A Constraint-Based Graphical Approach to Modelling Construction Systems:

An alternative to discrete-event simulation

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***Abstract* — An essential part of the planning and control of any construction system is the development of a model of the project's key 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. Most other modelling techniques have limited scope being aimed at specialized types of project. Linear scheduling, for example, provides excellent visual insight into the performance of a system but is limited to modelling construction processes that progress along a line, such as tunnels and highways. Discrete-event simulation is the most versatile of all modelling methods, but it lacks the simplicity in use of CPM and for this reason has not been widely adopted in practice. This paper demonstrates an alternative modelling approach designed to provide the visual insight of linear scheduling, the modelling versatility of simulation, and yet be relatively simple to use and understand. The principles and use of the approach are demonstrated in application to three example construction industry projects.**

Keywords – interactive modeling, discrete-event simulation, process modeling, graphical constraint-based modeling, visualization.

I. INTRODUCTION

The last 100 years has seen the development and application of a wide range of methods for modelling construction processes. An analysis of the genealogy [1] 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. For example, 4D-CAD and nD-CAD planning methods [2] [3], 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 are, unfortunately, only relevant to a restricted range of construction planning problems. 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 [4]. 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 [5]). 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.

Finally, discrete-event simulation (see, for example, Halpin and Woodhead [6]; Sawhney et al. [7]; Hajjar and AbouRizk [8]) 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. That is, performance is an output from the model after it has been fully developed; it is not an integral

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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 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. This paper goes back to basics and proposes a new modelling paradigm, *Foresight*, that addresses the above issues. Section II introduces the principals of the *Foresight* modelling system. Sections III to V provide three case studies demonstrating the application of *Foresight* to construction projects that would otherwise best be modelled using discrete-event simulation: a simple earthmoving operation, a tunnelling operation; and an underground utility laying operation.

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. [9] and Ceric [10]) 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 '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

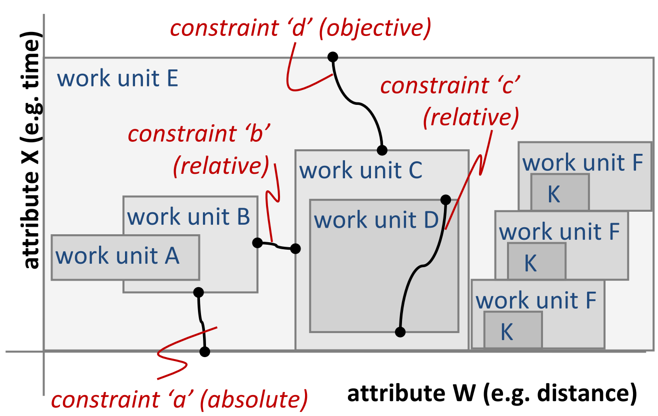

Figure 1. Schematic illustrating the three principal concepts of Foresight.

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 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. Simple Earthmoving Operation

The first system to be modelled is that of a simple earthmoving system comprising an excavator used to load dump trucks. Figure 2 shows a CYCLONE [6] simulation process diagram of this system for a situation where there are three trucks (each of 5 cu-yds capacity), and one excavator (with a 1 cu-yd bucket). The excavator must therefore perform five cycles to load a truck.

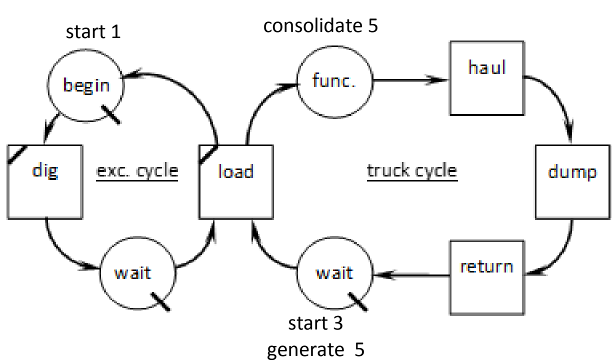

Figure 2. CYCLONE simulation process diagram for a simple earthmoving operation.

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.

The *Foresight* representation of this system is presented in Figure 3. Part (a) of this figure shows the hierarchical form of the model (without the main constraints added) whereas part (b) shows the model in its normal format with all constraints added representing, for example, work unit durations, and precedence. Parts (c) and (d) of Figure 3 show the model using the variables trucks versus time, and excavators versus time respectively. Figure 3(c) only shows the model to the 2nd level in its hierarchy, even though the truck activities go down to the 3rd level, to allow a more generalized understanding of its performance. Likewise, Figure 3(d) shows the activities of the excavator down to the 4th rather than 5th level. These plots effectively show the demand for these productive resources over time, indicating any idle time and thus possible imbalance in the resource combinations. Appropriate statistics concerning these factors can be readily extracted.

Several important differences between CYCLONE and Foresight can be understood by comparing the model representations of Figs. 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 Figure 3(b)). 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. 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 clay and the lining is formed from concrete ring segments. The example is used to illustrate the steps in developing a *Foresight* model for a problem that, given its complexities, should otherwise 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-

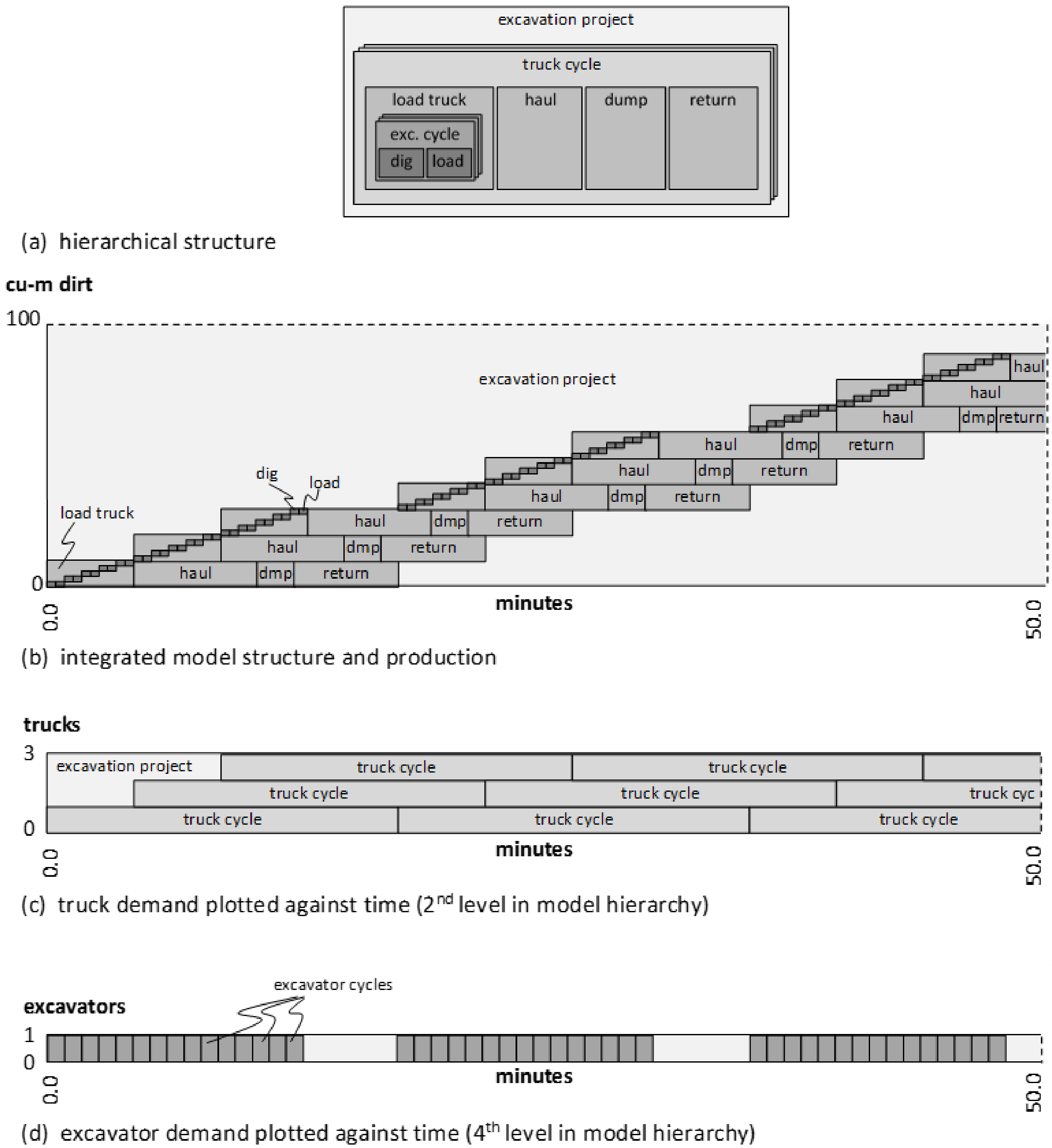

Figure 3. Foresight model of a simple earthmoving operation.

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. 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 *Excavation* representing the cutting of 1 m length of the tunnel, and *Concrete Lining* which involves placing and grouting concrete ring segments in the 1 m cut. *Excavating* and *Concrete Lining* are repeated 3 times thereby constructing a 3 m length of tunnel, which is then followed by *Light Track* which lays a 3 m length of track used to carry a manually propelled train for removal of spoil and delivery

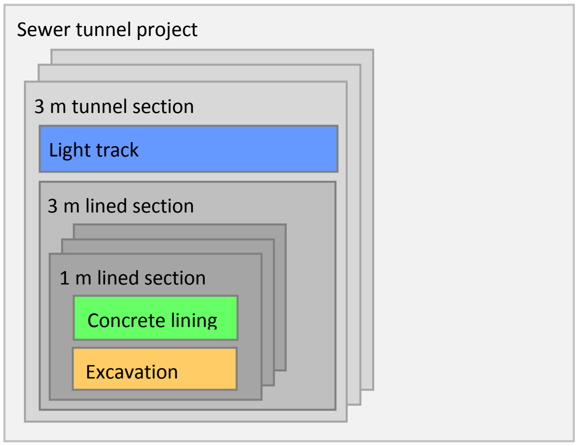

Figure 4. Foresight hierarchical model structure representing a tunneling operation.

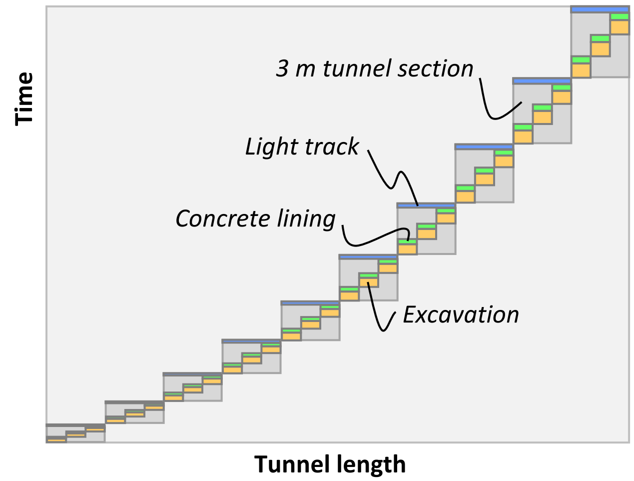

Figure 5. Tunnelling model with constraints added.

of concrete ring segments. 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 the tunnel model, the main constraints would be as follows:

- 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.
- *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 heights of the *Excavation*, *Concrete lining*, and *Light Track* work units, indicating their respective durations, the result of which is shown in Figure 5. For convenience, only the first 30 m of tunnel construction is shown. Note, the progress of the project follows a curve, which results from the fact that the duration to remove spoil and bring concrete ring segments to the tunnel face increases with tunnel length. Such a dependence can be readily established as a function of the 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 *Excavation*, *Concrete lining* and *Light track* works units. *Excavation* 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.

To illustrate the visual power of these models, consider the problem where two separate crews will be employed for tunnelling, each starting at the same point but heading in opposite directions. If crew-performance records indicate that 1 crew tends to operate about 50% faster than the other then we would want to find a starting location that would minimize the total project duration. If the tunnel was 60 m in length and employed two crews starting at the midpoint, with the slower crew heading to the left and the faster crew heading to the right, then the model would appear as shown in Figure 6. It can be seen from this chart that the faster crew should probably start 3 m or 6 m to the left of the midpoint to minimize the project duration – both choices could be tested quickly. Alternatively, an additional dimension 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. UNDERGROUND UTILITY LAYING OPERATION

A *Foresight* model of an electrical cable laying project, complete with constraints, is shown in Figure 7. The operation is typical of the type of process that would be

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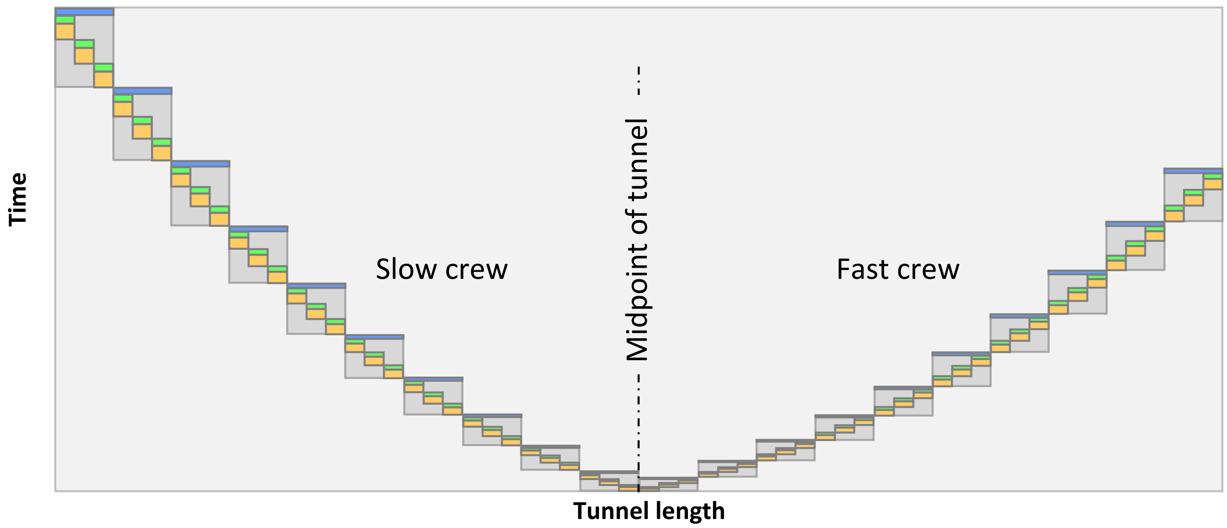

Figure 6. Tunnelling model with two crews starting at centre and heading in opposite directions.

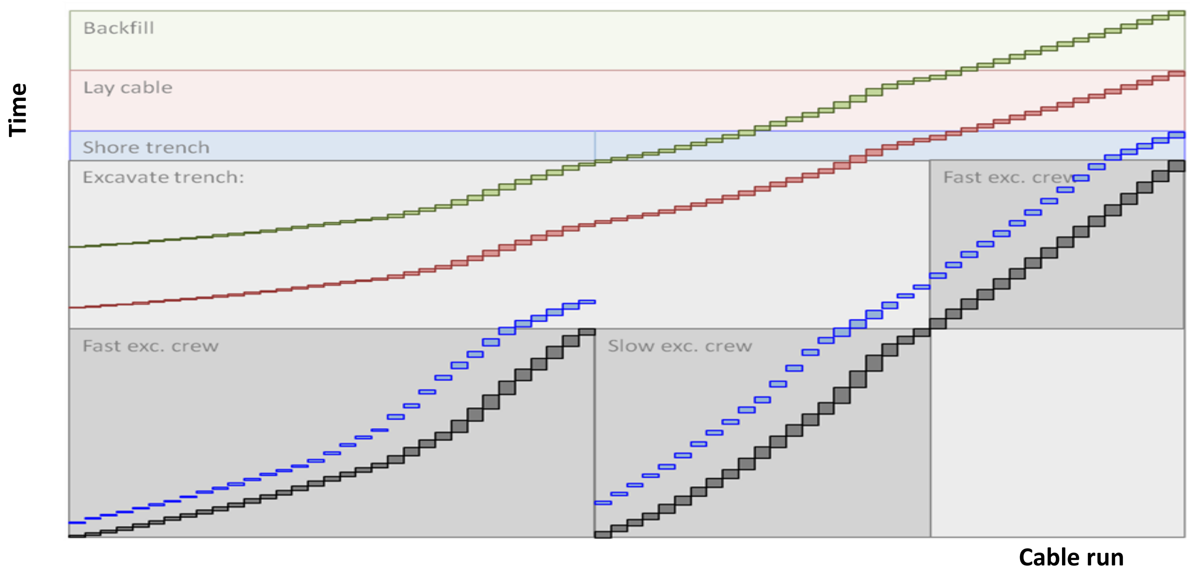

Figure 7. Underground electrical cable laying operation.

modelled using linear scheduling except that it includes some logical features that are beyond conventional linear scheduling methods.

The project comprises four main tasks: *Excavate trench*; *Shore trench*; *Lay Cable*; and *Backfill*, each of which is colour coded. The smaller sized work units represent work on 1 m lengths of the project while the larger work units are essentially summaries of each task. Important feature of this model are:

- There are two crews available for excavation work and two crews available for shoring. The first excavation crew is faster than the second and will leap frog them when they reach their starting point.
- *Shore trench* has two constraints relative to *Excavate trench*, a minimum and a maximum permissible distance. The minimum working distance is for safety and to prevent interference between the crews. The maximum distance is to minimize the chances of the trench collapsing before being shored. In this example, the Shore trench crew must spend some time idle to ensure that the minimum distance constraint is not violated. If they operated considerably slower then the excavation crew would have had to spend time idle to ensure the maximum distance buffer was not violated.
- A constraint is imposed on both *Lay cable* and *Backfill* that prevents gaps between their work units within the model (effectively meaning they cannot spend time

idle). This constraint reduces the amount of time their crews are employed on the project. As a consequence, *Lay cable* and *Backfill* are forced to start later.

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.

REFERENCES

[1] I. Flood, R.R.A. Issa, and W. Liu, “A New Modeling Paradigm for Computer-Based Construction Project Planning”, Proc. Joint Intnl. Conf. on Cmptg. and Decision-Making in Civil and Building Engineering, Montreal, Canada, ASCE, June 2006, pp 1-11.

[2] B. Koo and M. Fischer, “Feasibility Study of 4D CAD in Commercial Construction”, Journal of Construction Engineering and Management, ASCE, 126(4), 2000, pp 251-260.

[3] R.A. Issa, I. Flood, and W. O’Brien, (Eds.), 4D CAD and Visualization in Construction: Developments and Applications, A. A. Balkema Publishers, Steenwijk, 2003.

[4] R.B. Harris and P.G. Ioannou, “Scheduling Projects with Repeating Activities”, Journal of Construction Engineering and Management. ASCE, 124(4), 1998, pp 269-276.

[5] K.G. Matilla and D.M. Araham, “Linear-Scheduling: past research efforts and future directions”, Engineering, Construction, and Architectural Management, Blackwell Science Ltd, 5(3), 1998, pp 294-303.

[6] D.W. Halpin and R.W. Woodhead, Design of Construction and Process Operations, John Wiley and Sons, Inc., New York, NY, 1976.

[7] A. Sawhney, S.M. AbouRizk, and D.W. Halpin, “Construction Project Simulation using CYCLONE”, Canadian Journal of Civil Engineering, 25(1), 1998, pp 16-25.

[8] D. Hajjar and S.M. AbouRizk, “Unified Modeling Methodology for Construction Simulation” Journal of Construction Engineering and Management, ASCE, 128(2), 2002, pp 174-185.

[9] P. Huber, K. Jensen, and R.M. Shapiro, "Hierarchies of Coloured Petri Nets", Proc. 10th Int. Conf. on Application and Theory of Petri Nets, (LNCS 483), Springer-Verlag, 1990, pp 313-341S.M.

[10] V. Ceric, “Hierarchical Abilities of Diagrammatic Representations of Discrete-Event Simulation Models”, Proc. 1994 Winter Simulation Conference, (Eds. J. D. Tew, S. Manivannan, D. A, Sadowski, and A. F. Seila), 1994, pp 589-594.

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