

## PETRI NET BASED SIMULATION OF CONSTRUCTION SCHEDULES

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### ABSTRACT

Scheduling of a construction project requires: a) hierarchical decomposition of the project; b) incorporation of risk and uncertainty in the activity time and cost estimates; and c) modeling of dynamically allocated resources. Traditional network techniques that are being currently used by the construction industry provide limited modeling versatility and are ineffective in modeling a dynamic and stochastic system such as a construction project. In this paper a description of a hybrid scheduling technique that utilizes Petri Nets is provided. Petri Nets are graphical and mathematical modeling tools that can be used to perform static and dynamic analysis of systems. Under the proposed technique transitions and places, the two key elements of a Generalized Stochastic Petri Net (GSPN) are used to model the work tasks in a construction project. This automatically allows the incorporation of risk and uncertainty in the time and cost estimates of work tasks. Dynamic modeling of resources required to accomplish various construction work tasks is performed in the proposed system by using the concept of colored tokens and fusion places. Hierarchical transitions allow a systematic top-down breakdown of a construction project. The paper summarizes the steps required to perform scheduling of construction projects under the proposed hybrid technique and highlights its advantages. The objective of this paper is to illustrate the dynamic simulation capabilities of the proposed Petri Net based construction scheduling technique.

### 1 INTRODUCTION AND BACKGROUND

Planning, scheduling, and control of the functions, operations, and resources of a construction project are among the most challenging tasks faced by a professional construction manager (Barrie and Paulson 1992). The delivery of a civil engineering facility is a multi-phase task that begins with conceptual planning

and continues through detailed design, implementation, and maintenance phases. The successful completion of the facility delivery process requires numerous inputs. During the pre-construction phase there is a need to coordinate the design of the facility so as to produce working drawings and specifications that are "constructable" and will help in successfully delivering the facility within the pre-defined objectives. The major complicating factor in this phase is the involvement of a number of agencies such as the architect, engineering consultants, construction manager, and owner's representative. In the construction phase, projects require multitude of inputs including information and decisions of participating agents, numerous resources such as architectural drawings, specifications, construction crews, heavy equipment, and materials. This makes the task of delivering the facility challenging.

In order to succeed in such endeavors it is essential to deploy techniques to plan, schedule, and coordinate important decisions, milestones, flow of resources, and other required inputs. It is important to prepare some form of representation of the designed facility to allow such a planning, scheduling, and coordination effort. A very common form of representation used by the construction industry is the bar chart and other network based methods such as Critical Path Method (CPM), Program Evaluation and Review Technique (PERT), and Precedence Diagramming Method (PDM). These tools provide a means of obtaining a time schedule for the various work tasks associated with a construction project. However, they fall short of the planning, scheduling, and coordination effort required for the efficient delivery of a facility. The shortcomings of these methods are numerous and have been documented in many publications (for example, McCrimmon and Ryavec 1964, Levitt et al 1988 and Pritsker et al. 1989). The major problem is that the network techniques have been inherited from the aerospace and manufacturing industry with disregard to the nature of the construction projects. The three major

characteristics of construction projects that reduce the effectiveness of network based techniques include:

1. The task of delivering a facility can be decomposed into sub-tasks requiring services of architects, structural engineers, mechanical engineers, construction engineers, general contractors, and specialty contractors etc. These specialists normally belong to different agencies that are related to each other by contractual arrangements. The resultant decision making and the flow of information is as such complicated making the task of planning and scheduling complex.
2. Construction projects are performed in a dynamic environment that is characterized by stochastic phenomenon such as weather changes, labor productivity and skill fluctuations, and variation in site conditions.
3. Resources that control the progress of work tasks are dynamically allocated, for example, a tower crane assigned to a high-rise building project. The tower crane is dynamically allocated to perform functions such as lifting a concrete bucket, arranging structural steel members, and unloading fabricated members from trucks.

Traditional network based planning methods do not consider these important characteristics of construction projects during schedule development. The inheritance of the network based techniques and their subsequent critique has demonstrated to the owners, architects, engineers, and constructors (including researchers) the importance of construction planning and scheduling. Another important outcome of these research efforts was the indication that stochastic tools such as simulation can provide an excellent solution to the problem of construction scheduling. Van Slyke (1963) and Pritsker (1988) discussed the development of Graphical Evaluation and Review Technique (GERT) for extending the modeling capabilities of CPM and PERT. These experiments led to the use of simulation in project planning and scheduling. The following paragraph provides a summary of important research in this area.

Ang et al. (1975) developed a technique called Probabilistic Network Evaluation Technique (PNET). This technique applies probability theory to reduce the number of possible critical paths and evaluates the expected project duration based on representative paths in the network. Crandall (1976) used the monte-carlo simulation technique to carry out probabilistic scheduling. He developed a tree structure for network representation to perform the monte-carlo experiments. Riggs (1989) summarized the attempts made to use

simulation modeling for the planning of construction projects. Woolery and Crandall (1983), and Ahuja and Nandakumar (1985) provided a stochastic network model for scheduling.

One basic underlying drawback of the systems discussed above is that they attempt to mimic CPM or PERT based techniques in one form or the other. This inadvertently produces a less efficient tool. This research suggests a shift in the scheduling paradigm by adopting Petri Nets as the "backbone" of the scheduling system.

The paper has been organized as follows. The next section provides a brief description of Petri Nets. Section three explains the use of Petri Nets in scheduling of construction projects. Conclusions and recommendations are provided in the last section of the paper.

## 2 OVERVIEW OF PETRI NETS

Petri Nets are graphical and mathematical modeling tools that can be used to perform static and dynamic modeling of existing or new systems. Carl A. Petri is generally considered as the originator of the concept of Petri Nets (Petri 1966). Systems that are characterized as being concurrent, asynchronous, distributed, parallel, non-deterministic, and stochastic can be effectively modeled and analyzed by using Petri Nets (Murata 1989).

A Petri Net is a directed, weighted, bipartite graph consisting of four main types of modeling elements called places, transitions, arcs, and tokens (D'Souza and Khator 1994). Figure 1 shows the four modeling elements that are used to develop a classical Petri Net. A place—denoted by a circle—represents a condition such as input data, input signal, resource, condition, or buffer. A transition—denoted by a solid bar—represents an event such as a computation step, task, or activity. Arcs are utilized to connect places and transitions in a Petri Net. Arcs are directed (depicted by arrows) and are either drawn from a place to a transition or from a transition to a place. Arcs in a Petri Net have multiplicity. Multiplicity of an input arc, represented by an integer  $k$  (as shown in Figure 1), dictates the number of tokens required to fire or enable a transition. The fourth element called the token and denoted by a solid circle provides the dynamic simulation capabilities to Petri Nets. Tokens are initialized at a place and a place may contain zero or more tokens. With the use of tokens the modeler can provide the necessary dynamic links between the places (conditions) and transitions (tasks or events) in a Petri Net.

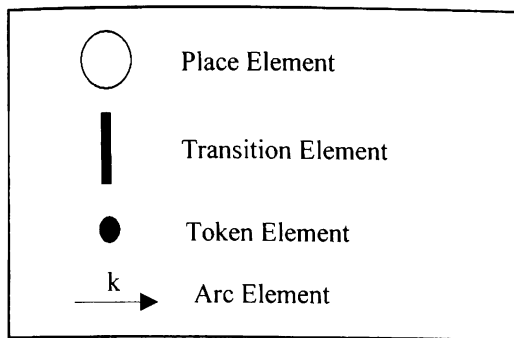


Figure 1: Modeling Elements of Petri Nets

The concept of transition “firing” allows a Petri Net to simulate the dynamic behavior of a system. A transition in a Petri Net can fire when each input place has “k” or more tokens available, where k is the multiplicity of the arc connecting the transition and the respective input place. Such a transition is said to be “enabled” (Murata 1989). Firing of an enabled transition removes the appropriate number of tokens from its input place and puts them in the output place.

In their original form transition firing in Petri Nets was assumed to be instantaneous. However, time can be incorporated into Petri nets by introducing a delay after a transition is enabled. This results in a timed transition that will have the ability to model tasks or activities. Such a Petri Net is known as a Timed Petri Net (TPN). If the transition times are deterministic, the Petri Net is called a Deterministic Timed Petri Net (DTPN) (Hillion 1989). If the transition times are allowed to be random variables, then it is called a Stochastic Timed Petri Net (STPN). A Petri Net that contains immediate transitions, deterministic transitions, and stochastic transitions is called a Generalized Stochastic Petri Net (GSPN) (Marsan 1989). In this research GSPNs are utilized to model construction schedules.

### 3 PETRI NET BASED CONSTRUCTION SCHEDULING

A construction schedule consists of a series of work tasks that are linked to each other in a logical manner. Schedule development requires a project network to be constructed showing technological and managerial constraints amongst work tasks. Network computations after the development of the schedule result in a timeline that determines the planned occurrence of the work tasks.

Figure 2 illustrates a simple project schedule. Figure 2(a) utilizes the CPM method to formulate the project network and Figure 2(b) shows the equivalent Petri Net based project network.

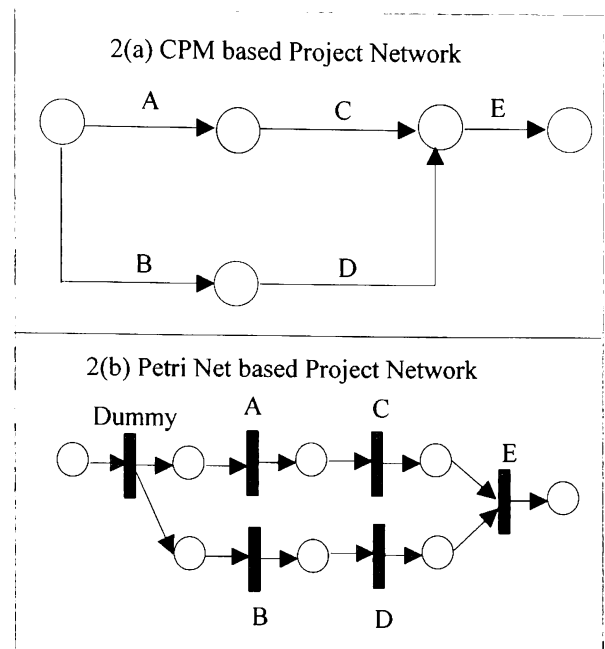


Figure 2: Petri Net based Project Schedule

It can be seen from the figure that the four modeling elements of a Petri Net can be utilized to develop the project network. In general a work task is depicted by a combination of an input place, a transition, and an output place. The development of “merge nodes” and “burst nodes” in a project network requires special attention. Figure 3 shows the Petri Net equivalent of a “merge node”

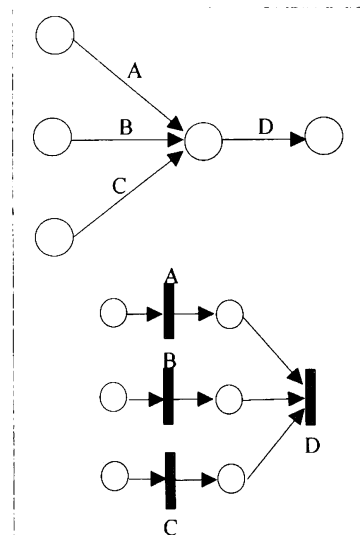


Figure 3: “Merge Node” of a Project Network

Figure 4 shows the equivalent of a “burst node”. Using these simple rules a construction manager can develop a new project network or convert an existing

project network into a Petri Net based network. Once the Petri Net based project network has been developed the dynamic simulation of the project network results in the scheduling computations for the project.

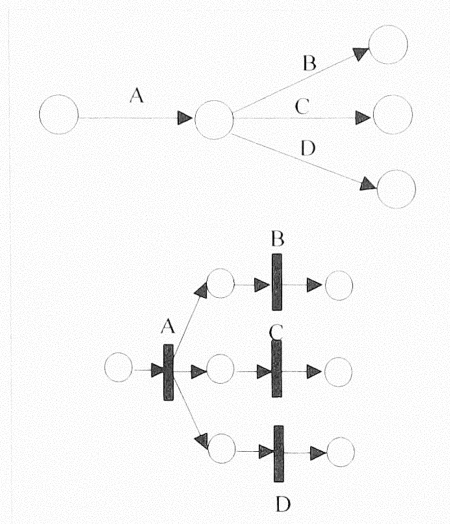


Figure 4: "Burst Node" of a Project Network

In order to allow efficient Petri Net based scheduling of construction projects it is important to incorporate the following three important requirements of construction projects:

1. Ability to provide hierarchical breakdown of a complex construction project.
2. Incorporation of risk and uncertainty in the activity time and cost estimates, and the network logic.
3. Modeling of dynamic resource allocation and utilization on a construction project.

In the following subsections a description of these three features of Petri Net based construction scheduling are provided.

### 3.1 Hierarchical Breakdown

Scheduling of complex construction projects is confronted with a problem of describing the project work tasks, their characteristics and interactions in a concise and understandable way. One of the basic strategies for accomplishing this function, devised both by nature and by human beings is the hierarchical approach (Simon 1981).

In order to provide hierarchical features in the Petri Net based scheduling method this research utilizes the concept of "hierarchical transition". The idea of hierarchical transition has been advocated and tested for modeling of complex processes by a number of researchers (Peterson 1977, Torn 1981, Torn 1985,

Jensen 1986, and Meta Software Corporation 1993). In the proposed form a hierarchical transition is utilized to depict a group of work tasks that are linked to each other. Figure 5 illustrates the use of hierarchical transitions to develop the schedule for a complex construction project.

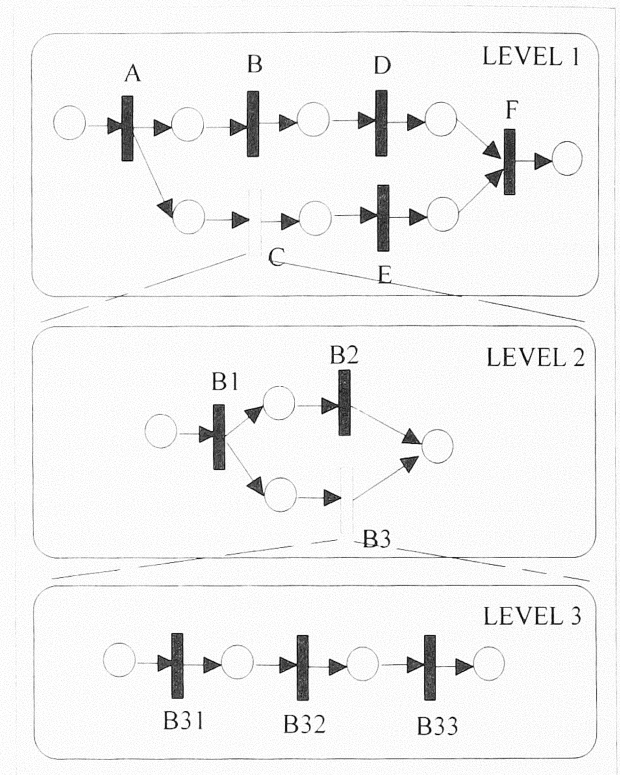


Figure 5: Hierarchical Breakdown

In the level 1 Petri Net—that depicts the project network at the highest level—a hierarchical transition "C" (depicted by a rectangle) is used to denote a level 2 Petri Net. Similarly in level 2 Petri Net the hierarchical transition "B3" represents a lower level Petri Net. This mechanism can be utilized to achieve hierarchical decomposition of a complex construction project. Under this scheme a large project could be divided into various levels of detail in a top-down fashion. The hierarchical concept can be used to structure the project information in an efficient manner. It allows the construction manager to break individual "work packages" of a construction project to different levels of detail, hence providing increased modeling versatility. At the top level it provides a higher level of abstraction and a complete plan without a great deal of detail. At the lowest level it provides a high degree of modeling detail in the form of Petri Nets that represent the construction site level work tasks.

The concept of hierarchical transitions in turn also provides modularity features to the Petri Net based construction scheduling technique. Many repetitive technological components can be found in construction projects. These recurring units of work can be combined in “modules” and referenced by a “hierarchical transition”. This “hierarchical transition” can then be referenced in the project network a number of times based on the repetitive components in the project. Thus modularity can be beneficially adopted for projects that involve repeated modules of work.

### 3.2 Incorporation of Risk and Uncertainty

A construction project is susceptible to a number of external factors—such as weather changes, site conditions, labor skill, and cash flow—that cannot be deterministically estimated during the planning phase. Ignoring these factors during planning and scheduling often leads to time and cost overruns on construction projects. It is therefore essential to incorporate the effects of these external factors on the time and cost estimates of work tasks. Petri Net based scheduling technique that is proposed in this research allows effective incorporation of uncertainty in time and cost estimates in the project network. The following two mechanisms allow construction managers to incorporate risk and uncertainty in the project networks:

1. **Statistical Distributions:** A transition that represents a work task or a group of work tasks can be assigned a stochastic time and cost estimate. Construction managers can utilize a large number of a statistical distributions to estimate the duration and cost of a work task. During the dynamic simulation of the Petri Net based project network the stochastic estimates are utilized to provide overall project time and cost estimates that are more realistic. This allows seamless incorporation of risk and uncertainty factors in the project schedule.
2. **Probabilistic Arcs:** In addition to the statistical distributions, Petri Net based scheduling technique also provides modeling tools that can be utilized to incorporate uncertainty in the construction logic. A probabilistic arc can be utilized in the Petri Net based project network to model this uncertainty. In the traditional network techniques branching is done on a deterministic basis, no cycling is allowed in the network, and work tasks are always completed successfully as the concept of

failure is non-existent. This deficiency is removed in the Petri Net based scheduling through the use of the probabilistic arc. Figure 6 explains the use of probabilistic arc with the help of a construction project.

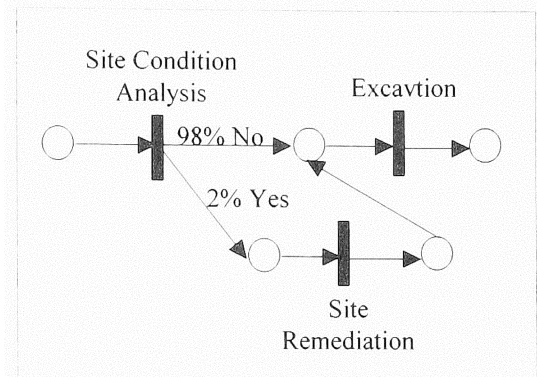


Figure 6: Probabilistic Arc

In the figure a situation commonly faced by construction managers is modeled. While working on a potentially contaminated construction site it is important for the construction manager to include work tasks related to site remediation in the project network. This is accomplished with the help of a probabilistic arc. The project network consists of the “site condition analysis” work task. The results of the site condition analysis dictate whether the “excavation” work task or “site remediation” work task will be performed. The two probabilistic arcs that connect the “site condition analysis” transition to its two output places represent this uncertainty in the construction logic. Based on past experience probability values are attached to the two probabilistic arcs. There is a 98% probability that the site condition analysis will not find any hazardous material and excavation can be directly started. However, there is a 2% probability that “site remediation” work task will be required before “excavation” work task can be started.

### 3.3 Dynamic Modeling of Resources

A construction project requires numerous resources such as construction equipment, labor, and construction material. These resources are utilized on a multitude of work tasks and are dynamically allocated to these work tasks. In order to realistically schedule a construction project it is essential to clearly identify various resources being used and to model their dynamic allocation. The Petri Net based scheduling technique provides modeling tools that allow both these aspects to be incorporated in the project network. These are described in the following paragraphs:

**Identification of Resources:** Various resources being utilized on a construction project are modeled by tokens that dynamically move from transition to transition in the Petri Net based project network. These resources are identified by the “color” of the tokens. In the classical form of Petri Nets the modeler is allowed to define only one type of token. This means that in a classical Petri Net it will be impossible to depict different objects that the tokens are used to model. Recognizing the need to allow the modeler to incorporate attributes of objects being modeled by a Petri Net, enhancements were made to classical Petri Nets. In the enhanced form the modeler is allowed to define more than one type of token in a given Petri Net by assigning a color or type to the token. These types of tokens are called colored or typed tokens and the resulting Petri Nets are called Colored Petri Nets (Jensen 1986, Jensen 1990 and Jensen 1992). Figure 7 illustrates the use of colored tokens to identify the resources in a project network.

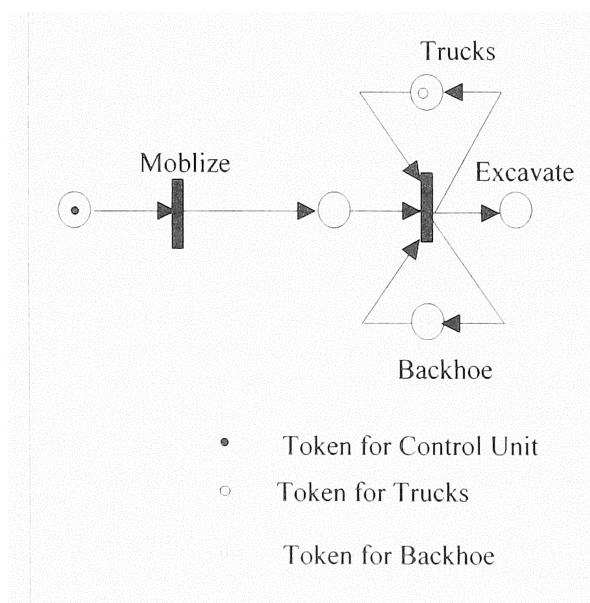


Figure 7: Modeling Resources using Colored Tokens

**Dynamic Resource Allocation:** Resources on a construction project are shared by a number of work tasks. For example, a tower crane assigned to a high-rise building project is used to perform functions such as lifting a concrete bucket, arranging structural steel members, and unloading fabricated members from trucks. In order to realistically schedule a construction project it is essential to model the dynamic allocation and usage of resources. In the proposed Petri Net based scheduling technique this feature is modeled by using “fusion places”. The concept of fusion places does not exist in classical Petri Nets. Design/CPN (Jensen 1994

and Meta Software Corporation 1993) has suggested enhancement of classical Petri Nets through the use fusion places. A fusion place is a place that has been equated with one or more other places, so that the fused places act as a single place with the same type and number of tokens. The fusion place capability allows places in a Petri Net that exist in different locations in the network to act functionally as if they were the same place. Such places are called fusion place, and a group of such places is called a fusion set (Jensen 1994 and Meta Software Corporation 1993). Modeling of resources that are shared by a number of work tasks on a construction project is accomplished by using fusion places in conjunction with colored tokens.

Figure 8 illustrates the concept of fusion places and their use to model resources on a construction project. In Figure 8(a) portion of a project network containing the “concreting”, “arrange steel members”, and “unload prefabricated members” work tasks is shown. The three activities share a common resource depicted by the place “tower crane” in the network. The place “tower crane” acts as an input place and output place for all the three work tasks. Assuming that there is only one token available in the “tower crane” place, the three activities can only be performed when the resource is available. Figure 8(b) models this scenario by using fusion places. A fusion set called “tower crane” is first defined for the network. Three fusion places representing resource requirements for the three work tasks are then defined. The three work tasks are connected to their respective fusion place as shown in the figure. It is important to note that places belonging to the fusion set “tower crane” have the same number and type of token. If the construction manager decides to use two tower cranes instead of one appropriate changes are made to the fusion set. This mechanism simplifies the project network and effectively models resource sharing between various work tasks on a construction project.

#### 4 CONCLUSIONS AND RECOMMENDATIONS

Petri Net based scheduling of construction projects described in this paper is a simple and effective method that can provide construction managers assistance in developing realistic time and cost estimates for complex construction projects. By the use of Petri Net as the basis of developing the project network a number of advantages can be attained. These advantages are as follows: 1) hierarchical and modular decomposition of complex construction projects can reduce the complexity of the project network; 2) cycling and probabilistic arcs can be used to model uncertainty in the construction logic; 3) uncertainty in the time and

cost estimates of the work tasks can be modeled by using appropriate statistical distributions; and 4) modeling of shared resources and dynamic allocation of resources in a project network by using fusion places allows a the construction manager to foresee resource availability problems.

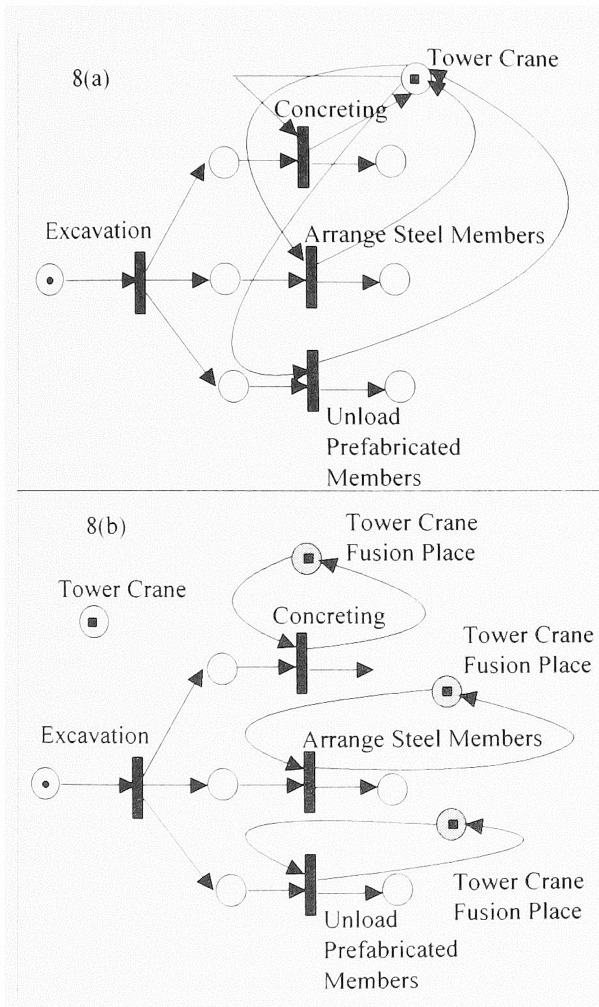


Figure 8: Dynamic Resource Modeling using Fusion Places

Initial investigation for this research was performed by using Design/CPN™ (Jensen 1994 and Meta Software Corporation 1993) and TemPRO™ (Software Consultants International Limited 1995). Both these software tools are general purpose Petri Net based analysis tools. The author is currently developing a prototype software specifically designed for Petri Net based scheduling of construction projects.

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