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SIMULATION OF THE STRUCTURAL STEEL ERECTION PROCESS

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ABSTRACT

The construction industry's growth and the adoption of newer means, methods, and materials of construction have resulted in an increase in complexity of on-site construction processes. Consequently, the construction industry's need for advanced tools and techniques to study, plan, and manage these complex construction processes has developed. This paper illustrates a Petri Net based hierarchical and modular modeling and analysis technique that can be used for simulation of complex construction processes. Through the use of hierarchy, modularity, and resource modeling, Petri Nets provide clear advantages in the modeling of complex construction processes. This paper highlights the advanced features of Petri Nets and their utilization in the modeling and analysis of a structural steel erection process.

1 INTRODUCTION AND BACKGROUND

The construction phase of a civil engineering facility is a complex enterprise characterized by a set of tasks or activities with complex relationships. The progress of these activities is heavily influenced by an environment that is characterized by stochastic phenomena such as, changing weather conditions, equipment breakdowns, etc. Hence, the planning, scheduling, and control of the various activities and resources of a construction project are among the most challenging tasks faced by a professional construction manager (Barrie and Paulson 1992). Tools and techniques to analyze, plan, and control the construction processes must be utilized. Over the last two decades, research and advancements in the area of modeling and analysis of construction processes have demonstrated the usefulness of computer simulation in this role. Modeling is an important step for understanding and improving a process' performance (Kartam et al. 1997). One of the more widespread construction modeling/simulation tools is CYCLONE, developed by D. W. Halpin in 1977. Recently, another powerful modeling tool, Petri Nets, has been developed and used for the modeling of construction processes. Illustrative examples of construction process modeling using Petri Nets, are presented by Wakefield and Sears (1997), Wakefield (1998), Sawhney et al. (1998) and Sawhney et al. (1999). Sawhney (1997) illustrated the simulation capabilities of a proposed Petri Net based construction scheduling technique. These efforts, however, concentrate on the utilization of the basic features of Petri Nets. In turn, this has motivated the authors to demonstrate the availability and utilization of the advanced features of Petri Nets for modeling of complex construction processes.

2 OVERVIEW OF CLASSICAL PETRI NETS

Petri Nets were introduced by Carl A. Petri in the early 1960s as a graphical and mathematical tool to model computer systems. They can generally be used for describing and studying systems that are characterized as being concurrent, asynchronous, distributed, parallel, non-deterministic, and stochastic (Murata 1989).

Classical Petri Nets consist of four types of modeling elements, namely : (1) places, (2) transitions, (3) arcs, and (4) tokens. The four basic Petri Net modeling elements are illustrated in Figure 1.

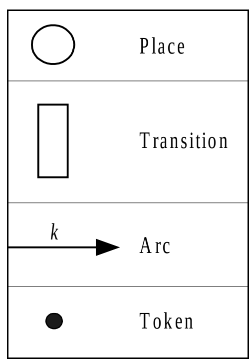

Figure 1: Modeling Elements of Classical Petri Nets

Petri Nets have two types of properties. The first type is similar to the flowchart of a computer program and is called the static property, while the second type resembles the execution of the computer program and is called the dynamic property (Shyam Kishore Bajpai 1982). Places, transitions, and arcs together are used to develop a static picture of a process while tokens provide the dynamic simulation capabilities to Petri Nets. They are initialized at a given place, which may contain zero or more tokens (Sawhney et al. 1998).

Interested readers can obtain more knowledge on the topic of application of classical Petri Nets in the modeling and analysis of construction processes in the works of Wakefield and Sears (1997) and Wakefield (1998). This paper focuses on the enhanced features of Petri Nets.

3 ENHANCED PETRI NETS

Enhanced features have been incorporated into the classical Petri Net in order to allow the modeling of complex processes. The following enhanced features, depicted in Figure 2, were used in the steel erection model described in this paper:

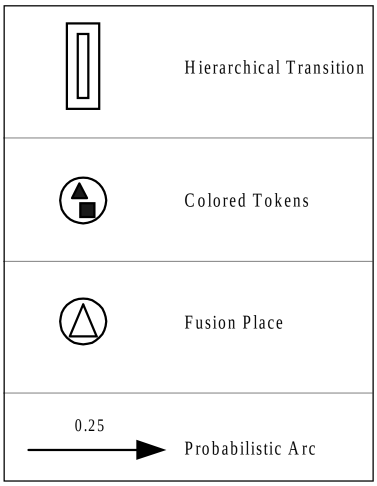

Figure 2: Enhanced Petri Net Modeling Elements

3.1 Hierarchy and Modularity

Developing a single model for a complex system, is in many cases, very difficult and may lead to a model too complex and poorly structured to be useful (Meta Software Corporation 1993). To improve modeling of such complex systems, enhanced Petri Nets allow the hierarchical breakdown of a complex process with the help of a special hierarchical transition, also called a box (Meta Software Corporation 1993; Moore and Brennan 1996). The hierarchical transition is denoted by two rectangles, one enclosing the other in Figure 2. A hierarchical transition represents not a single task, but a group of recurrent work tasks at a lower level of the process. A lower level sub-model, models these work tasks and constitute a module that can be repeatedly invoked by the higher level model using hierarchical transitions.

3.2 Fusion Places

Resources are shared by activities at different levels of a construction process. The use of fusion places enhances the resource modeling features of Petri Nets and permits the modeling of such situations (Meta Software Corporation 1993; Moore and Brennan 1996). Resources can now be modeled separately as a fusion place, represented by a polygon contained in a circle as shown in Figure 2, and then used throughout a higher level model by referencing to this fusion place. This is achieved by repeating the fusion place modeling element whenever the respective resource is needed. Thus, fusion places make the practical utilization of the concept of hierarchy and modularity possible.

3.3 Colored Tokens

Tokens are normally used to model resources in a construction process. Resources with different attributes must thus be modeled by different tokens. In enhanced Petri Nets, the modeler has the possibility to define more than one type of token for a Petri Net. This is achieved by assigning a color or type to the token. These types of tokens are called colored or typed tokens, while the resulting Petri Nets are called Colored Petri Nets (Jensen 1992). In the model of the steel erection process, described later in this paper, a token called "structural steel element" is defined. This token has an attribute (color) called "element type". The value of this attribute can be a column, a beam, or a decking element.

3.4 Probabilistic Arcs

Probabilistic arcs provide a way to model a situation in which one activity/transition is more likely to occur than another. Various output places or transitions representing the possible outcomes or alternative tasks are used and the various arcs are assigned probabilities.

4 THE STEEL ERECTION PROCESS

Figure 3 provides an overview of the project and process chosen to illustrate the use of enhanced Petri Nets in the role of planning and analysis of construction processes. The steel erection process was a part of Phase 1 of the Campus Redevelopment of Bronson Methodist Hospital in Kalamazoo, Michigan. -It involved a total of 129 columns, 1028 girders and beams as well as bundles of decking for a total of 186,000 ft^2. Under the erection scheme used for the project, sometimes referred to as "billboarding", the area was subdivided into six (6) zones as shown in Figure 3.

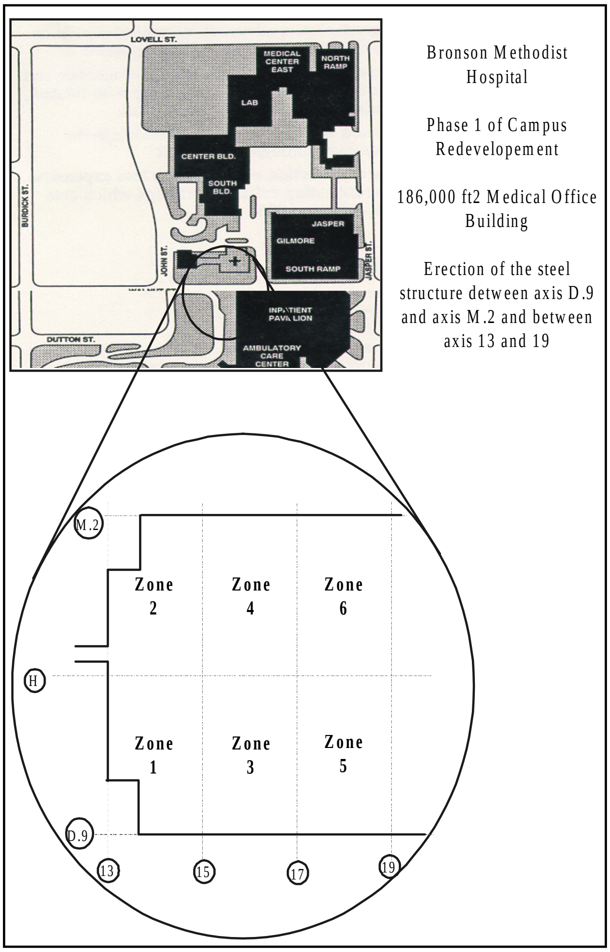

Figure 3: Overview of the Steel Erection Project

Zones typically had three (3) tiers of two (2) stories each. Tiers of two zones were erected and detailed alternately. Thus, initially, the first tier of zone 1 was erected. Subsequently, the first tier of zone 1 was detailed simultaneously with the erection of the first tier of zone 2. This was followed by simultaneous detailing of the first tier of zone 2 and the erection of the second tier of zone 1. Figure 4 provides a sequence diagram of the erection process.

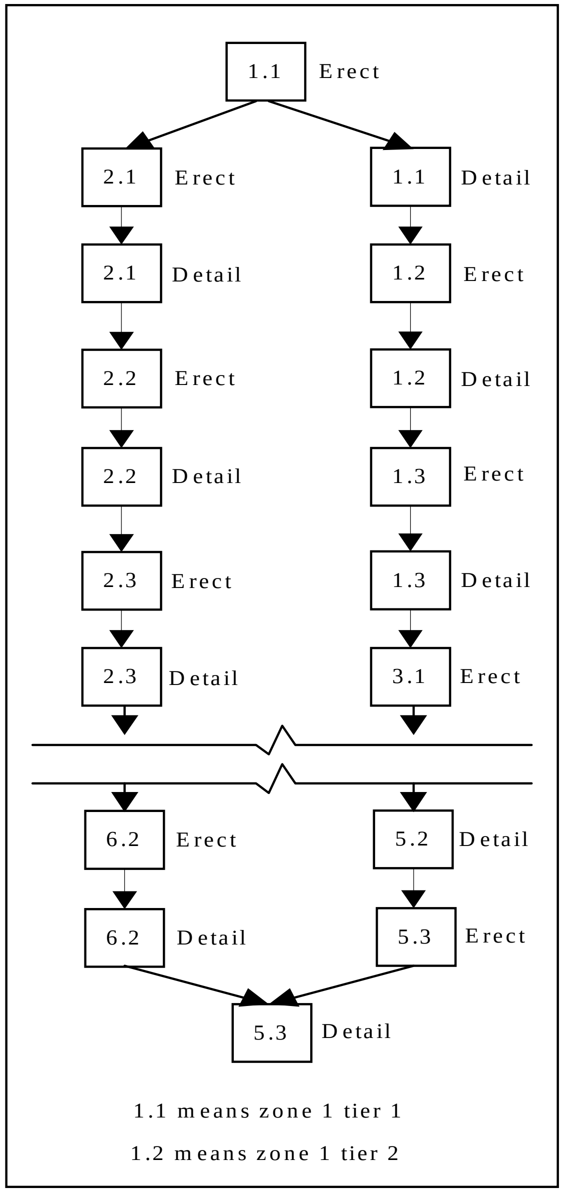

Figure 4: Schematic Representation of the Steel Erection Process

5 MODELING OF THE STEEL ERECTION PROCESS USING PETRI NETS

5.1 Hierarchical and Modular Model

Figures 5 through 8 show the hierarchical and modular model for the structural steel erection process. The main steel erection model is depicted in Figure 5, due to paucity of space it models four zones only. The model utilizes three hierarchical transitions, "Erect," "Move Crane," and "Detail" to invoke the lower level sub-models containing the work tasks of these three main activities. The advantages of hierarchical breakdown and modularity in the model can be clearly perceived. It only takes a simple model of small size and three small sub-models to model the overall process and all the work tasks involved.

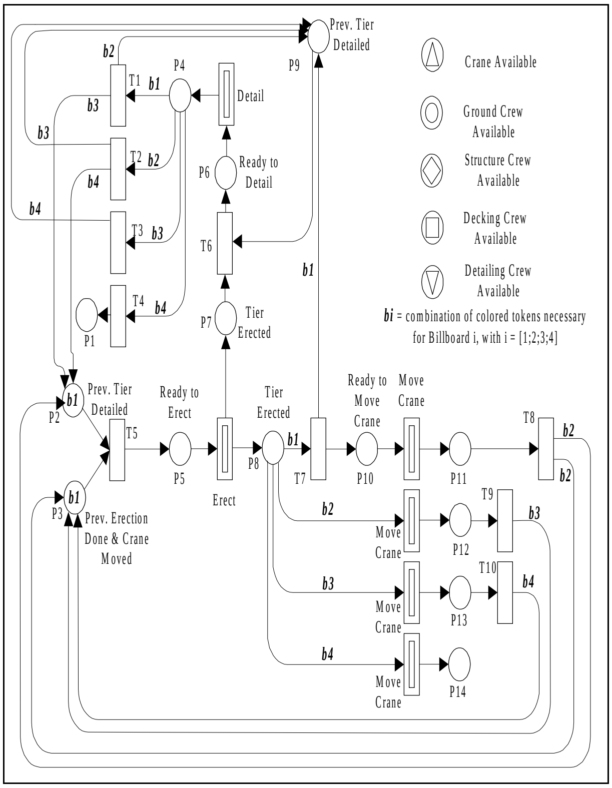

Figure 5: Petri Net Main Model of Steel Erection Process.

Construction begins with erection of Billboard 1. At the outset, the dummy transition T5 (the term dummy is used to designate modeling elements that do not have any relevance from the construction point of view and are only needed to make the Petri Net model complete) is the only enabled transition with ***b1*** colored tokens initialized at input places P2 and P3. Firing T5 leads to the transfer of ***b1*** tokens to place P5 "Ready to Erect". These tokens, representing structural steel elements, are then passed, one at a time, to the sub-model "Erect". The erection sub-model, which is described later, places the same amount of tokens in places P7 and P8. The initiation of the erection tasks for subsequent billboards is controlled by the places P2 and P3.

The tokens placed in P7 wait for dummy transition T6 to be enabled by tokens in place P9 while the tokens at P8 are used to enable the first of the "Move Crane" hierarchical transitions. In the case of Billboard 1, transition T7 is used to place one token in place P10 and tokens representing all the steel members of Billboard 1, in place P9. This, together with the tokens previously placed in P7, enables dummy transition T6 which then fires and places in place P6 the tokens corresponding to the steel elements in Billboard 1. This enables the hierarchical transition "Detail" which starts to process tokens from place P6 and to place tokens in place P4. In the meantime, the token in place P10 enables the hierarchical transition "Move Crane."

After the crane is moved, the dummy transition T8 places ***b2*** tokens, representing all the steel members for Billboard 2, in places P2 and P3. The dummy transition T5 fires and places ***b2*** tokens for the erection of Billboard 2 in place P5, "Ready to Erect", thereby, starting the second erection cycle. However, starting at Billboard 2, the hierarchical transition, "Move Crane," places the tokens necessary for the subsequent billboard (Billboard 3) only in place P3. Only when the detailing of the steel members of Billboard 1 is completed, does dummy transition T1 place the tokens for the erection of the members of Billboard 3 in place P2, thereby enabling dummy transition T5. T1 also places the tokens for the detailing of Billboard 2 in place P9 "Previous Tier Detailed." The erection of Billboard 3 and the detailing of Billboard 2 can then start. The remaining billboards are erected and detailed in the sequence described in Figure 4.

5.2 Erect Sub-Model

The tasks involved in the erection of individual structural steel elements are modeled in the "Erect" sub-model shown in figure 6. The "Pick-up" task requires the resources "Crane" and "Ground Crew", which are modeled by two fusion places that have been initialized in the main model. The tokens representing the steel elements are passed from the main model to this sub-model. After being picked up an element is lifted and placed. The "Place" transition, however, requires an additional resource called "Structure Crew". Once the element has been placed the crane is sent back to pick-up the next element.

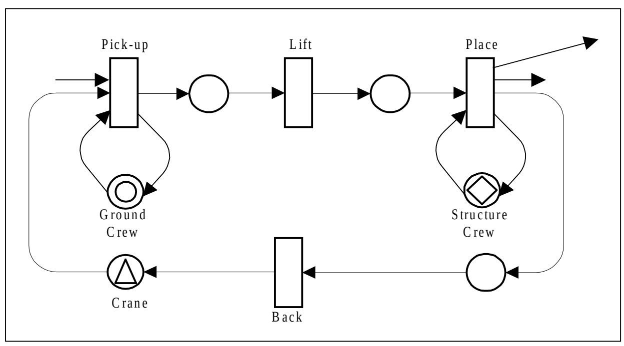

Figure 6: Erection Tasks Sub-Model

5.3 Move Crane Sub-Model

Together with the resource "Crane," modeled by a fusion place, the tokens at place P8 in the main model enable the transition "Move," which represents the actual relocation of the crane on the construction site. The "Move Crane" sub-model is shown in Figure 7.

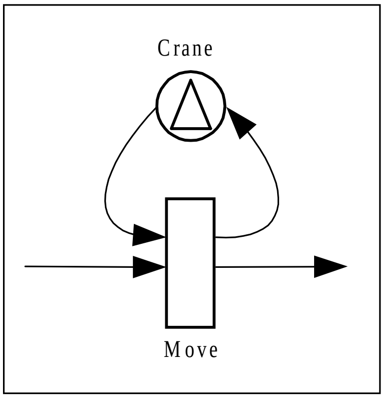

Figure 7: Crane Moving Sub-Model

5.4 Detail Sub-Model

In the sub-model for the hierarchical transition "Detail," depicted in Figure 8, tokens representing the columns, beams, and bundles of decking enter the sub-model one at a time and are put in place DP1 after the firing of a dummy transition, DT1. According to their coloring (i.e. type of steel member), the tokens take appropriate paths in the sub-model.

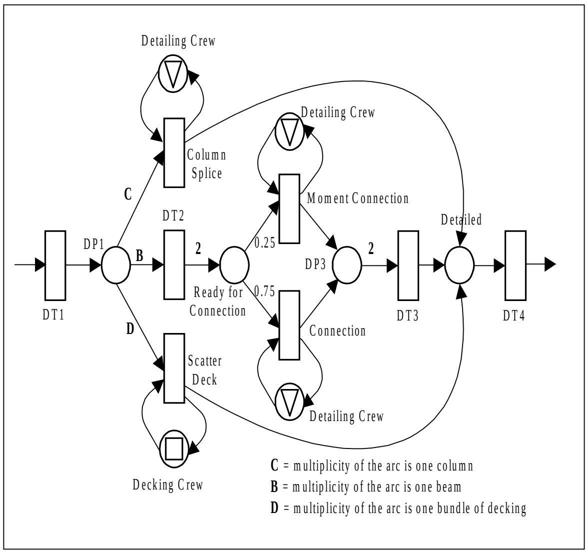

Figure 8: Detailing Tasks Sub-Model

The duration of various tasks modeled in the main model and the three sub-models are based on historical information and have been obtained from the construction site.

6 PETRI NET BASED ANALYSIS OF THE STEEL ERECTION PROCESS

Once the models were completed the analysis phase was started. For this purpose a general-purpose simulation toolkit was used. In this study, the authors developed a base scenario with resources similar to the ones used on the actual construction site. Thirty (30) simulation runs (replications) were performed.

To study the impact on duration of resource variations, nine further scenarios, I1 to I9, were identified. Again, thirty (30) simulation runs (replications) were performed for each scenario. From the resource availability data obtained in the simulation results, it was possible to determine that the critical resource were the decking crews. This was further confirmed by the fact that variations in the number of cranes and related crews, as simulated in scenario I1, failed to have any noteworthy impact on the completion time. Thus, the analysis focussed on the study of the effect of variations in the number of decking crews. The results are graphically displayed in Figure 9.

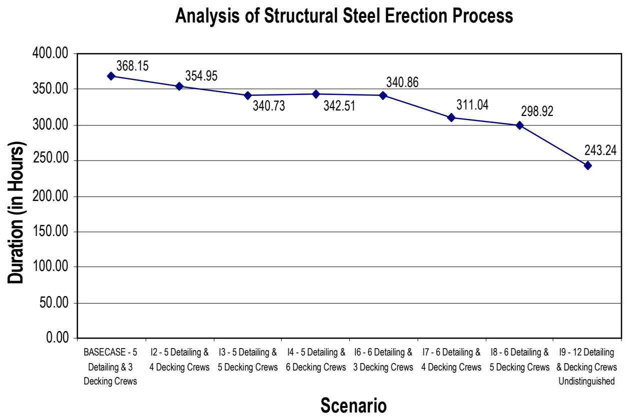

Figure 9: Graphical Display of the Simulation Results

7 CONCLUSION

This paper illustrates enhanced Petri Net based process modeling and analysis. A steel erection process is modeled to demonstrate the usefulness of computer simulation in the role of planning, controlling, and analyzing factors, tasks, and resources involved in construction operations. The simulation results of the steel erection process permitted to establish which resources were critical to the project duration. Enhanced Petri Nets proved to be efficient construction process modeling tools. Particularly, the modularity and the hierarchical breakdown features of enhanced Petri Nets proved to be a useful asset in producing a simpler model.

8 ACKNOWLEDGEMENTS

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