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MODELING CONSTRUCTION MANUFACTURING PROCESSES USING FORESIGHT

Ian Flood

Rinker School
College of Design, Construction, and Planning
University of Florida
Gainesville, FL 32611-5703, USA

ABSTRACT

An essential part of the planning and control of any manufacturing system is the development of a model of the key processes. The Critical Path Method (CPM) is the most widely used modeling method in construction due to its simplicity. Discrete-event simulation is more versatile than CPM and is well suited to modeling manufacturing processes since these tend to be repetitive, but it lacks the simplicity in use of CPM and thus has not been widely adopted in construction. This paper demonstrates an alternative modelling approach, Foresight, developed to provide the modeling versatility of simulation, and yet be relatively simple to use and visually insightful. Previous work demonstrated the application of Foresight to *in-place* construction work and compared its performance to conventional simulation. This paper extends this work, demonstrating the application of Foresight to manufactured construction processes whereby streams of jobs, with design variances, are executed within a factory.

1 INTRODUCTION

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 grouped into three main categories: the Critical Path Methods (CPM); the linear scheduling techniques; and discrete-event simulation. Most other tools are either an enhancement or an integration of these approaches. For example, 4D-CAD and nD-CAD planning methods (Issa et al. 2003; Koo & Fischer 2000), where one of the dimensions is time, are strictly CPM models hybridized with 3D-CAD for visualization purposes.

Each category of modelling method is, unfortunately, only relevant to a restricted range of construction planning problems. CPM methods (the most widely adopted in construction) are 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 and Ioannou 1998). Moreover, CPM models become cumbersome when used to model repetitive processes (as are prevalent in manufacturing 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 time-wise dependencies only. Manufacturing processes are subject to a wide range of dependencies beyond the timing of events and would benefit from a modeling system that can illustrate all such logic graphically.

Linear scheduling, as an alternative, 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 an integrated framework. Consequently, they provide the modeler 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). In these respects the approach may seem well suited to modelling manufacturing processes. However, linear scheduling cannot be used to model non-repetitive work and, more importantly for modeling manufacturing processes, it includes some simplistic assumptions which make it difficult to model anything other than simple progress dependencies between different tasks.

Finally, discrete-event simulation (see, for example, Halpin and Woodhead (1976); Sawhney et al. (1998); 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 sufficiently accurately using CPM or linear scheduling. In addition, simulation models provide no direct visual indication of how a system's logic determines its performance. 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. This also makes debugging of a model (verification) difficult since the model must be complete before it can be used to generate output and performance predictions.

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 represent all situations (typically CPM) compromises a user's ability to plan and control work optimally.

Ideally, what is needed is a single tool that is well suited to modelling the broad spectrum of repetitive and non-repetitive construction work, is highly versatile, provides insight into better ways of organizing work, and is easy to use. Foresight (Flood 2010) is a new method of systems modeling that addresses the above issues. It has been demonstrated to be a realistic alternative to CPM, linear scheduling and discrete-event simulation (Flood 2010), and has been shown to have greater simplicity in use than discrete-event simulation but without compromising modeling versatility (Flood and Nowrouzian 2014). To date, Foresight has been applied to *in-place* construction work, where the items under construction are at fixed locations and productive resources are moved between processes. This paper considers the alternative approach to manufacturing whereby the item under construction is moved between processes and productive resources are usually kept at fixed locations. Characteristics of these processes are task and job repetition, frequent reorganization of work to account for design variances, and batch processing of alternative components. The application of Foresight to modeling manufacturing systems is demonstrated in a study of a prefabricated reinforced concrete component factory. A comparison is then made with a discrete-event simulation approach to this problem.

2 FORESIGHT

The goal in developing the new approach to modeling 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. (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 modeling concepts of Foresight are as follows and should be read with reference to 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 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 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 a Batch of Components'), a low level (such as 'Assemble Forms') 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' and 'c' 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.

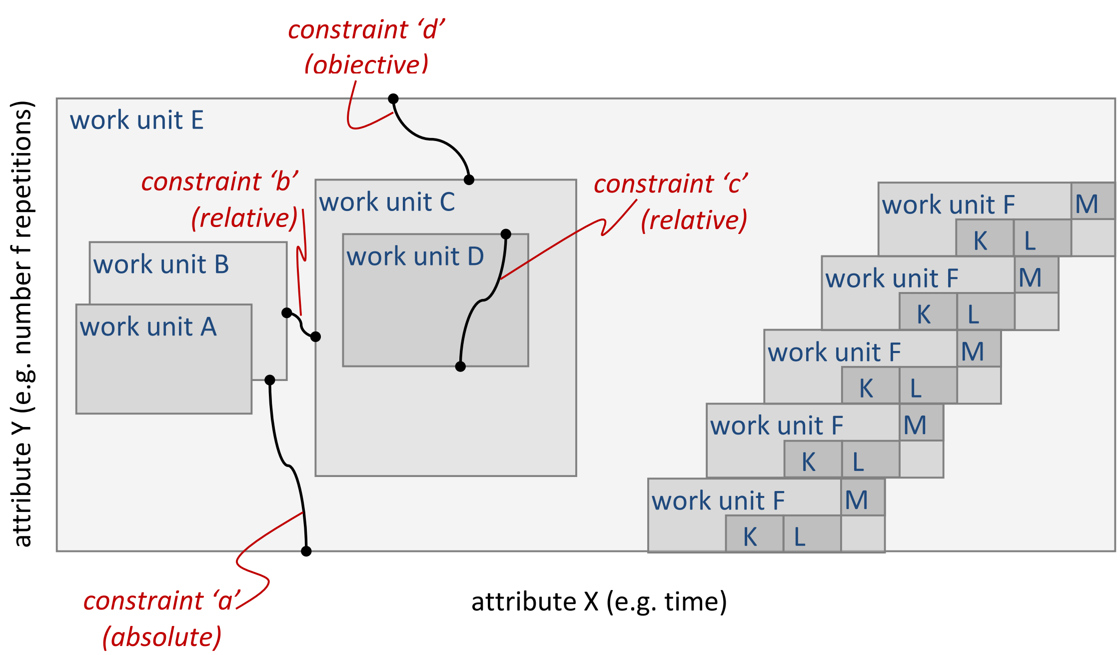


Figure 1: Schematic illustrating the primary Foresight modeling concepts.

There are two secondary concepts in the Foresight modeling system, both concerned with overall model structure:

- **Nesting**. 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' which is respectively part of '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.

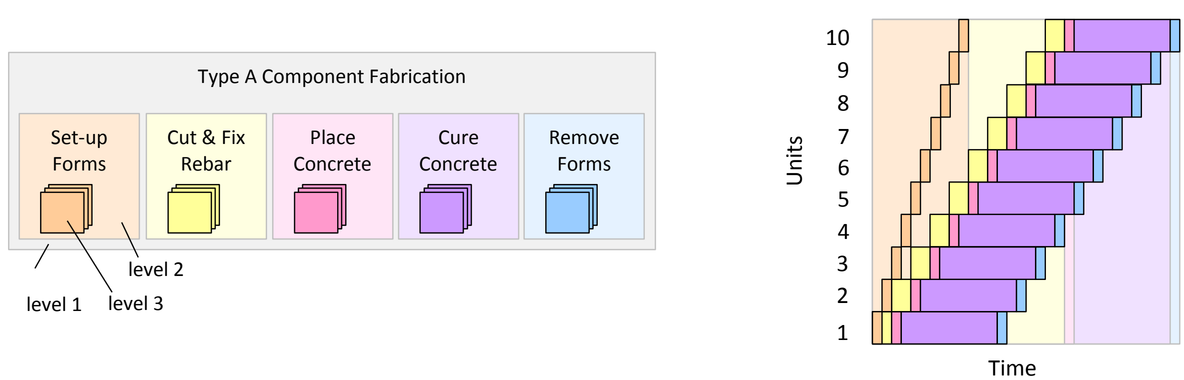
- **Repetition**. Work units can be repeated (such as work unit F in Figure 1) and can be implemented at any level within the nesting hierarchy, thus minimizing the amount of work required to define a model. Repetition of a work unit will include a repetition of all relevant constraints and its nested work units and their constraints.

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 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.

3 PREFABRICATED REINFORCED CONCRETE COMPONENT PRODUCTION SYSTEM

Prefabricated reinforced concrete component systems are a classic example of the manufacturing planning problem, comprising for example multi-level repetition of work, batch production requirements, dependence on external supply lines, and constraints on storage of components. Figure 2a shows the hierarchy of work units involved in a batch run of one type of prefabricated reinforced concrete component. At the second 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 third level are the individual repetitions of these tasks.

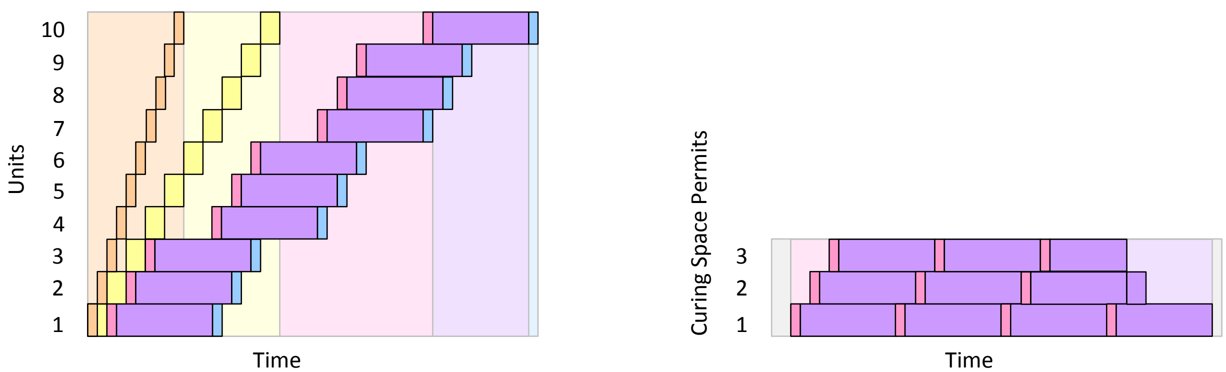


(a) three level hierarchy of work units excluding constraints (b) inclusion of main constraints

Figure 2: Foresight model of the manufacture of the first ten units of component type A.

Figure 2b shows this section of the model with some of the main constraints added, and is plotted for two attributes: "Units" (counting the number of components produced); and "Time". The constraints added so far include: (a) the durations of each third level work unit (the relative distance between the start and end of a work unit measured in the time dimension); (b) a batch limit of 10 components; (c) *Set-Up Forms* and *Cut & Fix Rebar* both precede *Place Concrete* for each component; (d) *Place Concrete* precedes *Cure Concrete* for each component; and (e) *Cure Concrete* precedes *Remove Forms* for each component.

The next constraint to be added assumes that the curing room (a high humidity space designed to facilitate the concrete hydration process) only has space for three components at a time. This means that *Place Concrete* should not start for a component until space in the curing room will be available. The impact of this constraint on the system is shown in Figure 3a. It is implemented using an attribute "Curing Space Permits". All third level work units within *Place Concrete* and *Cure Concrete* have a scope of 1 in the "Curing Space Permits" dimension, and the first level work unit for the system has a scope of 3 in this dimension, effectively limiting the number of components in the curing room to 3. Figure 3b shows the occupation of the curing room by the prefabricated components measured as "Curing Space Permits" versus "Time". Once the model is complete, the planner may inspect this aspect of the model to determine whether it is worthwhile investing in the construction of a second or larger curing space, in terms of both cost and impact on production rate.



(a) inclusion of limited storage space constraint

(b) demand for curing space permits

Figure 3: Foresight model of the manufacture of the first ten units of component type A where space for storage of curing units is restricted.

Typically, prefabricated reinforced concrete facilities will produce a range of component types, and produce these in batch sizes designed to satisfy the quantity and timing demands of the construction projects being supplied. To illustrate the application of Foresight to this situation, a demand for two types of prefabricated component (A and B) will be considered, produced in three batches as shown in Figure 4. Note that the Type B components go through the same processes as the Type A component but the durations of the third level components are different reflecting differences in the design of the two component types. In this example the Type A components are produced in two batches interposed with one batch of component Type B to satisfy scheduling demands of the construction project. The second batch of component Type A has a reduced production limit set to 3 components, while the component Type B batch is set to 6 components. Patterns such as this could be readily repeated by enveloping the three batches shown in a parent work unit and then repeating this element as required.

The constraint on the number of components that can be stored in the curing room is applied across the complete model. If some components were larger than others, taking up more space, then this could be simply accounted for by replacing the attribute "Curing Space Permits" with one measuring physical space the consumption of which could be different for each component type.

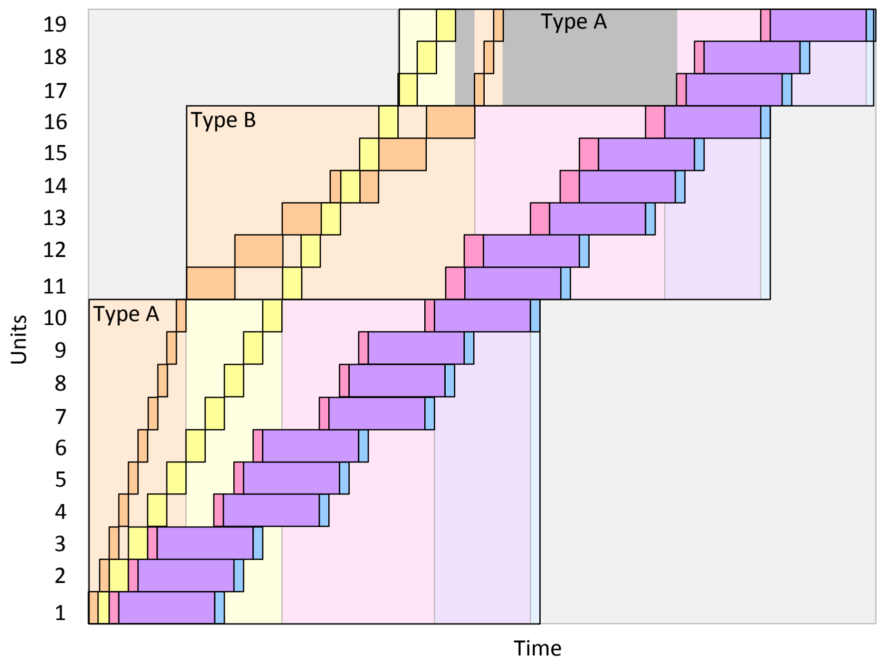
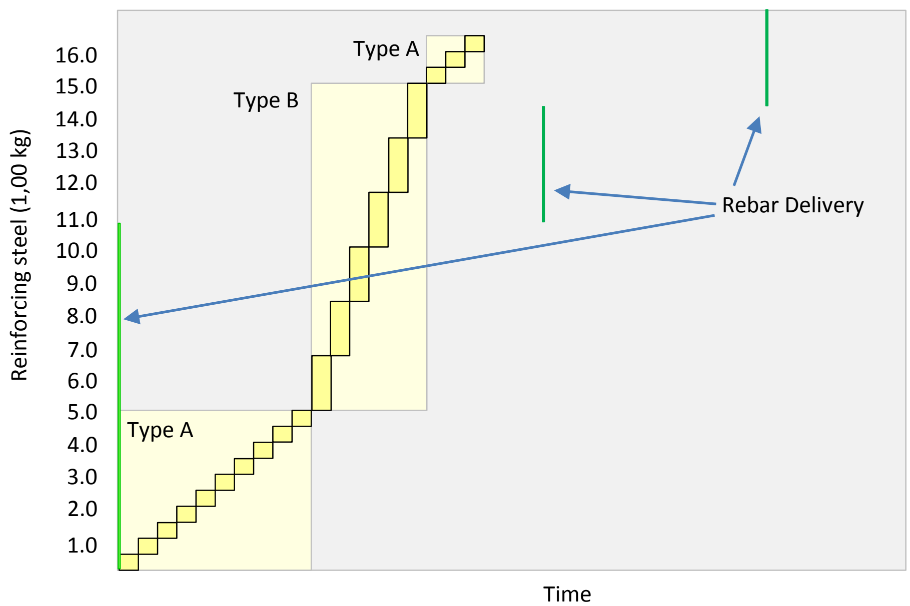


Figure 4: Foresight model of the manufacture of two batches of component type A interposed by a batch of component type B.

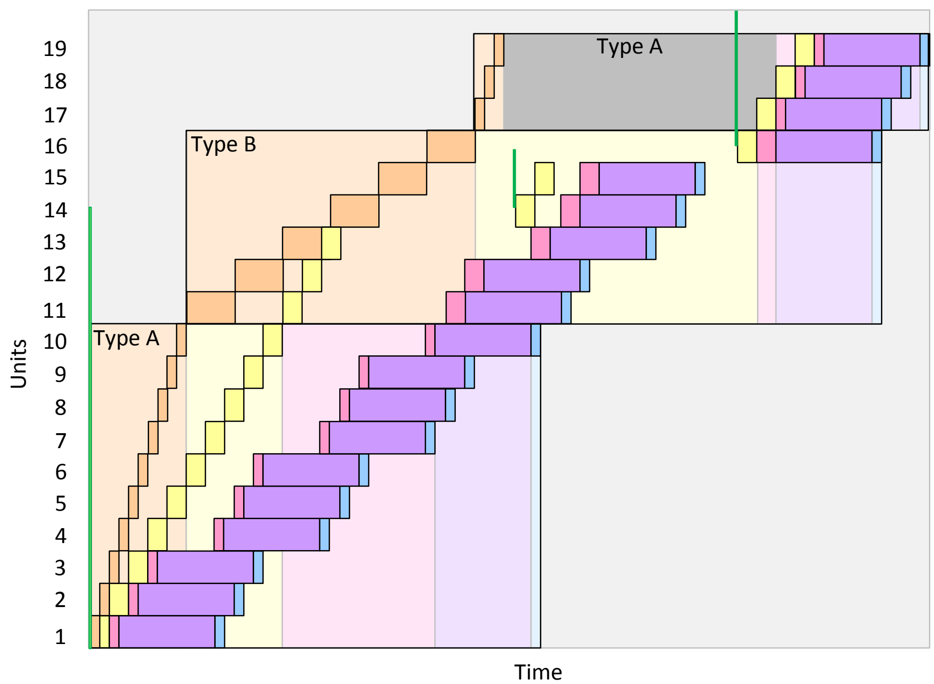
Another common type of constraint that manufacturing systems can experience is supply line delays. Consider, for example, a situation where the delivery of reinforcing steel becomes an issue impacting the *Cut & Fix Rebar* process. Figure 5a shows a possible supply scenario for reinforcing steel in terms of timing and quantities, represented as 3 work units color coded in green. Also shown in yellow is the set of *Cut & Fix Rebar* work units, which in effect represent the demand for the reinforcing steel. Note, the amount of reinforcing steel (measured vertically in Figure 5a) is greater for Type B components than Type A components. Figure 5a shows this section of the model before the dependence between the supply and demand of reinforcing steel has been implemented. Once this dependence has been implemented the resultant delays to work units and impact on production are as shown in Figure 5b.

4 COMPARISON WITH DISCRETE-EVENT SIMULATION

For comparison, a conventional discrete-event simulation model was developed of the prefabricated reinforced concrete component manufacturing system considered in section 3 above. Figure 6 shows a CYCLONE simulation diagram representing the process logic and resource assignments for this system. CYCLONE (Halpin and Woodhead 1976) was chosen since it was developed specifically for modeling construction processes and is the most widely used form of discrete-event simulation in construction. The model as drawn only considers two batches of components, 10 Type A's followed by 6 Type B's. Although the CYCLONE model could have included the third batch of 3 Type A components, this would have required a complicated switching mechanism regulating the flow of resources between the alternative processes representing Type A and Type B component manufacture. Such an extension could actually be better handled using the STROBOSCOPE simulation modeling system (Martinez 1996), a derivative of CYCLONE. However, although STROBOSCOPE is functionally more sophisticated than CYCLONE, it requires considerably more expertise to use. The CYCLONE model also does not consider the supply line for reinforcing steel. Again, this would require another complicated extension to the model that could be better handled using the STROBOSCOPE simulation modeling system.



(a) rebar delivery versus rebar demand (delivery/demand dependence not yet implemented)



(b) rebar delivery/demand dependence now implemented showing impact on schedule

Figure 5: Addition of a supply line constraint: late delivery of reinforcing steel and its impact on schedule.

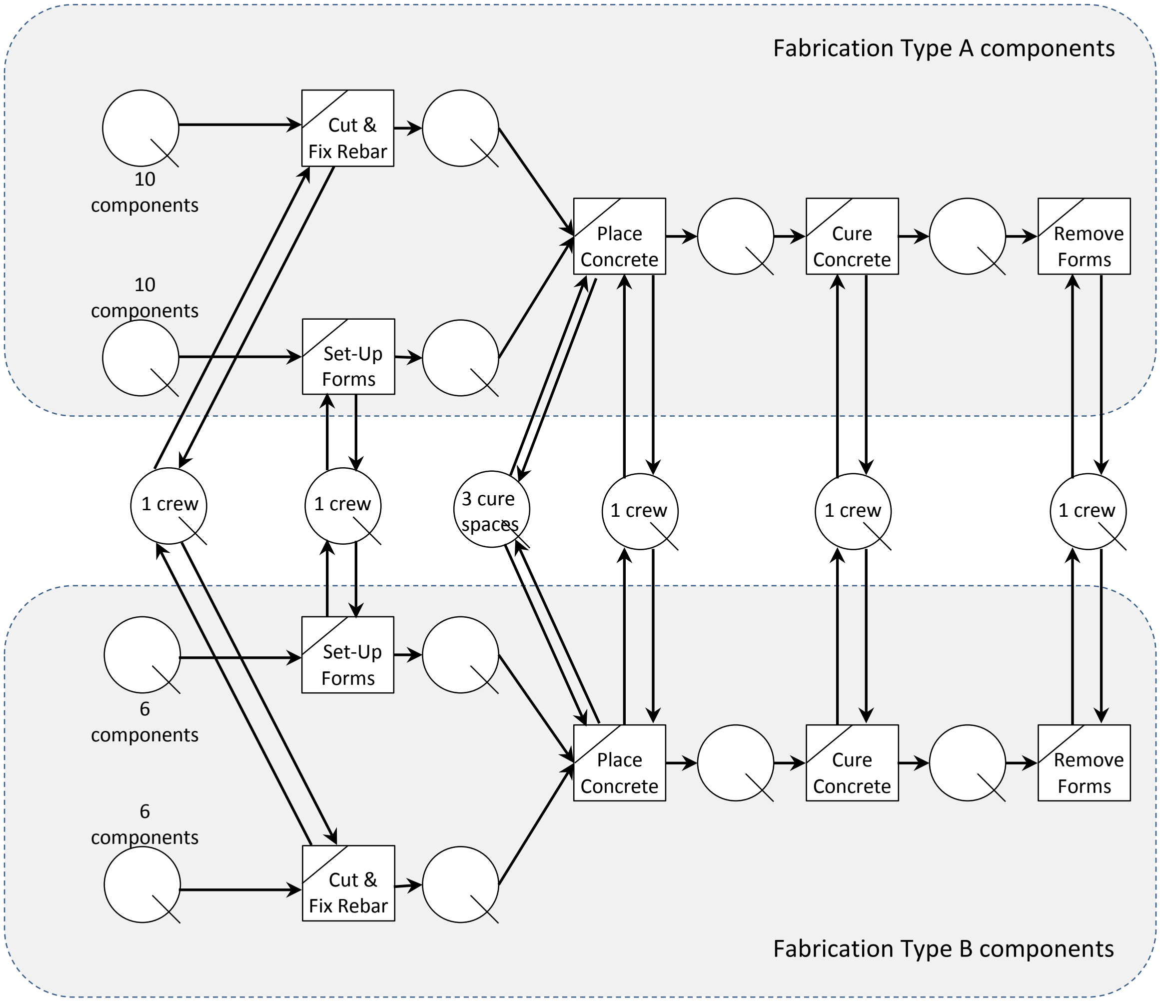


Figure 6: CYCLONE model of the manufacture of prefabricated reinforced concrete components.

Several important differences between CYCLONE and Foresight can be understood by comparing the model representations of Figure 5b and Figure 6. First, it should be understood that CYCLONE requires the complete logic of the model (as represented by the CYCLONE diagram of Figure 6) 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 Figure 5b). This gives Foresight a couple of significant advantages. First, as elements are added to the model and its parameters altered, the impact of these edits on the estimated performance of the system are seen immediately - the model does not have to be 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 and has the advantage of aiding verification and validation of the model. The second advantage of Foresight is that the way in which a model's logic and structure impact performance is directly visible, which in turn assists in the optimization of the design of the system.

Another significant advantage of Foresight over conventional simulation is that it is much simpler to use, as demonstrated by Flood and Nowrouzian (2014). Their study made a direct comparison between Foresight and STROBOSCOPE for a couple of relatively simple construction processes and found that Foresight required around one third of the number of terms to define a model. For models of more complicated systems it was contended that this advantage becomes more marked. 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: (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.

5 CONCLUSIONS AND FUTURE DEVELOPMENTS

The paper has proposed a new approach, Foresight, for modeling construction processes built on concepts relevant to contemporary project planning, and demonstrated its application to manufacturing systems. The principles upon which Foresight is based provide it with the versatility necessary to model the broad spectrum of construction systems that until now have required the use of several different modeling tools. The resultant models are highly visual in form, representing the progress of work within the model structure. This facilitates model verification and validation, provides insight into how the design of a process will impact its performance, and suggests ways of optimizing project performance. Foresight is also simpler to use than conventional simulation, employing fewer modeling concepts and allowing models to be defined using a fraction of the number of terms.

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 modeling tool.

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AUTHOR BIOGRAPHIES

IAN FLOOD is Holland Professor and University of Florida Research Foundation Professor in the Rinker School of Construction Management, College of Design, Construction and Planning, at the University of Florida. He holds a Ph.D. in Construction Management and Computer Simulation from the University of Manchester, UK. His email address is flood@ufl.edu.