FORESIGHT: GRAPHICAL CONSTRAINT-BASED MODELING VERSUS SIMULATION

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ABSTRACT

An essential component of construction project planning is the development of a model of the construction processes. The Critical Path Method (CPM) is the most popular modeling method in construction since it is simple to use and reasonably versatile. Linear scheduling is an alternative popular approach that provides a strong visual understanding of the way project activities interact, but is limited to a very narrow class of projects. Discrete-event simulation is the most versatile of all existing modeling methods, but it lacks the simplicity in use of CPM, and the visual understanding of linear scheduling. Foresight is a new graphical constraint-based method of modeling manufacturing and construction processes designed to offer the simplicity in use of CPM, the visual insight of linear scheduling, and the versatility of simulation. Earlier work has demonstrated the modeling versatility of Foresight. This paper continues that work by comparing Foresight with discrete-event construction simulation methods in terms of ease-of-use and understanding. Foresight is shown to outperform Stroboscope (a sophisticated variant of the popular CYCLONE approach to construction simulation) in terms of the simplicity of the resultant models produced and their visual insight, for a series of case studies of earthmoving and concrete production systems.

Keywords: Construction Simulation; Discrete-Event Simulation; Excavation System; Concrete Production System; Foresight; Model Complexity; Stroboscope; Visual Insight.

1. INTRODUCTION

The last 100 years has seen the development of a diverse range of methods for modeling construction processes. An analysis of the genealogy of these tools (Flood et al. 2006) shows that they can be divided into three main categories: the Critical Path Methods (CPM); the linear scheduling techniques; and process simulation. Most other tools are either an enhancement or an integration of these three basic classes of model. For example, 4D-CAD and nD-CAD methods (Koo & Fischer 2000; Issa et al. 2003), where one of the dimensions is time, are strictly CPM models hybridized with 3D-CAD for visualization purposes.

Each of these three main categories of modeling are, unfortunately, only relevant to a restricted range of construction planning problems. The CPM methods (the most popular tool for planning, monitoring and control of construction processes) are well suited to modeling projects at a relatively general level of detail, but are limited in terms of the types of interactions they can consider between tasks (Harris & Ioannou 1998). Moreover, CPM models can become unduly complicated when used to model repetitive processes, and provide little understanding of the interactions between repetitive tasks. When presented in Gantt Chart format, a CPM model provides some visual insight into how a system's logic affects its performance (thus suggesting more optimal ways of executing work) but this is limited to event-based logical dependencies and their impact on time-wise performance.

Linear scheduling, on the other hand, is targeted at projects where there is repetition at a high level, such as high-rise, tunneling, and highway construction work (see, for example, Matilla and Abraham (1998)). These models are very easy to understand and represent the system's logic and its performance within a single framework. Consequently, they provide powerful visual insight into more effective ways of executing a project. For example, they show in graphic form how the relative progress of repetitive tasks can lead to conflict, for any key variable including time and physical work completed. However, linear schedules cannot be used to model non-repetitive work, and they include some simplistic assumptions which often make it difficult to model real-world repetitive processes. For example, velocity diagrams (a linear scheduling technique) cannot easily represent operations that follow different physical paths, such as two underground utility lines that interact at a cross-over point but otherwise follow different routes.

Finally, simulation (see, for example, Halpin and Woodhead (1976); Hajjar and AbouRizk (2002)) is very versatile in that it can in principle model any type of interaction between tasks and any type of construction process (including repetitive and non-repetitive work). However, the effort involved in defining and validating a simulation model means that in practical terms it is best suited to systems that cannot be modeled with sufficient depth and accuracy using CPM or linear scheduling. In addition, simulation models provide no visual indication of how a system's logic determines its performance. That is, performance is an output from the model after it has been fully developed and debugged; it is not an integral part of the model and therefore its dependence on the model's logic is not directly apparent.

Most construction projects include a variety of processes some of which may be best modeled using CPM while others may be better represented by linear scheduling or simulation. However, it is not normally practical to expect planners to employ more than one modeling method to plan, monitor and control a project. In any case, using several tools that are not fully compatible makes it impossible to seek a globally optimal solution to a planning problem. On the other hand, the alternative approach of using one tool to represent all situations (typically CPM) compromises the ability to plan and control work optimally.

Ideally, what is needed is a single tool that is well suited to modeling the broad spectrum of repetitive and non-repetitive construction work, that is highly versatile, provides insight into better ways of organizing work, and is easy to use. Earlier work (Flood, 2010) has proposed a new modeling paradigm, Foresight, that addresses the above issues. Foresight is being evaluated in an on-going study comparing its utility to the alternative construction process modeling techniques. This paper is concerned with part of this work, comparing Foresight to traditional construction simulation (specifically Stroboscope (Martinez, 1996)). Section 2 introduces the principles of the Foresight modeling system. Sections 3 and 4 compare the complexity of Foresight and Stroboscope models within two construction modeling case studies: variants of an excavation system, and a concrete production and distribution system. Section 5 provides a more general comparison of the Foresight and Stroboscope modeling systems in terms of their utility in developing and optimizing a model.

2. FORESIGHT MODELING

CYCLONE (Halpin and Woodhead, 1976) is the most widely published construction simulation language, and Stroboscope (Martinez, 1996) is the most advanced derivative of CYCLONE in terms of functionality. This study will compare the modeling utility of Foresight with that of Stroboscope. It is assumed that the reader has a basic understanding of discrete-event simulation and of Stroboscope. Further information on Stroboscope can be found in Martinez (1996). The following provides an introduction to Foresight. The main goals in developing the Foresight modeling language were to attain the simplicity in use of CPM, the visual insight of linear scheduling, and the modeling versatility of simulation. In addition, hierarchical structuring of a model (see for example, Huber et al. (1990) and Ceric (1994)) and interactive development of a model were identified as requisite attributes of the new approach since they facilitate model development and aid understanding of the organization and behavior of a system. The three principle concepts of the Foresight modeling approach are as follows and illustrated in Figure 1:

(i) Attribute Space. This is the environment within which the model of the process exists. Each dimension defining this space represents a different attribute involved in the execution of the process, such as time, cost, excavators, skilled labor, number of repetitions of an item of work, permits to perform work, and materials. The attributes that make-up this space are the resources that are used to measure performance, and/or could have a significant impact on performance.

(ii) Work Units. These are elements that represent specific items of work that need to be completed as part of the project. They are represented by a bounded region within the attribute space. A unit can represent work at a high level (such as 'Construct Structural System'), a low level (such as 'Erect Column X') or any intermediate level. Collectively, the work units must represent all work of interest but should not represent any item of work more than once.

(iii) Constraints and Objectives. Constraints define the relationships between the work units and the attribute space, either directly with the attribute space (such as constraint 'a' in Figure 1) or indirectly via relationships with other work units(such as constraints 'b', 'c', and 'd' in Figure 1). These constraints effectively define the location of the edges of the work units. A constraint can be any functional relationship between the borders of the work units and/or the space within which they exist. Practical examples include: (i) ensuring that crews at different work units maintain a safe working distance; (ii) ensuring that the demand for resources never exceeds the number available; (iii) determining the duration for a task based on the number of times it has already been repeated, and (iv) ensuring that idle time for a task is kept to a minimum. The objectives are the specific goals of the planning study, such as to maximize profits or to complete work by a deadline (such as constraint 'd' in Figure 1). Fundamentally, they are the same thing as constraints, albeit at a higher level of significance, and therefore are treated as such within the proposed new modeling system.

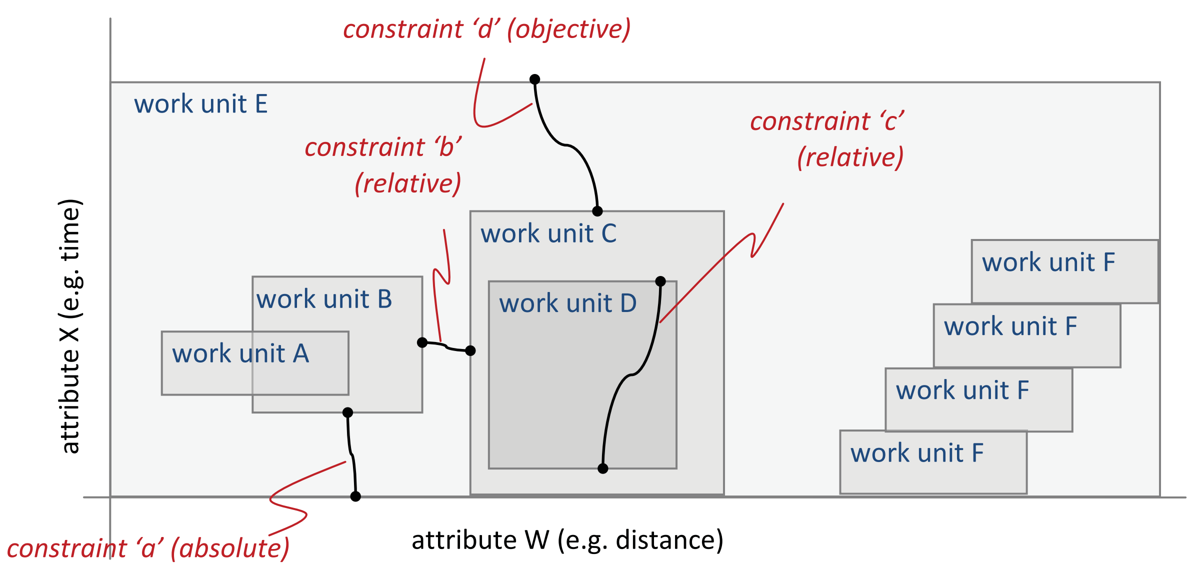


Figure 1: Schematic of the three principle concepts of Foresight

Note that work units can be nested within other work units (such as work unit 'D' in Figure 1 which is shown to be within work unit 'C'). Nesting of work units can be defined explicitly, allowing the model to be understood at different levels of abstraction, increasing its readability, reducing the likelihood of errors in the design of the model, and reducing the amount of work required to define and update a model.

Work units can also be repeated (such as work unit F in Figure 1) and can be implemented at any level within the nesting hierarchy, thus minimizing the amount of work required to define a model.

A specification of Foresight is that model development be implemented interactively. That is, the visual presentation of a model is updated and all constraints are resolved as the work units and constraints are either edited or added to the model. This way, the modeler can see immediately the impact of any changes or additions that are made. Another point to note is that these models are presented as a plot of the work units within at least two dimensions of the attribute space. This form of presentation allows the progress of work to be visualized within the model's functional structure. This is an extrapolation of the way in which linear scheduling models are presented, and has the advantage of allowing the user to visualize directly how the performance of the model is dependent on its structure. These points will be illustrated in the following case studies.

3. EXCAVATION SYSTEM

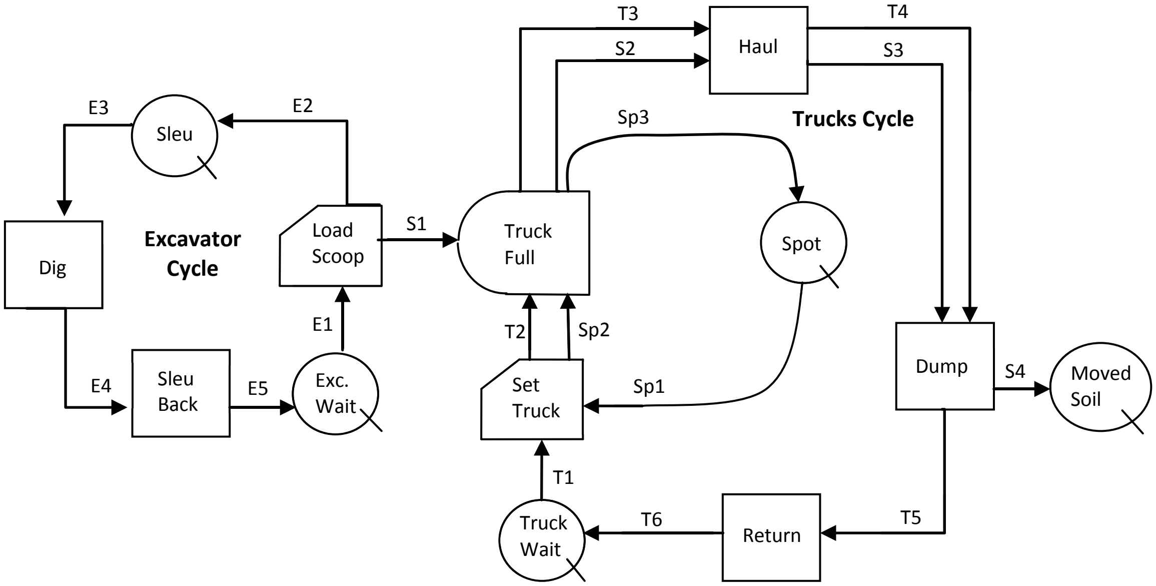
One measure of the ease of use of a modeling system is the complexity of the resultant models. In this section the complexity of a model will be measured in terms of: (i) the number of different modeling concepts that had to be employed; and (ii) the number of terms that had to be defined to complete the model. The first of these metrics provides a measure of the depth of understanding or expertise that the model builder must have, while the second provides a measure of the effort they must input to complete the model. Modeling complexity as such was used to compare the ease-of-use of Foresight and Stroboscope for a range of variations of an excavator and distribution-truck based excavation system.

Figure 2 shows the Stroboscope representation of a simple excavation system comprising a number of dump trucks of various capacity and an excavator with a 1 cu-m bucket (see Martinez, (1996)). Part (a) of this figure shows the Stroboscope diagram which is a logical representation of the processes involved in the operation, while part (b) shows the resultant time-wise output from the model measured at the dump activity for a situation where there are 2 dump trucks of 10 cu-m capacity each. Figure 3 shows the Foresight equivalent model of the same excavation system. Part (a) of Figure 3 shows the hierarchical structure of the model while part (b) shows the complete model with all constraints defined, for 2 dump trucks of 10 cu-m capacity each.

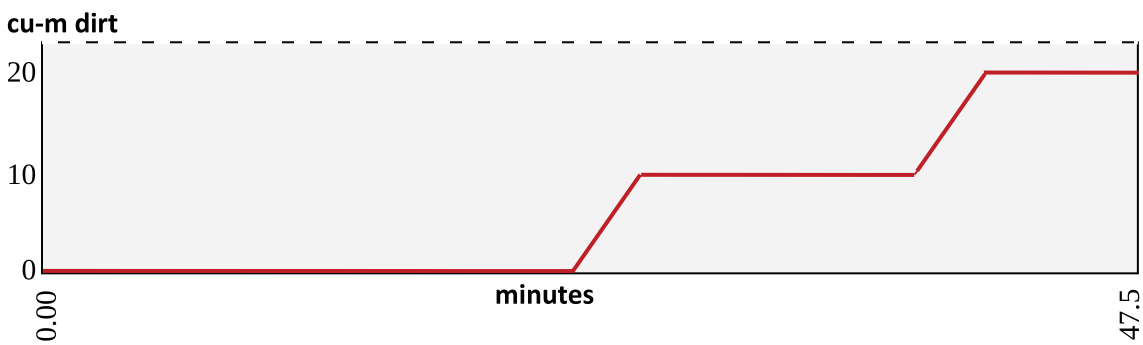
A comparison of Foresight and Stroboscope was made for the following variants of this excavation model:

(i) 1 Truck (10 cu-m capacity).
(ii) 2 Trucks (10 cu-m capacity) + 2 Trucks (15 cu-m capacity)
(iii) 3 Trucks (10 cu-m capacity) + 3 Trucks (15 cu-m capacity) + 3 Trucks (20 cu-m capacity)

All other modeling parameters were kept constant between the model variants, including the activity durations for the different truck capacities. Figure 4(a) shows the number of terms required to define each of the three variants of the excavation model, for both Stroboscope and Foresight. A term is taken to be any definition or parameter required to specify the structure and operation of the model. For Stroboscope, example terms are the definitions of queue nodes and activities and their linkage and durations, the definition of the excavator and trucks and their numbers and capacities, and the definitions of the amount of work to be simulated. For Foresight, example terms are the attributes such as time and soil, the work units and their constraints, and the repetition of work units (note, the amount of work to be modeled is implicitly defined by the constraints on the highest level work unit). Referring to Figure 4(a) it can be seen that the amount of information required by Foresight to define these models is about 30% of that of Stroboscope. This is significant given that the Foresight and Stroboscope models are identical in terms of the process logic represented.

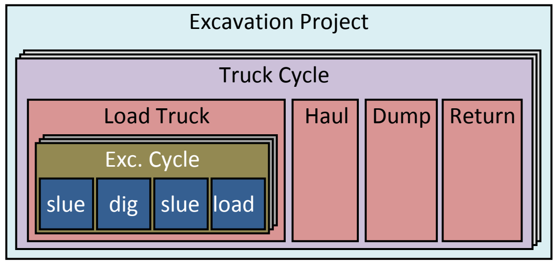


(a) Stroboscope process diagram

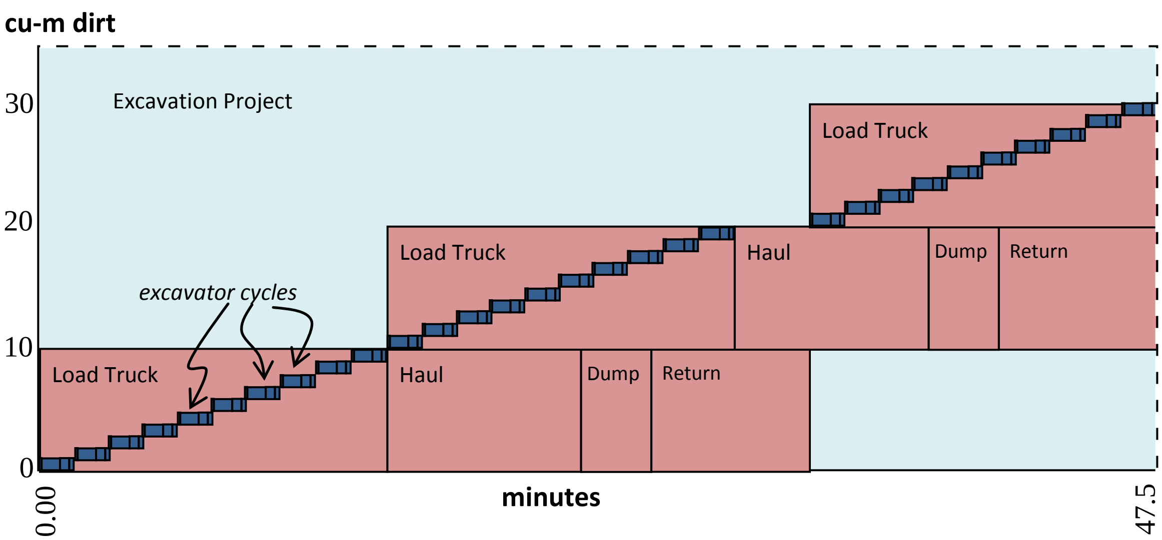


(b) Typical simulation output (moved soil; 2 dump trucks; first 47.5 minutes of production)

Figure 2: Stroboscope model of an excavation system (see Martinez (1996))

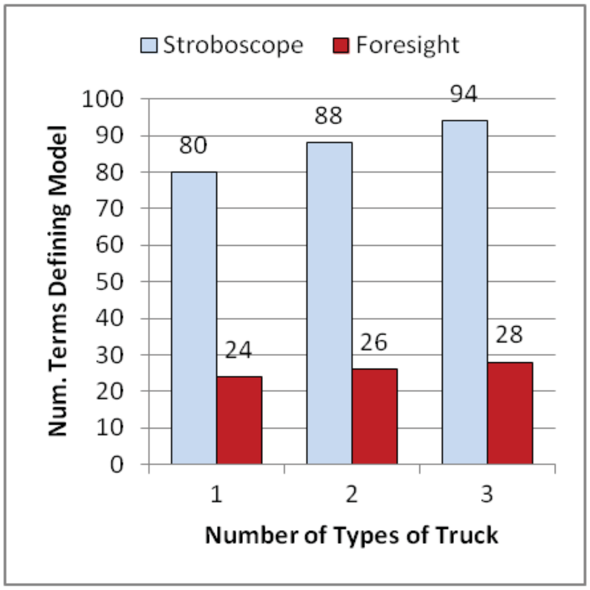


(a) Hierarchical model structure

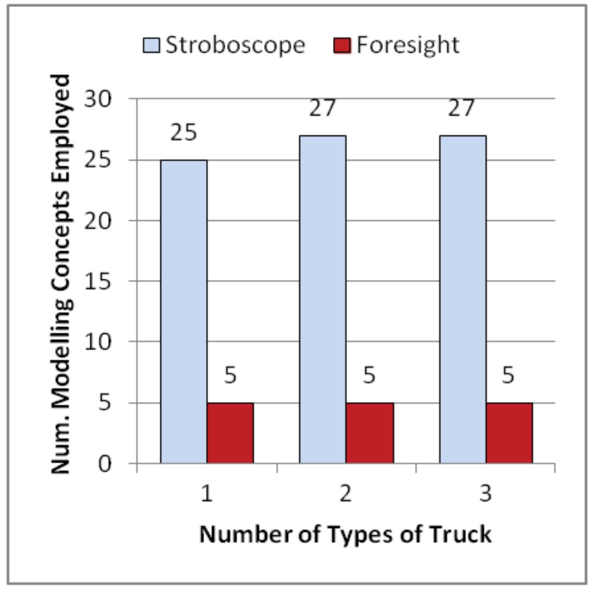


(b) Constrained model (2 dump trucks; first 47.5 minutes of production)

Figure 3: Foresight model of an excavation system



(a) Number of terms required to define a model



(b) Number of modeling concepts employed

Figure 4: Foresight vs. Stroboscope: Complexity of variants of the excavation model

4. CONCRETE PRODUCTION AND DISTRIBUTION SYSTEM

A second case study was undertaken, comparing the complexities of Foresight and Stroboscope models for a more elaborate system, that of producing and distributing wet concrete via a hopper. Figure 5 shows the Stroboscope model of the operation. The system comprises a mixer that produces wet-concrete in 1 cubic-meter batches, a 5 cubic-meter hopper for temporary storage of the wet-concrete, and 2 trucks of 3 cubic-meters capacity each used to distribute the wet-concrete. Note, the Stroboscope model represents the hopper as a cycle of activities executed by resources representing either concrete in the hopper or space for concrete in the hopper depending on where they are within the cycle. Figure 6(a) shows the Foresight version of this model in hierarchical format, while Figure 6(b) shows the model complete with constraints.

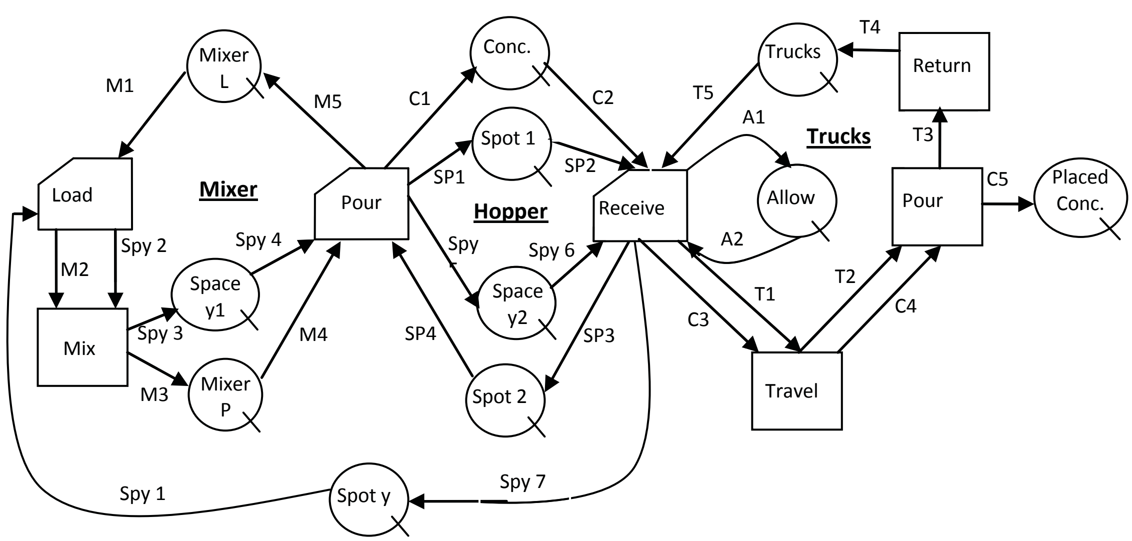
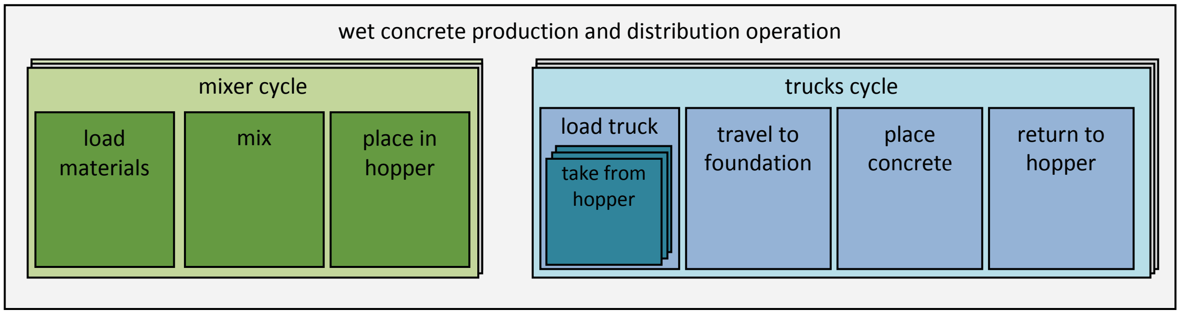
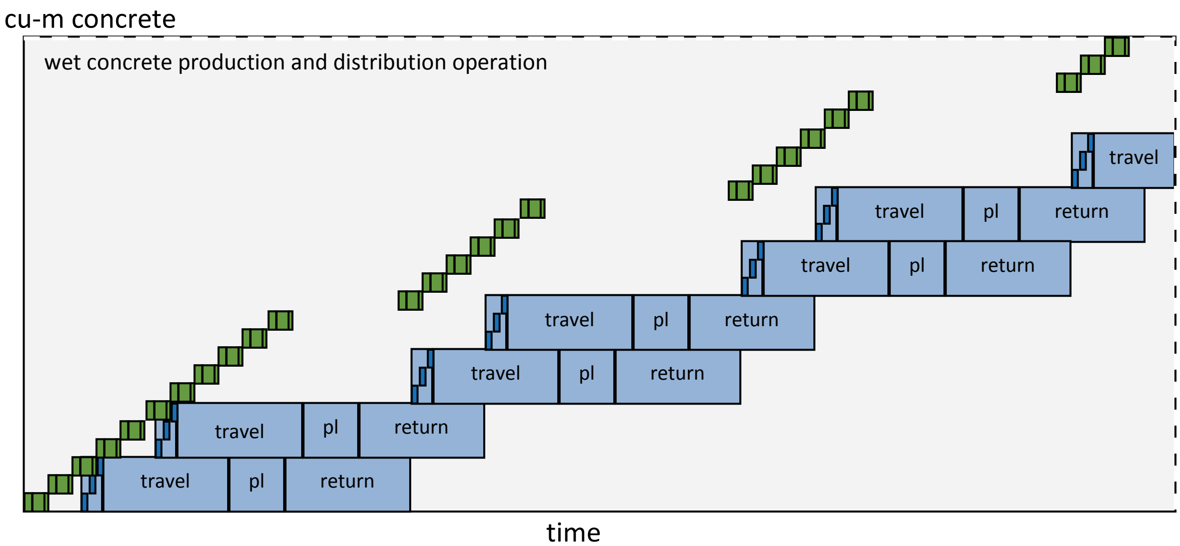


Figure 5: Stroboscope model of concrete production and distribution system



(a) Hierarchical model structure



(b) Constrained model (first 6 distribution truck cycles)

Figure 6: Foresight model of concrete production and distribution system

For one mixer and two concrete-distribution trucks, the Stroboscope version of this model required 105 terms to define the complete system. In comparison, the Foresight required just 24 terms to define the system. Thus, the amount of information required by Foresight was just 23% of that of Stroboscope, a better advantage than that realized for the excavation models.

4. VISUAL INSIGHT

The previous two sections demonstrated the advantage of Foresight over Stroboscope in terms of the relative simplicity of the resultant models. Another important advantage of Foresight over simulation is the visual insight provided by these models. This results from the fact that the logic and performance of a system are represented within a single framework in Foresight, whereas simulation techniques separate system logic from system performance. Indeed, using simulation techniques the model-builder must usually build the entire model (including defining all its parameters) before any measure of performance can be obtained. For example, the Stroboscope process diagram shown in Figure 2(a) provides no direct indication of system performance and it must be fully defined before the simulation can be executed to generate the performance results (shown in Figure 2(b)). In contrast, the Foresight model (Figure 3(b)) integrates both logic and performance within one graph, so the impact of work units and constraints on system performance is visually apparent. Moreover, the impact on performance can be seen on-the-fly as these elements are added, amended, and deleted.

This can also be seen in Figure 6(b), the Foresight version of the concrete production and distribution system. In this case, the model shows directly the fact that the concrete mixer spends considerable time idle. This could be corrected by the addition of a third distribution-truck. While a similar conclusion could be reached using a simulation approach, this would require an analysis of queue statistics or a graphical post-processing of resource activity.

This characteristic of Foresight (integrating model logic and performance within a visual framework) greatly extends the utility of the approach. First, it aids model verification (debugging) by allowing the model-builder to see the impact on performance of each model edit. Second, they provide the model-builder with a visual insight that helps identify more optimal designs for a construction system. For example, by inspecting the Foresight model in Figure 5 it can be seen that by positioning the access shaft 3 m to the left would balance the two crews in a way that minimizes the project duration.

5. CONCLUSIONS AND FUTURE WORK

The paper has outlined a new construction modeling method, Foresight, that integrates the advantages of CPM, linear scheduling, and discrete-event simulation, along with hierarchical and interactive approaches to model development and analysis. The principles upon which Foresight is based provide it with the versatility necessary to model the broad spectrum of construction projects that until now have required the use of several different modeling tools. Compared to simulation, the resultant models are significantly less complex and require far fewer modeling concepts to be understood. In addition, Foresight models have the advantage of representing the progress of work within the model structure. This provides visual insight into how the design of a process will impact its performance, aids model verification on–the-fly, and suggests ways of optimizing project performance.

Future research will evaluate the ease with which new-users learn to develop and use Foresight models in comparison to the main alternative modeling approaches: CPM, linear scheduling, and simulation.

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