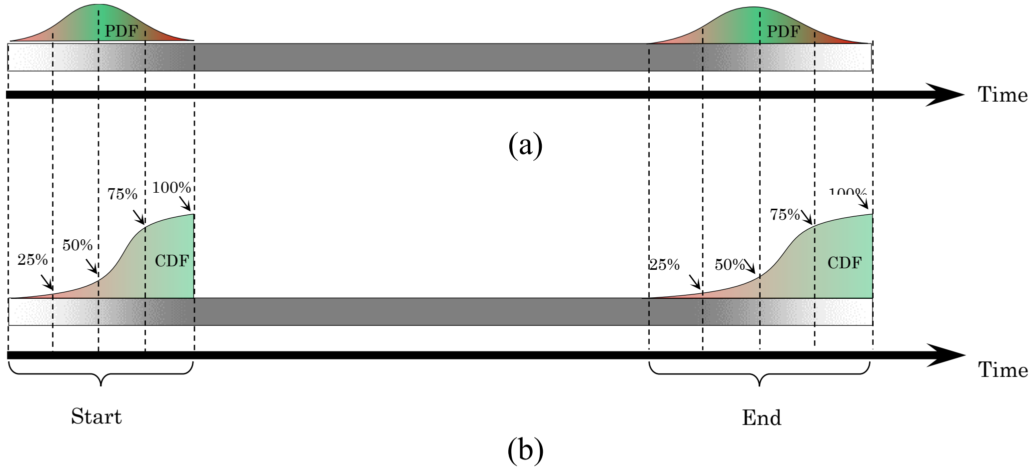


Figure 2: Schematic representation of uncertainties in a task shown as (a) probability distribution function, and (b) cumulative distribution function

After defining the resolution and generating the pool of activities, the activities' duration corresponding to a certain confidence level are combined to generate a homogenous schedule associated with that level of confidence. For example, the start and end time with 50% probability of each activity are integrated to generate the schedule that represents the 50% confidence level. The important point is that since the task dependencies are already captured in the DES model, it is enough to arrange the activities chronologically to generate the schedule. By doing this, all temporal dependencies are fully embedded in the generated schedules. Depending on the resolution, this step is repeated until all confidence levels are addressed.

In the final step, the multiple schedules need to be integrated with the 3D model of the building to generate the 4D model of the project which is augmented by the scheduling uncertainties. The integration of schedules with the 3D model is done through associating the 3D building elements with the activities in the schedule using one-to-one (i.e., a single element is placed as a result of an activity) or many-to-one (i.e., many elements are placed as a result of an activity). It is important to note that depending on the level of the detail of the schedule and the 3D model, there can be several activities in the schedule that do not result in visualizable products (i.e., building elements). One way to think of the level of detail is by comparing a summary schedule with the look-ahead schedule. The selected level of detail is important because it will impact the variables of generating the schedule and performing the clash analysis.

Figure 4 depicts the schematic representation of a 4D model that is augmented with the scheduling uncertainties. As shown in this figure, at any given point in time, the visualization not only shows the completed elements (i.e., gray components in the figure) but also the components that are likely under construction with different levels of confidence. For instance, components illustrated in dark red has only 5%~15% chance of being under construction, while this value increases to 95%~100% for the components in dark green. It should be noted that the number of steps in the risk spectrum and the interval between the uncertainty level is a direct product of the resolution determined by the analyst in the previous step.

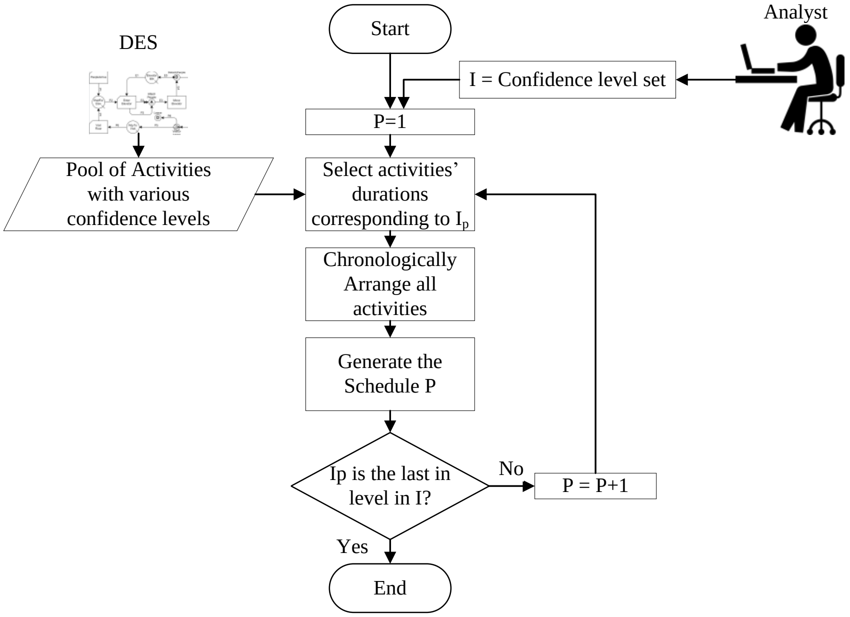


Figure 3. Flowchart of Generating the Stochastic Schedules

The same principle can be used to define the workspaces required for completing the placement of construction elements and develop the stochastic 4D models. The application of 4D model augmented with the uncertainties for the purpose of clash detection between workspaces has the main advantage of describing the constructability conflicts in terms of likelihood of occurrence. Principles of calculating the conflict likelihood are elaborated in the previous work of the authors (Mawlana et al. 2015). Nevertheless, a brief discerption of the method is presented below for completeness.

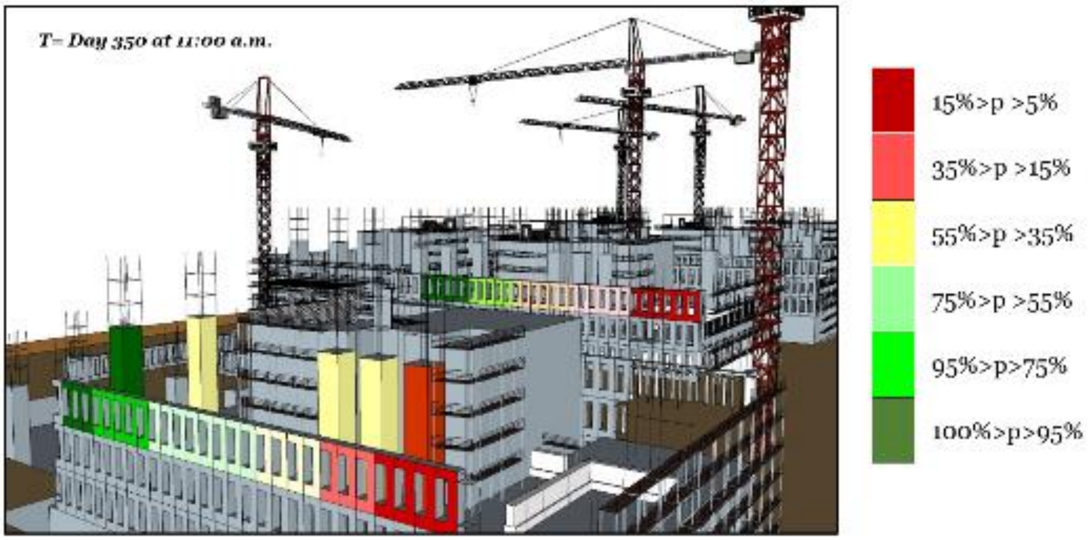


Figure 4. A schematic representation of 4D visualization augmented with scheduling risks

3 PROBABILISTIC SPATIOTEMPORAL CLASH ANALYSIS

It is crucial to analyze the behavior of construction operations and workspaces in the presence of uncertainties in the schedule. Probabilistic spatiotemporal clash analysis refers to the process of examining the 4D model to identify the potential spatiotemporal clashes that may occur due to the schedule uncertainties and estimating their probability of occurrence. As mentioned earlier, the level of detail would impact the variables used in the clash analysis.

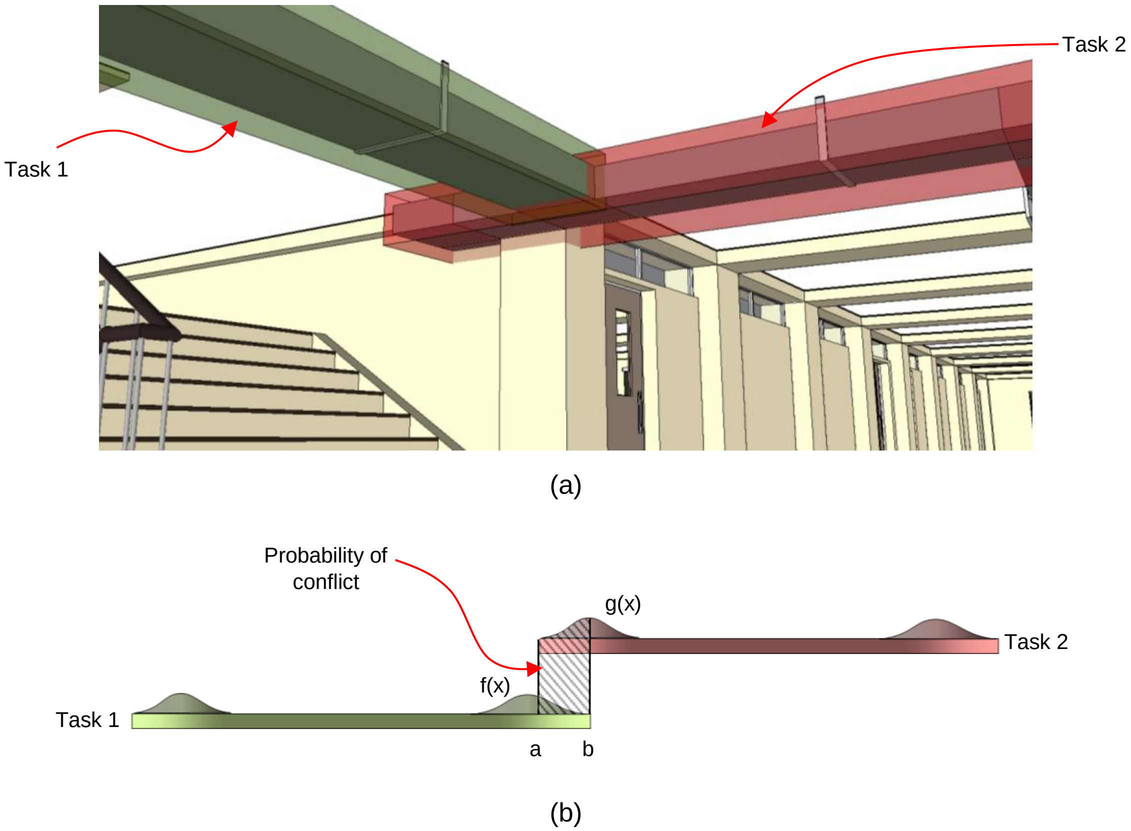


Figure 5. (a) A schematic representation of conflicting tasks and (b) the mathematical representation of the conflict

Identifying potential spatiotemporal clashes is done by studying the overlap between the distribution of stochastic durations of the tasks that have a spatiotemporal conflict between their required workspaces. In theory, the two tasks would clash if: (1) one clashing task starts before the end of another clashing task; and (2) two or more clashing tasks start at the same time. In other words, if the start and/or end distributions of one task overlaps with start and/or end distributions of another task, a clash would occur. The clash probability is calculated through the concurrent consideration of the start and end time density functions of the clashing tasks.

Figure 5a presents a schematic representation of an instance of such a clash. In this scenario, the two HVAC ducts are being installed. As shown in the figure, the two ducts are connected but their installation should be coordinated in such a way that the installation of one is started after the completion of the other. This can potentially cause a spatiotemporal conflict. Figure 5b represents the relationship between the start and end time of the conflicting tasks. In such a case, the probability of conflict between the two tasks can be represented by Equation 1 (Mawlana et al. 2015). In this equation, f(x) and g(x) represent the probability distribution function of the activities, and a and b represent the earliest and latest point of conflict, respectively.

$$P = \int_a^b \int_a^x f(x)g(y)\,dydx \qquad \text{Equation (1)}$$

The acceptable level of risk (i.e., the probability of a clash) is determined by the risk attitude of the project manager or the planner. This value could range anywhere between 0% and 50% depending on the level of risk the planner is willing to accept in view of the attractiveness of the involved plan in terms of total cost and duration. Based on this analysis, one can select different starting times for the tasks involved in the clash in order to avoid or reduce the probability of this clash taking place. By changing the start time of a task, the overlap in the distribution functions is either reduced or eliminated. Keeping in mind that this shift might delay the project or cause other spatiotemporal clashes in the successor tasks. Therefore, this analysis is repeated until no further stochastic clashes are found or if the probability of the clash is accepted by the analyst.

4 IMPLEMENTATION AND CASE STUDY

To demonstrate the feasibility of the proposed method, an implementation is developed to generate the stochastic schedules from a simulation model. Stroboscope (Martinez 2016) is used to generate the DES model of the project and generate the distributions associated with the start and end time of various activities. Visual Basic for Application (VBA) within Microsoft Excel is used to run a Stroboscope model, import the distributions, and generate multiple schedules for a different level of confidences that can be later used to generate the 4D model according to the algorithm shown in Figure 3. As for the visualization, since the available 4D modeling tools (e.g., Autodesk Navisworks) do not support the feature for the concurrent simulation of multiple schedules, a way around is to assign different number of tasks to the same component in Autodesk Navisworks (2016) and associate each with an schedule with a different level of confidence level and a corresponding code color.

For the case study, a typical welded wire mesh installation for a concrete slab project is selected. Figure 6 represents the DES model of the operation used in this case study. In a nutshell, the operation begins by loading the sheets on a truck and transporting them to the construction site. Each pack contains three sheets and each time the crane hoists 4 packs to the floor where they have to be installed. Once on the floor, the packs are transported to the installation point where they will be unpacked and installed. The operation is supported by a crane to lift the packs, crews on the ground floor to rig the packs, and the installation crew on the floor who would unhook the packs and perform the installation. The assumption of the model is that the crane would place all the packs at the center of the floor and the crew would move the packs from there to the installation points. Also, it is assumed that the installation starts from corners to the center. Therefore, as time goes by the transportation and thus the installation time decreases. Nonetheless, since the uncertainty would have a snowball effect, as the process proceeds, there are more uncertainties involved with the starting and end time of each installation.

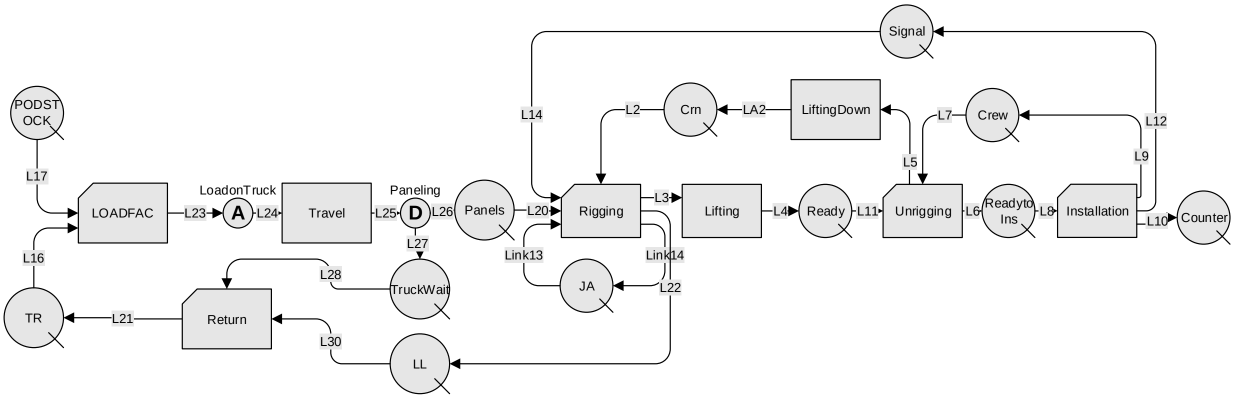


Figure 6. DES model of the installing slab panels for a residential building

As a demonstration of the concept, only the visualization of the installation activities is chosen. Figure 6 depicts the output of a stochastic schedule used for the purpose of 4D visualization for the resolution set of [10%, 50%, 70%, 90%, 100%].

As can be seen in Figure 6, the impact of the modeling assumptions (i.e., increased uncertainties and decreased durations) are captured in the schedule.

In the next step, the 3D model of the building, which is developed in Revit, is imported in the Navisworks and the linkage between the schedule and components are made. Figure 7 illustrates the snapshots of resulted 4D model augmented with scheduling uncertainty.

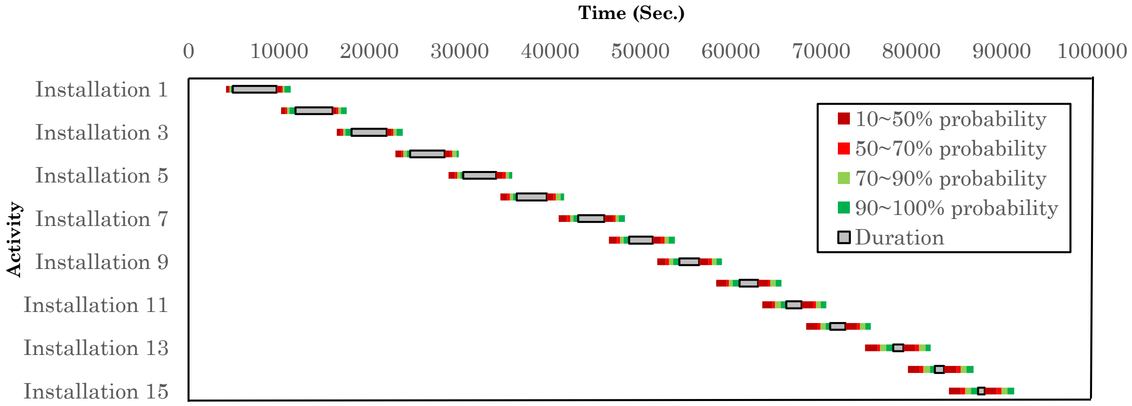
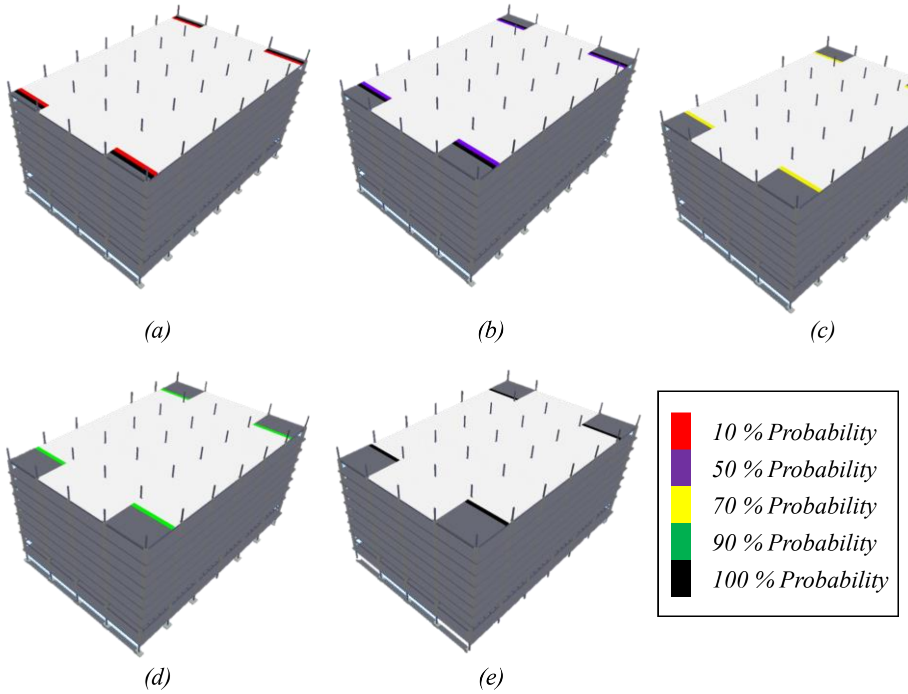


Figure 6. Stochastic schedule generated for 4D modeling



(a) (b) (c)

(d) (e)

Figure 7. 4D visualization augmented with scheduling uncertainties

5 CONCLUSIONS AND FUTURE WORK

This paper presented a framework to visualize the scheduling uncertainties through the application of stochastic modeling. The simulation models of the construction operations are used to generate the stochastic schedules that represent the start and end times of various activities with the associated confidence level. Then, these schedules are coupled with the 3D model of the project to produce the 4D model of the project. The generated 4D model uses a color coding scheme to represent the confidence level associated with the statues of various building elements at any given point in time. A case study was developed to demonstrate the feasibility of the proposed method.

In the light of the results of the case study, it is shown that the proposed framework allows managers and practitioners to visually review the impact of uncertainties on the progress of the project and to quantitatively measure the probability of various constructability conflicts. Using this framework, project managers and schedulers can be better sensitized to the possibilities of conflict between various simultaneous construction activities when developing the project schedule. Additionally, this framework can contribute to the logistic and transport planning on the site by allowing to avoid highly probable conflicts or undesirable congestion spots.

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