Constraint-Based Graphical Modelling of On-Site and Factory-Based Construction Production Systems

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***Abstract* — Planning and control of a construction project requires the development of an appropriate model of the project's processes. The Critical Path Method (CPM) is the most widely used process modelling method in construction since it is simple to use and reasonably versatile. Discrete-event simulation is the most versatile of existing modelling methods in terms of the type of work and detailed logic that can be represented, but it is not easy to use compared to CPM and for this reason has not been widely adopted in practice. *Foresight* is a new modelling method designed to combine the simplicity of CPM and versatility of simulation. Earlier work has demonstrated the modelling simplicity and versatility of *Foresight* relative to other project planning tools for a range of on-site based processes. This paper continues this investigation, focussing on the relative performance of *Foresight* and discrete-event simulation in terms of modelling both on-site and factory-based (manufactured) process logic. The principles and relative performances of the two approaches are demonstrated in application to three example problems. The study demonstrates the advantages of *Foresight* over simulation hold for both on-site and manufacturing type processes.**

Keywords – discrete-event simulation; Foresight modeling; interactive modeling; process modeling; visualization.

I. INTRODUCTION

This paper extends earlier work comparing the performance of conventional simulation and constraint based modelling techniques in application to both on-site and factory-based construction production [1].

A wide range of methods for modelling construction processes have been developed over the last 100 years since the introduction of the Gantt Chart. An analysis of the genealogy [2] of these tools shows that they can be grouped into three main categories: the Critical Path Methods (CPM); the linear scheduling techniques; and discrete-event process simulation. Most other tools are either an enhancement or an integration of these methods or have a very limited scope of application. For example, 4D-CAD and nD-CAD planning methods [3] [4], where one of the dimensions is time, are strictly CPM models hybridized with 3D-CAD for visualization purposes.

Each of the three main groups of modelling method have, unfortunately, practical limitations in terms of their application to construction planning. The CPM methods (the most popular in construction) 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 [5]. Moreover, CPM models become cumbersome 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 [6]). These models are very easy to understand and represent the system's logic and its performance within an integrated framework. Consequently, they provide the modeller with strong visual insight that can help identify more optimal ways of achieving the project's production goals. For example, they show in graphic form how the relative progress of repetitive tasks can lead to conflict, both in terms of time and physical interference between productive resources (such as crews and equipment). However, linear scheduling cannot be used to model non-repetitive work, and it includes 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 paths, such as two underground utility lines that interact at a cross-over point but otherwise follow different routes.

Discrete-event simulation (see, for example, Halpin and Woodhead [7]; Sawhney et al. [8]; Hajjar and AbouRizk [9]) is an established tool that 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 relatively high degree of expertise and effort required to develop and validate a simulation model has limited its adoption in the field. In addition, simulation models provide no direct 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; it is not an integral part of the model and therefore its dependence on the model's logic is not directly apparent.

Most 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 and plan-users to employ more than one modelling method to manage 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 model all situations (typically CPM) compromises a user's ability to plan and control work optimally.

The ideal solution would be a single tool that combines the versatility of discrete-event simulation (in terms of modelling the broad spectrum of repetitive and non-repetitive construction work), the visual insight of linear scheduling, and the ease-in-use of CPM. *Foresight* [10] has been developed to meet these objectives, and has been demonstrated capable of modelling all types of work covered by CPM, linear scheduling and discrete-event simulation. Construction processes are traditionally performed on-site; however, some are performed within a controlled environment such as a factory, and in recent years there has been a slowly growing interest in manufactured and modular component production. The logistics of manufactured processes can be quite different from on-site processes, often characterized by a job-to-process flow of work (as opposed to process-to-job flow), and batch processing of multiple component types. This paper compares *Foresight* with *CYCLONE* [7] (a commonly adopted simulation modelling system designed specifically for construction) in application to a variety of construction processes including a factory based production system.

Section II introduces the principals of the *Foresight* modelling system. Sections III to V provide three case studies: a multiple-cycle earthmoving operation that includes an intermediate storage facility, a tunnelling operation; and a factory-based process that produces batches of various types of prefabricated reinforced concrete components. The paper concludes in Section VI with a summary of the findings and an identification of continuing research.

II. PRINCIPAL MODELING CONCEPTS OF FORESIGHT

The goal in developing the new approach to modelling was to attain the simplicity of CPM, visual insight of linear scheduling, and the modelling versatility of simulation. In addition, hierarchical structuring of a model (see for example, Huber et al. [11] and Ceric [12]) 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:

(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.

(2) *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 or overlapping subsets of attribute space.

(3) *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 quantity available; (iii) determining the duration for a work unit based on the number of times it has already been repeated; and (iv)

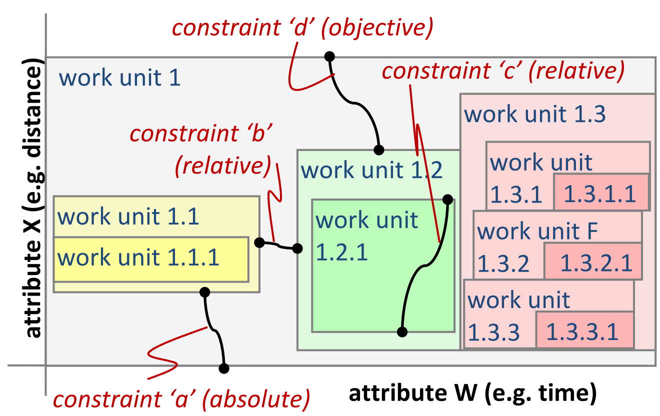

Figure 1. Schematic illustrating the three principal concepts of Foresight.

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:

(1) *Nesting.* Work units can be nested within other work units (such as work unit '1.2.1' in Figure 1 which is shown to be within work unit '1.2' which is respectively part of '1'). Nesting of work units is 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.

(2) *Repetition.* Work units can be repeated (such as occurs within work unit 1.3 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.

A standard 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 three example applications.

It should be noted that *Foresight* is, strictly speaking, a simulation system in that it requires the use of a three-phase simulation algorithm to resolve its constraints.

III. Earthmoving Operation

The first system to be modelled is that of an earthmoving system comprising a bulldozer used to push dirt from the cut area into a stockpile, and an excavator used to load dump trucks which, in turn, haul the dirt to a fill area. Figure 2 shows the *CYCLONE* [7] simulation diagram of this system for a situation where there is 1 bulldozer that can push 3 cu-m of dirt on each cycle, a loader with a 1 cu-m bucket, and 3 dump trucks of 5 cu-m capacity each. The loader must therefore perform five cycles to load a truck.

This model, once defined within the computer and validated, would be run several times to gain measures of performance of the system, such as production rates and queue length distributions. To the lower left of Figure 2, for example, is a measure of the amount of dirt in the stockpile plotted against time resulting from a single simulation run. Similarly, to the lower right of the figure is a measure of output from the system against time, measured as truck loads at the "dump" activity.

The *Foresight* representation of this system is presented in Figure 3. The first part of this figure shows the hierarchical form of the model (without the main constraints added) whereas the second part shows the model in its normal format with all constraints included representing, for example, work unit durations, and precedence. In this case, the model is displayed within the attribute dimensions of "quantity of dirt" and "time". The model is shown for the first 10 cu-m of dirt removal.

Inspecting the second part of Figure 3, it can be seen that the bulldozer (yellow) and loader (blue) cycles are well balanced, operating at a similar rate of performance. The loader and trucks, however, are not well balanced leaving the loader in an idle state for much of the time. It can be seen from the second part of this figure that the addition of one or two more dump trucks would improve this situation.

One of the benefits of the Foresight mode of representation is that it is possible to see how the performances of different sections of a model are related. For example, the growth in the amount of dirt in the stockpiles (the green bars) can be seen in terms of both the input rate (the leading edges defined by the performance of the bulldozer) and the output (the trailing edge defined by the performance of the loader and dump trucks). However, sometimes it is helpful to isolate a part of a model and inspect that on its own terms. This can be at any level in a model hierarchy; for the stockpiles, this is shown in part 3 of Figure 3. Alternative filtering could have been undertaken to monitor the utilization of any item of equipment, time-wise variance in the length of a queue, or output from the system. Other attributes that may have been included to impose additional constraints on the system or to monitor performance, include cost and location.

Several important differences between *CYCLONE* and *Foresight* can be understood by comparing the model representations of Figures 2 and 3. First, it should be understood that *CYCLONE* requires the complete logic of the model (as represented by the *CYCLONE* diagram of Figure 2) to be finalized before the system's performance can be predicted in a simulation run. In contrast, the *Foresight* model integrates the structure and logic of the model and the estimated performance of the system within a single format as represented by the second part of Figure 3. This gives *Foresight* a couple of significant advantages. First, as work units are added to a model and their parameters altered, the impact of these edits on the estimated performance of the system are seen immediately - the model does not have to be

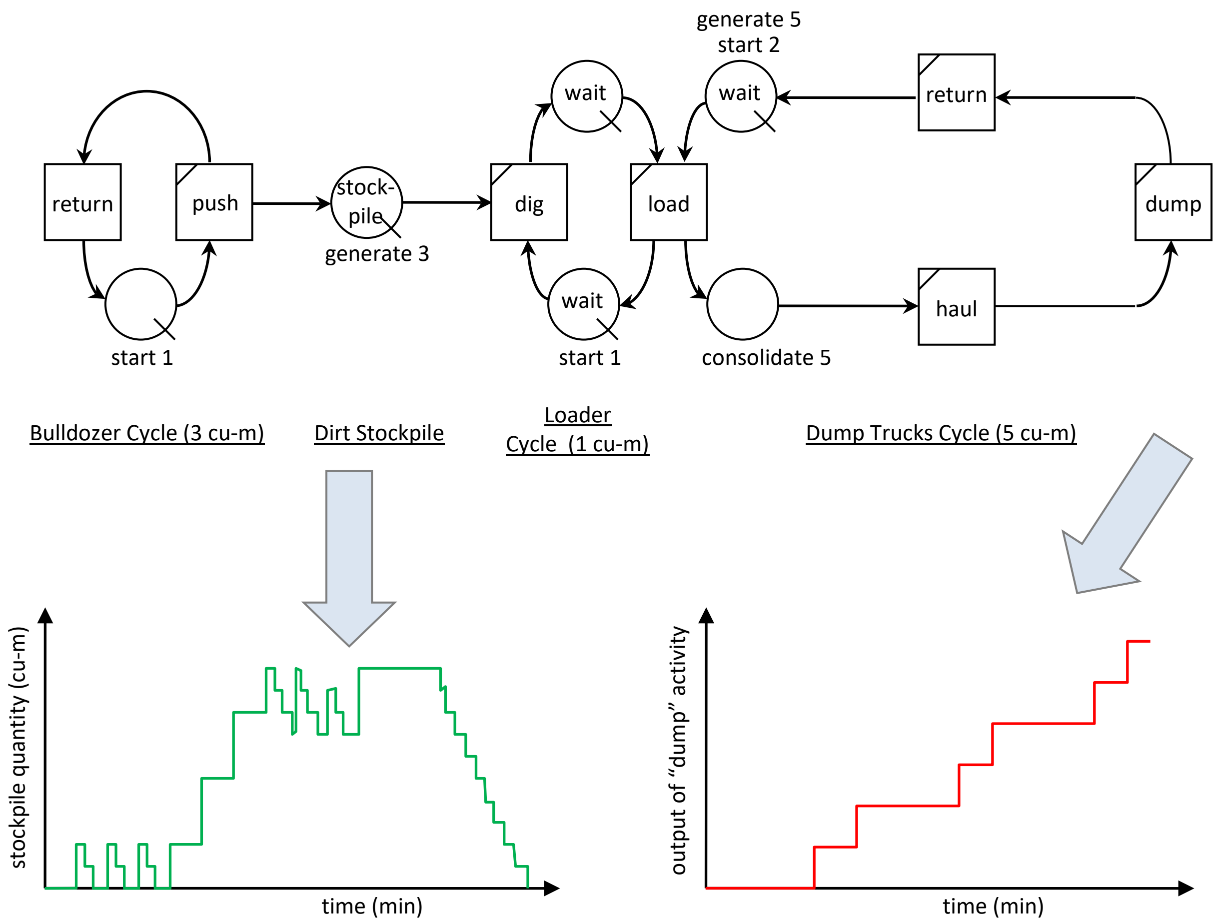

Figure 2. CYCLONE simulation model of an earthmoving operation.

completed before the simulation results are produced. This is a similar advantage to that seen in other graphically based planning tools such as linear scheduling. The second advantage is that in a *Foresight* model, the way in which the logic and structure of the model affect the performance of the system is directly visible, which in turn assists in the optimization of the design of the system - this point will be illustrated in the next case study of a sewer-tunneling operation.

IV. Tunnelling Operation

The second study is concerned with modelling the construction of a 2 m internal diameter sewer, where tunnelling is through a stiff clay and the lining is formed from concrete ring segments grouted in place. The example is used to illustrate the steps in developing a *Foresight* model for a problem that, given its complexities, would best be modelled using simulation methods.

A component oriented approach should be adopted when developing a *Foresight* model, such that each work unit represents the construction of a physical component or sub-component of the facility under construction. A top-down, hierarchical approach is an effective strategy for developing these models, starting with the highest level component (the complete facility) and then breaking it down into its constituent components. The first part of Figure 4 shows the hierarchical structure of the *Foresight* model of the tunnelling operation. At the lowest level in this breakdown are the work units "excavate" representing the cutting of 1 m length of the tunnel, and "line tunnel" which involves placing and grouting concrete ring segments in the 1 m cut. The work units "excavate" and "line tunnel" are repeated 3 times to construct a 3 m length of tunnel. These are followed by "lay track" which adds a 3 m length of track used to carry a manually propelled train for removal of spoil and delivery of materials. If two crews are used for the project then the model shown in Figure 4 would be duplicated (once for each crew) and placed within a parent work unit.

The work unit at the second highest level represents the process of constructing a 3 m section of tunnel, and will be repeated for the length of the tunnel.

Addition of constraints can occur as work units are added to the model. For this tunnel model, the main constraints were as follows:

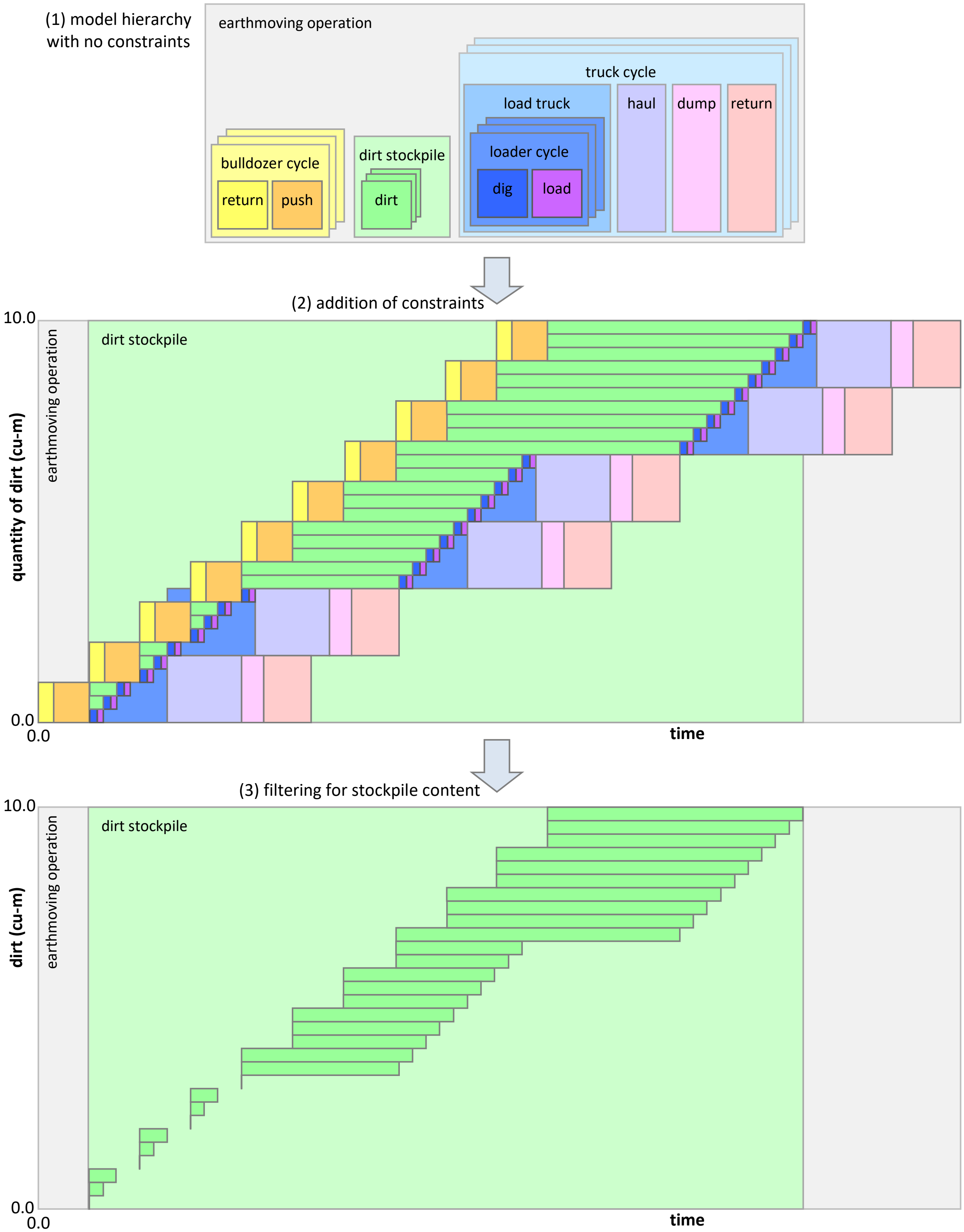

Figure 3. Foresight model of a simple earthmoving operation.

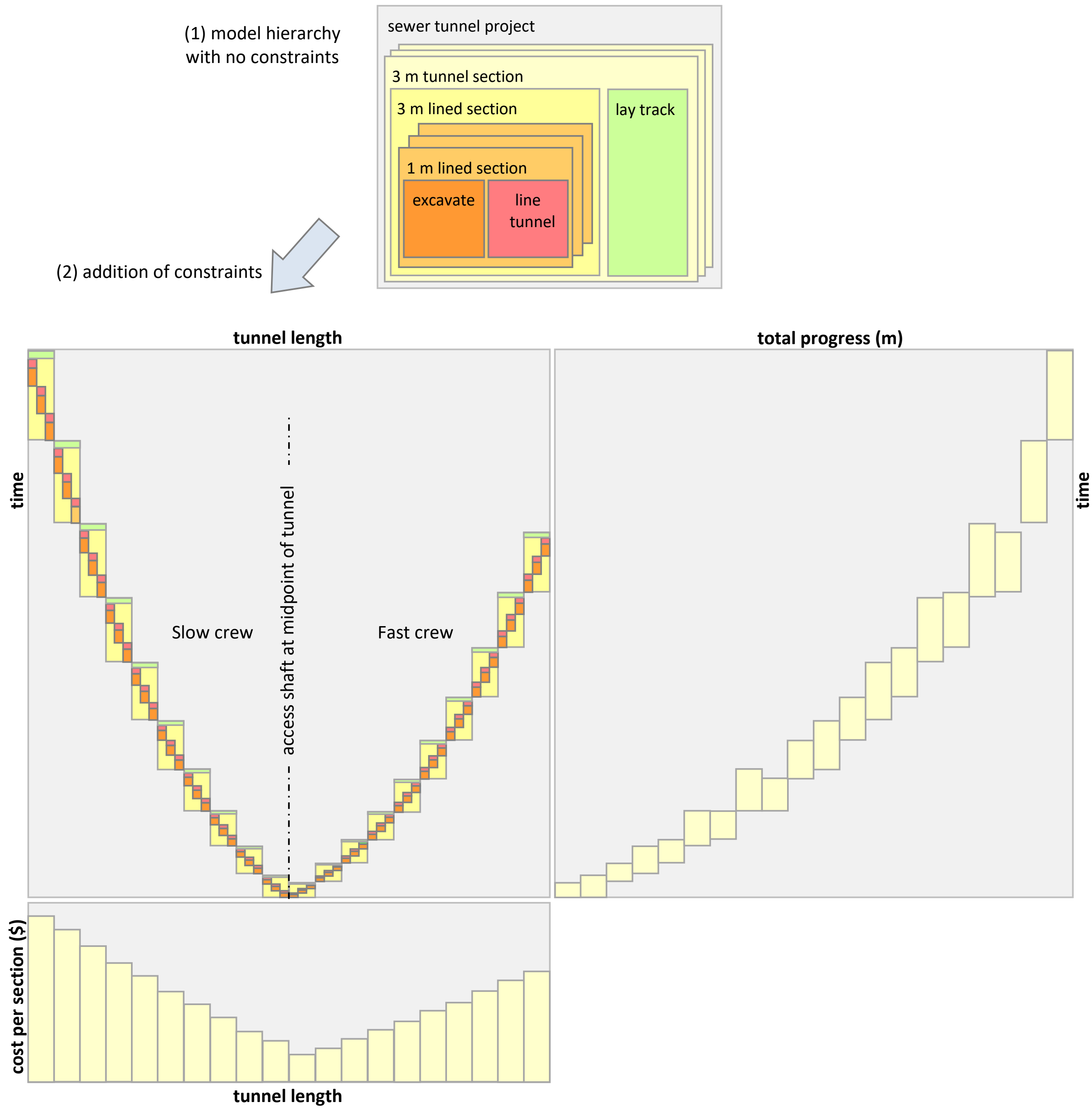

Figure 4. Foresight model of a sewer tunneling operation.

- The work units representing “3 m tunnel sections” are positioned serially both in the “time” and “tunnel length” dimensions.
- The work unit representing the “sewer tunnel project” extends in the “tunnel length” direction to a value equal to the tunnel length.
- The “3 m tunnel section” work units start at the left side of the “sewer tunnel project” work unit and extend all the way to (but not beyond) the right side of the “sewer tunnel project” work unit.
- The “1 m lined section” work units are positioned serially both in the “time” and “tunnel length” dimensions.
- The “1 m lined section” work units span from the left to right side of their “3 m tunnel section” work unit.
- The work units “excavation” and “concrete lining” are positioned sequentially in the “time” dimension.

Completion of any *Foresight* model requires addition of the constraints. For the tunnelling model, this includes adding functions specifying the individual durations of the "excavation", "concrete lining", and "light track" work units, the result of which is shown in the part 2 of Figure 4, specifically the upper left quadrant of the diagram. In this model, two tunnelling crews have been added by duplicating the highest level work unit. The crews are started at the access shaft located at the midpoint of the tunnel, then head in opposite directions but with different rates of production. For convenience, only the first 60 m of tunnel construction is shown. Note, the progress of the crews follows a curve (reducing with time) which results from the fact that the duration to remove spoil and bring concrete ring segments to the tunnel face increases with tunnel length. This dependence was established by making the duration for a work unit a function of its position along the length of the tunnel.

There are many refinements that may be made to this model to provide more accuracy and/or greater detail to allow decisions to be made about equipment types to be employed. Additional detail may involve, for example, further decomposition of the "excavate", "line tunnel" and "lay track" works units. Furthermore, "excavate" may contain work units representing digging at the tunnel face, loading the light train, hauling the spoil from the tunnel, dumping the spoil, and returning the light train. Other attributes may be added, such as crew members, allowing these to be shared between different work units concurrently.

The visual power of these models is apparent by inspecting the upper left quadrant of the second part of Figure 4, which shows clearly the relative performances of the two crews across the length of the tunnel. In this case crew-performance records had indicated that 1 crew operated about 50% faster. From the *Foresight* model it is apparent that, for a 30 m tunnel, the optimum position for the access shaft would be 3 m to the left of its current position, giving the slow crew just 27 m of tunnel to construct and the fast crew 33 m of tunnel.

Alternatively, an additional attribute could be added to the model representing starting the crews at different positions along the tunnel length, thus providing an automated sensitivity analysis of project duration versus starting point for the crews.

V. Manufacture of Reinforced Concrete Prefabricated Components

This third case study compares the performance of *Foresight* with *CYCLONE* based simulation for modelling a manufacturing process. Specifically a prefabricated reinforced concrete component production system was considered comprising job-to-process flow logic, multiple batch production, a constraint on storage space for components in mid-process, and a dependence on an external material supply line.

Figure 5 shows the *CYCLONE* diagram of this system where production starts with a batch of 10 type A components, followed by a batch of 6 type B components, and finishes with a second batch of 3 type A components. The system is also dependent on the supply of steel reinforcing (rebar) which is delivered to the factory in three lots at different points in time. Finally, there is a limit of 3 components allowed within the curing room at any time (a high humidity space), which is implemented by a permitting resource "cure space". Note, the model would be set-up with a component numbering system that gives priority to the batches in the required order of manufacture.

Figure 6 shows the equivalent *Foresight* model for this manufacturing process. The first part of Figure 6 shows the hierarchy of work units involved in the batch production of the types A and B prefabricated reinforced concrete component, and the supply of rebar. At the third level in the hierarchy are work units representing stations in the factory where tasks such as setting-up forms are executed or temporary storage is provided such as for the curing of the cast concrete components. At the fourth level are the individual repetitions of these tasks.

The second part of Figure 6 shows this section of the model with all constraints added, and is plotted for: Units (counting the number of components produced); and Time. The constraints, which would be added as the work units are added, include:

- The durations of each third level work unit which are defined as the difference between the start and end of a work unit measured in the time dimension.
- Two batches of 10 and 3 units respectively for the Type A components, interposed with a batch of 6 Type B components. The limits on each batch are defined in a similar way to the durations, as difference between the limits of the parent work unit.
- The time dependences between the finishes and starts of Set-Up Forms, Cut & Fix Rebar, Place Concrete, Cure Concrete, and Remove Forms.
- Place Concrete precedes Cure Concrete for each component.
- Cure Concrete precedes Remove Forms for each component. This is implemented by introducing a new attribute Curing Space Permits, assigning all fourth level work units within Place Concrete and Cure Concrete a value of 1 in the Curing Space Permits dimension, and setting the first level work unit for the system to a value of 3 in this dimension. The impact of this limit can be seen in the second part of Figure 6 whereby every 3rd component experiences a delay to Place Concrete.
- The final constraint is concerned with the delivery of rebar. This may be constrained in another dimension, measuring say weight of steel, although for convenience here it is measured in components. The constraint limits the start of Cut & Fix Rebar and is shown in green in Figure 6. The impact of the scheduled delivery is also indicated within this figure.

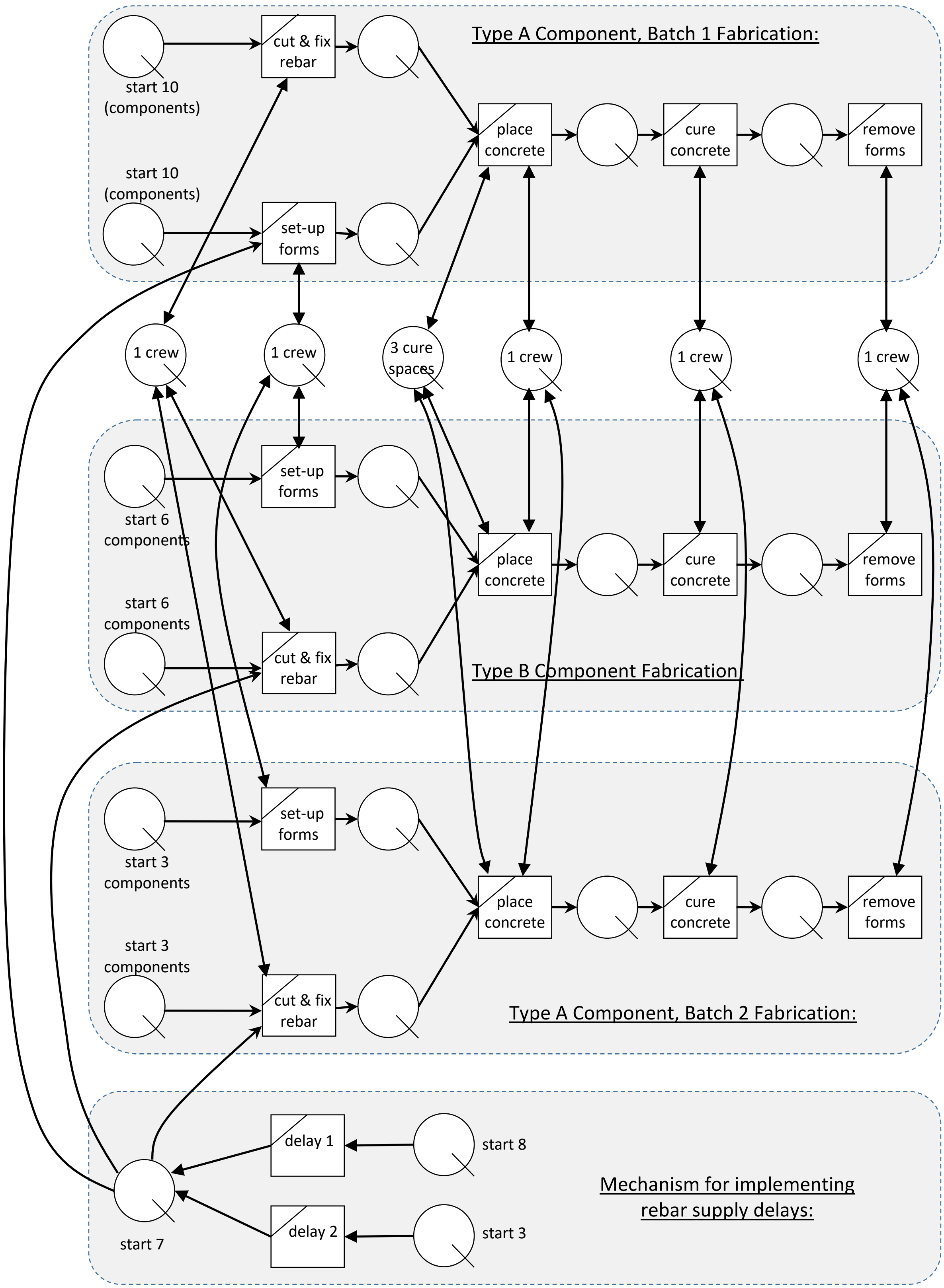

Figure 5. CYCLONE model of manufacture of RC prefabricated components (*adapted from Flood [13]*)

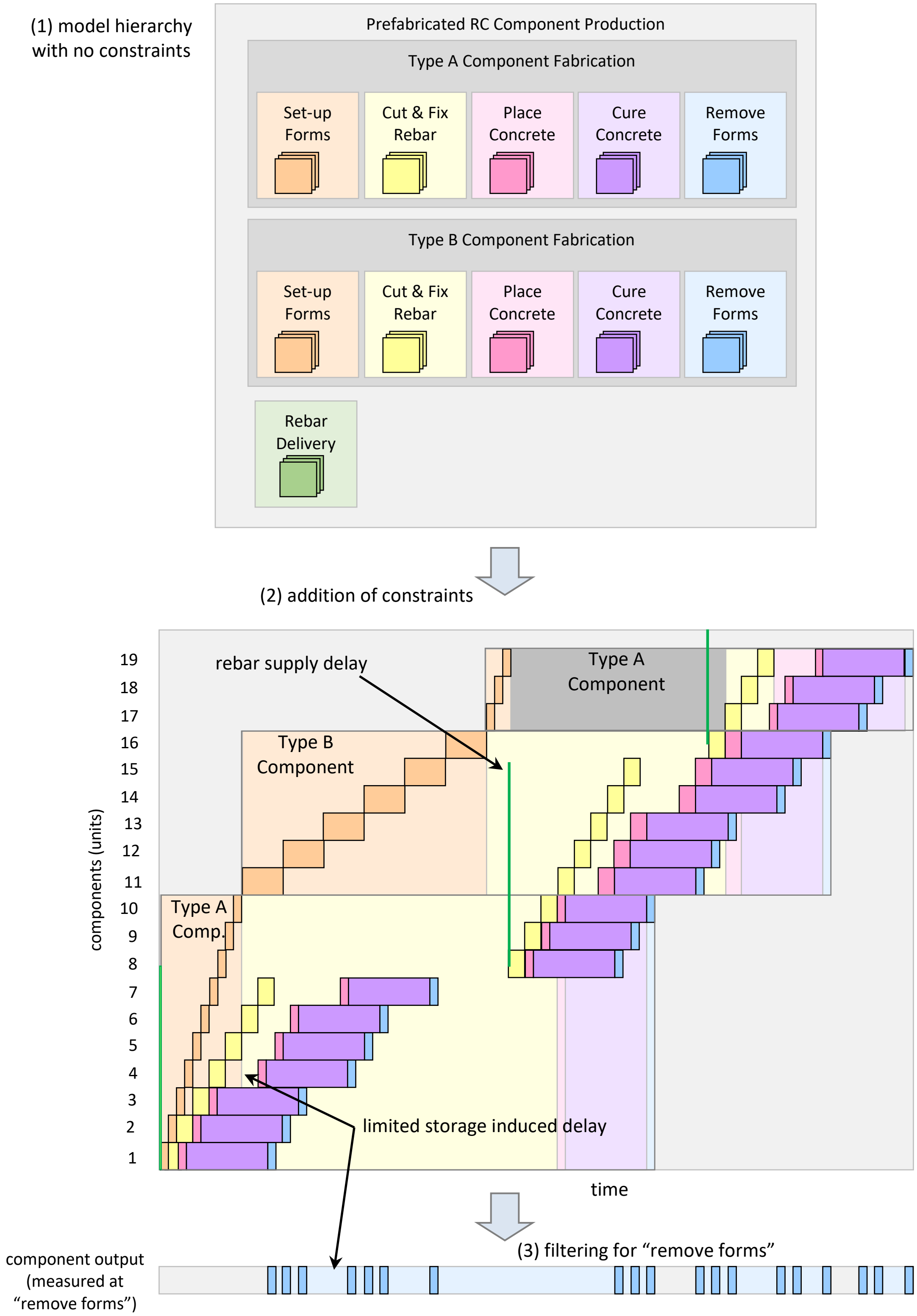

Figure 6. Foresight model of manufacture of RC prefabricated components (*adapted from Flood [13]*)

An important advantage of Foresight over *CYCLONE* is the relative simplicity of the models. A total of 95 terms are required to define the *CYCLONE* model shown in Figure 5 while just 30 terms are required to define the Foresight equivalent. This is similar to the findings made by Flood and Nowrouzian [14] where they made a direct comparison between Foresight and *STROBOSCOPE* [15] (a derivative of the *CYCLONE* modelling system) for construction operations and found that Foresight required around one third of the number of terms to define a model. It was also shown that while *STROBOSCOPE* may employ 25 or more modeling concepts for a relatively simple model, the number of basic modeling concepts employed in *Foresight* will never exceed 5 (the work unit, constraint, attribute, nesting, and repetition). This comparison is for deterministic versions of both the *CYCLONE* and *Foresight* models; if stochastic factors were considered then both models would require the input of additional information describing the uncertainty. For *CYCLONE* these parameters would define uncertainty in the activity durations, for *Foresight* they would define uncertainty in the value of a constraint. This highlights another advantage of *Foresight* over *CYCLONE* that uncertainty can be applied to any model parameter not just activity duration, although simulation in general is also capable of this.

It can be seen visually from Figure 6 that delays in production due to limited curing room space could be removed by expanding this facility to enable storage of an additional 4 components. However, it is also apparent that the most significant cause of poor performance results from the delays to the delivery of rebar.

VI. CONCLUSIONS

In this paper the author has proposed a new approach, named *Foresight*, for modelling construction processes built on concepts relevant to contemporary project planning. 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. The resultant models are highly visual in form, representing the progress of work within the model structure. This provides insight into how the design of a process will impact its performance, and suggests ways of optimizing project performance.

Research is on-going developing detailed models using this method for a variety of project types. The objective of these studies is to determine the successes and limitations of the proposed planning method in the real-world, and to determine refinements that will increase its value as a modelling tool.

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