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Discrete-Event Simulation versus Constrained Graphic Modelling of Construction Processes

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Abstract

Effective construction project planning and control requires the development of a model of the project's construction processes. The Critical Path Method (CPM) is the most popular project modelling method in construction since it is relatively simple to use and reasonably versatile in terms of the range of processes it can represent. Several other modelling techniques have been developed over the years, each with their own advantages and disadvantages. Linear scheduling, for example, has been designed to provide highly insightful visual representations of a construction process, but unfortunately is largely incapable of representing non-repetitive construction work. Discrete-event simulation is generally agreed to be the most versatile of all modelling methods, but it lacks the simplicity in use of CPM and so has not been widely adopted in construction. A new graphical constraint-based method of modelling construction processes, Foresight, has been developed with the goal of offering the simplicity in use of CPM, the visual insight of linear scheduling, and the versatility of simulation. Earlier work has demonstrated the modelling versatility of Foresight. As part of a continuing study, this paper focuses on a comparison of the Foresight approach with discrete-event construction simulation methods, specifically Stroboscope (a derivative of CYCLONE). Foresight is shown to outperform Stroboscope in terms of the simplicity of the resultant models for a series of case studies involving a number of variants of an earthmoving operation and of a sewer tunnelling operation. A qualitative comparison of the two approaches also highlights the superior visual insight provided by Foresight over conventional simulation, an attribute essential to both the effective verification and optimization of a model.

Keywords: Construction process, Foresight, Process modelling, Construction simulation, Stroboscope, Model complexity, Visual insight.

Background

A wide range of methods for modelling construction processes have been developed over the last 100 years. 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. Unfortunately, each of these three main classes of modelling is restricted in terms of its scope of application and/or usability.

First, the CPM methods (the most popular tool for planning, monitoring and control of construction processes) are well suited to modelling 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, tunnelling, 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 the amount of physical work completed. However, linear scheduling 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 is the case for 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 modelled 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, the simulation diagram only shows the logic of the model and its physical resources; performance is presented in a separate output after the model has been fully developed and debugged. In other words, the logic of the model and its performance are not integral parts of a single model and therefore the dependence between performance and model logic is not directly apparent.

Most construction projects include a variety of processes some of which may be best modelled 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 modelling 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 (which is typically CPM) compromises the ability to plan and control work optimally. Ideally, what is required is a single tool that is highly versatile in terms of the scope of construction processes it can model, provides visual insight into better ways of organizing work all aspects of work, and is easy to use. Earlier work (Flood, 2010) has proposed a new modelling paradigm, Foresight, that addresses the above issues. Foresight is being evaluated in an on-going study comparing its utility to the alternative construction process modelling 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 modelling system. Section 3 provides a case study comparing the complexity of Foresight and Stroboscope models for variants of an earthmoving operation. Section 4 provides a similar comparison for a more complicated construction process, that of a sewer tunnelling operation. Section 5 provides a qualitative comparison of Foresight and Stroboscope in terms of their utility in developing and optimizing a model.

Foresight and Stroboscope Modelling Approaches

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, both of which are implemented using discrete-event simulation principles. This study will compare the modelling 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 modelling language were to attain the simplicity in use of CPM, the visual insight of linear scheduling, and the modelling 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 behaviour of a system. The three principle concepts of the Foresight modelling approach are as follows and illustrated in Figure 1:

> **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 labour, 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 that could have a significant impact on performance.
>
> **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. Work units may exist in different subsets of attribute space.
>
> **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 modelling system.

There are two secondary concepts of the Foresight modelling system, both concerned with its structure:

> **Nesting.** Work units can be nested within other work units (such as work unit 'H' in Figure 1 which is shown to be within work unit 'G' which is respectively part of 'C' and then 'E'), or overlap with each other (such as work units 'A' and 'B'). 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.
>
> **Repetition.** Work units can 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. Repetition of a work unit will include a repetition of all relevant constraints and its nested work units and their constraints.

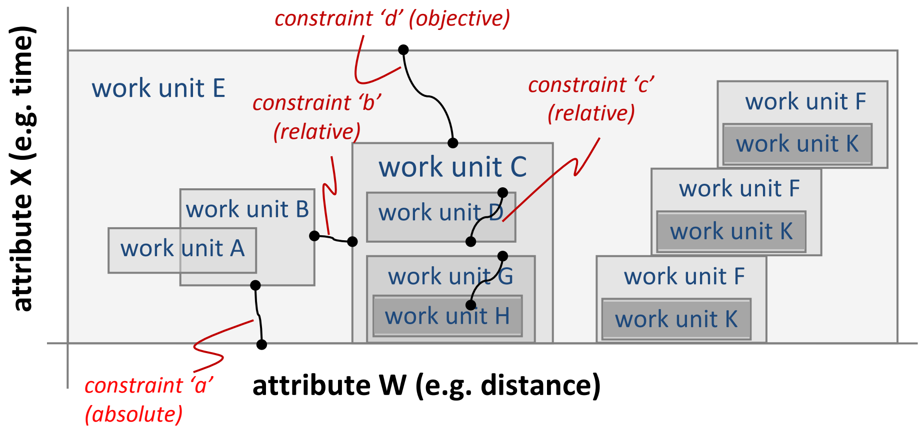


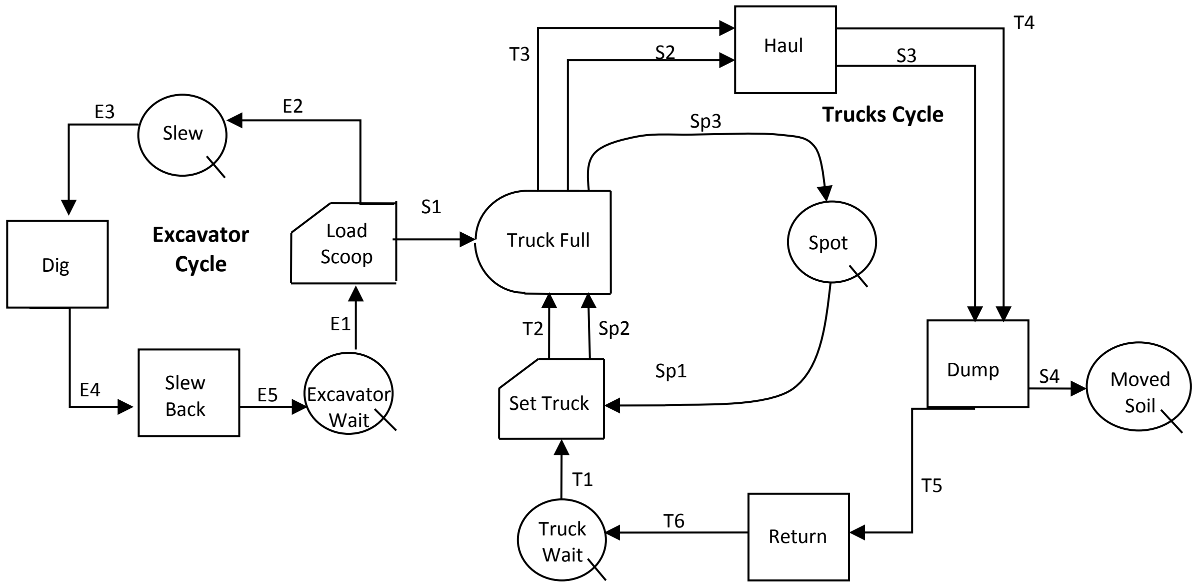
Figure 1: Schematic of the principle concepts of Foresight

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 modeller 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.

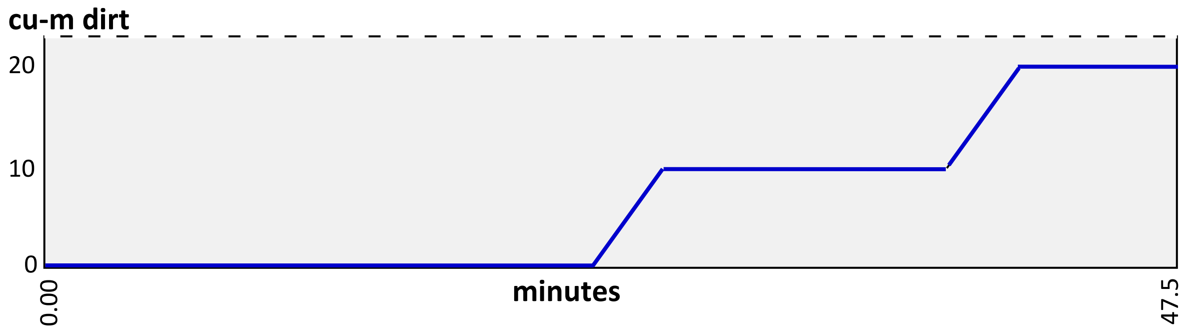
Case Study I: Earthmoving Operation

One measure of the ease of use of a modelling 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 modelling 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 possess, while the second provides a measure of the effort they must input to complete the model. Modelling 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 earthmoving operation comprising a number of dump trucks of various capacities 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.



(a) Stroboscope process diagram



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

Figure 2: Stroboscope model of an earthmoving operation (see Martinez (1996))

Figure 3 shows the Foresight equivalent model of the same earthmoving operation. Part (a) of Figure 3 shows the hierarchical structure of the model while part (b) shows the complete model with all constraints defined, for a system comprising 2 dump trucks of 10 cu-m capacity each.

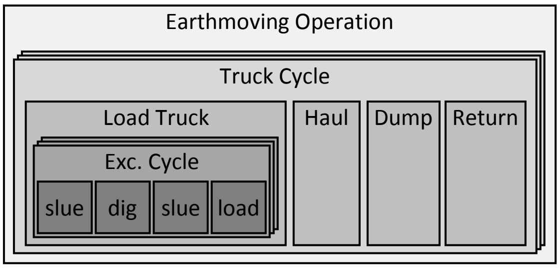
A comparison of Foresight and Stroboscope was made for the following variants of this excavation model:

(i) 1 Truck (10 cu-m capacity).

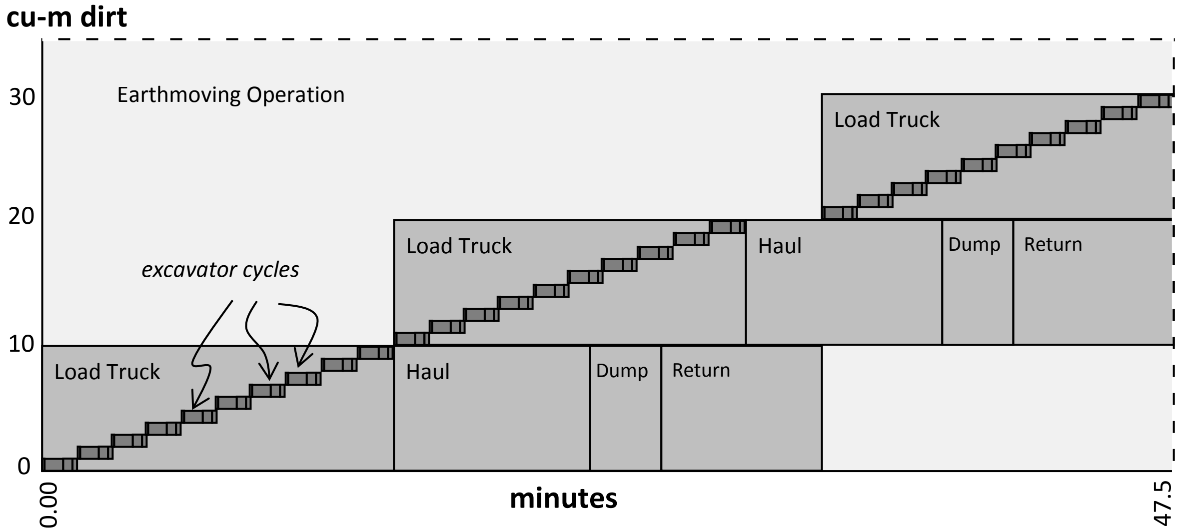
(ii) 2 Trucks (10 cu-m capacity) + 2 Trucks (15 cu-m capacity).

(iii) 3 Trucks (10 cu-m capacity) + 3 Trucks (15 cu-m capacity) + 3 Trucks (20 cu-m capacity).

All other modelling parameters were kept constant between the model variants, including the activity durations for the different truck capacities, and the number of excavators.



(a) Hierarchical model structure

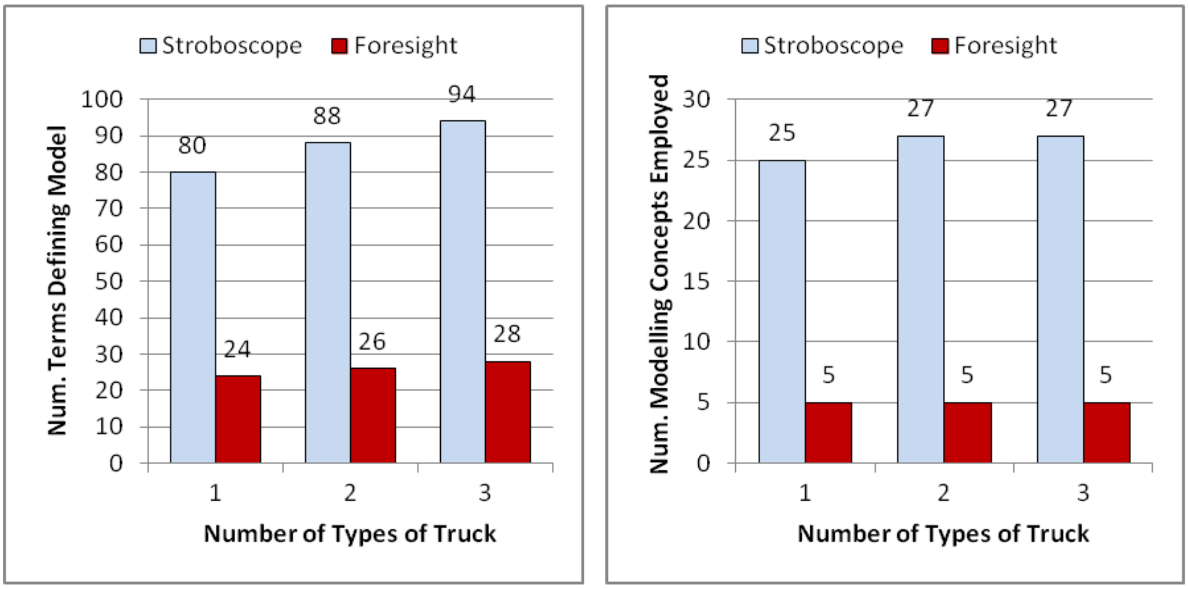


(b) Constrained model (2 dump trucks; first 47.5 minutes of production)

Figure 3: Foresight model of an earthmoving operation

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 modelled 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.

Figure 4(b) makes a similar comparison but in terms of the number of concepts employed in the definition of a model – note, each concept is counted just once in this analysis no matter how many times it is employed within a model. For Foresight, there are only five concepts used to develop a model: (i) the types of attribute; (ii) the work units; (iii) the constraints defining the relative locations of the various boundaries of the work units; (iv) nesting of work units; and (v) repetition of work units. For Stroboscope, examples of concepts employed in defining a model are: queue nodes, combi' activities, normal activities, consolidate functions, durations, and simulation limits. In this case, the number of concepts employed by Foresight is around 19% to 20% of that employed by Stroboscope. It could be argued that a Foresight model-builder must learn how to use the 5 base concepts to represent each logical construct in a system, such as ensuring that the excavator completes the correct number of cycles to fully load a truck. However, a Stroboscope model-builder must also learn how to configure the various Stroboscope modelling components to achieve each logical construct.



(a) Number of terms required to define (b) Number of modelling concepts

Figure 4: Foresight vs. Stroboscope: Complexity of variants of the earthmoving operation

Case Study II: Sewer Tunnel Operation

A second case study is presented, comparing the complexities of Foresight and Stroboscope models for a more elaborate system, that of constructing a 2 meter internal diameter sewer tunnel where tunnelling is through clay and the lining is formed from concrete ring segments grouted in place. The system is described in detail in Flood (2010). Briefly, the system comprises two tunnelling crews that start in the middle and head in opposite directions. Each crew excavates clay with a pneumatic spade. Excavated material is placed in a skip mounted on light track for removal via an access shaft at the midpoint of the tunnel. Three skip loads of excavated material are required for each 1 m length of tunnel. When a 1 m length of the tunnel has been excavated, the crew brings in a set of concrete ring segments to line that section of tunnel. Once a 3 m section of the tunnel has been excavated and lined the crew lay a new section of light track. Figure 5 shows the Stroboscope equivalent of this model for 1 crew. To consider the two crews (one heading in each direction) the model as shown in Figure 5 would have to be duplicated making it effectively twice the size.

Figure 6 shows the Foresight model of the same operation except with two crews working in opposite directions from the access shaft. Part (a) of this figure shows the hierarchical structure of the model (for 2 crews) while part (b) shows the complete model with all constraints defined with the 2 crews heading in opposite directions. For the one crew version of this operation, Foresight required 46 terms to define the model whereas Stroboscope required 139 terms. Thus, the amount of information required by Foresight was just 33% of that of Stroboscope, a similar advantage to that realized for the earthmoving models. For the two crew versions of the model, the number of terms required to define the Foresight model increases by just 1 (totalling 47 terms), whereas the Stroboscope model requires a doubling in the number of terms (totalling 278 terms).

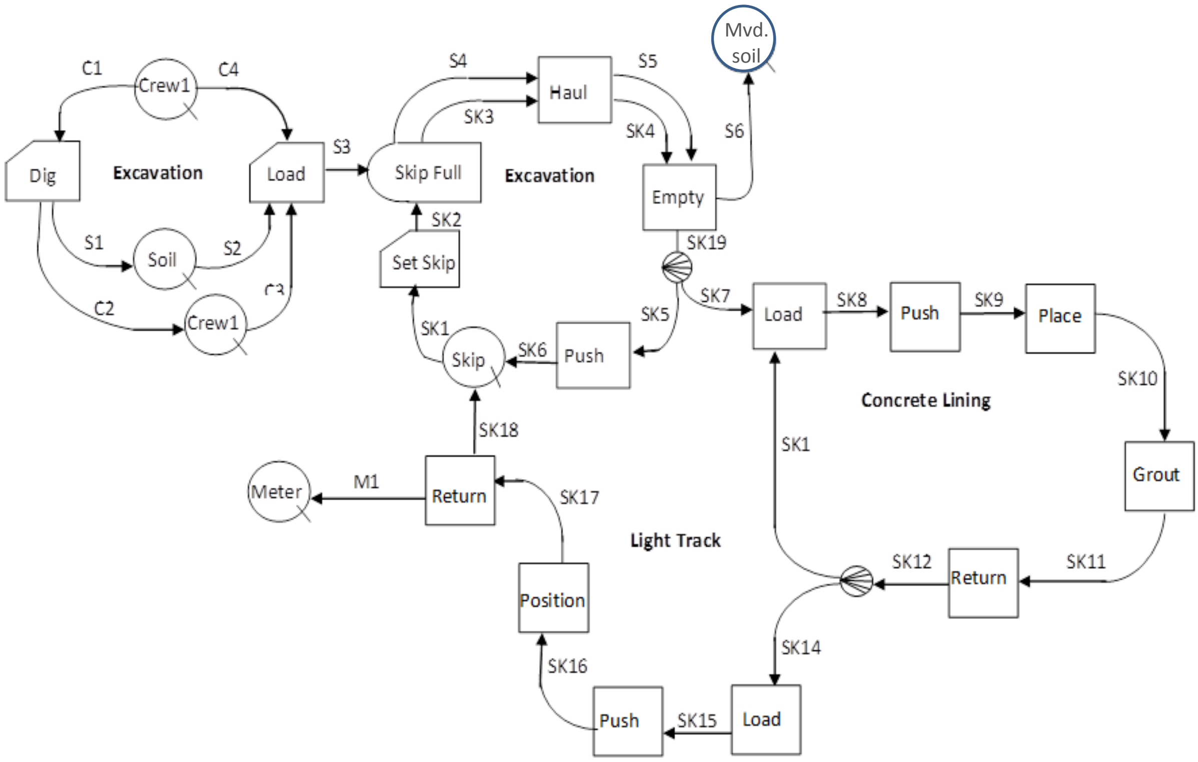
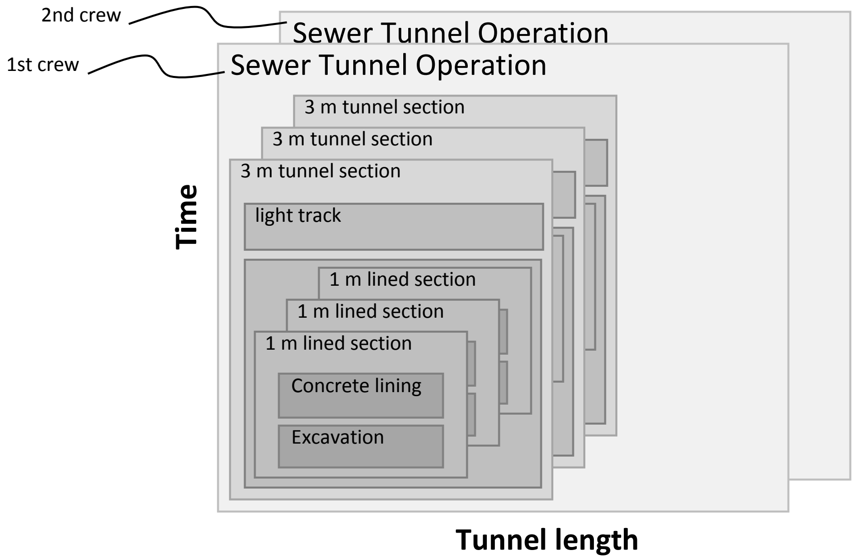


Figure 5: Stroboscope model of a sewer tunnel operation (1 crew)

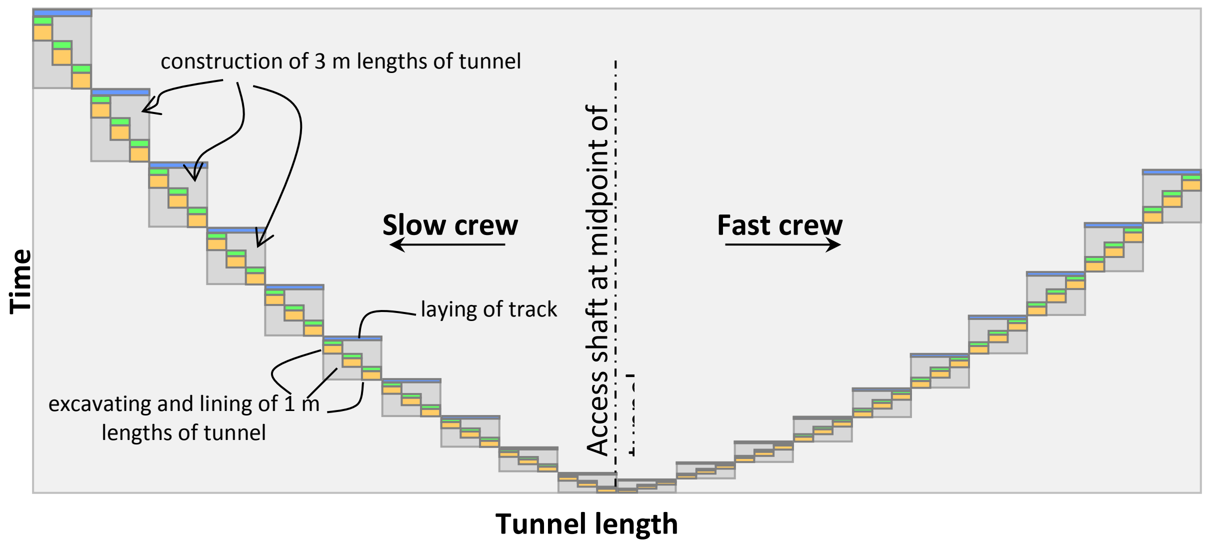
Qualitative Comparison

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.

These characteristics of Foresight greatly extend the utility of the approach. First, they aid 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 6(b) 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.



(a) Hierarchical model structure (2 crews)



(b) Constrained model (2 crews)

Fig. 6: Foresight model of a sewer tunnel operation (2 crews)

Conclusions and Future Work

The paper has outlined a new construction modelling 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 modelling tools. Compared to simulation, the resultant models are significantly less complex and require far fewer modelling 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 modelling approaches: CPM, linear scheduling, and simulation.

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