PETRI NETS FOR SIMULATION AND MODELING OF CONSTRUCTION SYSTEMS

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ABSTRACT: Simulation and modeling of construction systems have been actively researched over the past 20 years. This paper demonstrates how Petri nets, a powerful modeling tool previously used for modeling computer networks and automated manufacturing systems, can be used effectively for modeling construction systems. This paper describes the Petri net approach to modeling and shows how models of construction systems can be developed. Several common Petri net structures and features useful in construction system modeling are described. Time and color Petri nets and their application in modeling specific characteristics of construction systems are discussed. Two illustrative examples are presented and the advantages and disadvantages of Petri nets as tools for the modeling and simulation of construction operations are detailed.

PETRI NETS FOR SIMULATION AND MODELING OF CONSTRUCTION SYSTEMS: INTRODUCTION

It is well established that computer simulation is a useful tool for analyzing construction operations [see e.g., Halpin (1977), Pilcher and Flood (1984), Halpin and Riggs (1992), Lutz and Hijazi (1993), Vanegas et al. (1993), Farid and Koning (1994)]. Cyclone, developed by Halpin (1977), is a popular example of a construction simulation tool. The development of Cyclone over the past 20 years has been well documented in the literature. Other simulation tools used for construction simulation include ithink (also known as Stella) (Senogles and Peck 1994; High 1994) and SLAM II (Gonzalez-Quevedo et al. 1993; Pritsker 1986). More recently, another powerful modeling tool, Petri nets (PNs), for modeling computer networks has been developing. This paper introduces PNs and shows how they can be used as a useful tool to model construction systems and provide information on construction processes.

PNs are a formal graphical modeling tool that have been widely used to model communication systems, computer software and hardware, manufacturing, safety analysis, and queuing systems. For a comprehensive review of developments in this area see Viswanadham and Narahari (1992). Structural properties of the model (Al-Jaar and Desrochers 1990; Murata 1989; Peterson 1981), performance evaluation (Holliday and Vernon 1987; Lin and Lee 1993), and simulation (Balbo and Chiola 1989; Lin and Lee 1993) can be directly obtained from PN models. When compared with other modeling schemes, such as queuing theory and discrete event simulation, PNs are generally considered to be superior for systems with concurrency, where several state changes happen simultaneously and where event-driven characteristics are present (Lin and Lee 1993). Both of these phenomena are present in construction systems. Another advantage PN shares with ''microcyclone'' (Halpin 1992) and ''ithink'' (High 1994) is their graphical nature, which makes them relatively easy to explain and communicate to others. PNs can be converted into algebraic representations that can be analyzed to ensure that logic requirements are met.

The aim of this paper is to show how PNs can be applied to construction systems and to demonstrate their advantages. An overview of PNs use for the modeling of discrete event systems will be given initially. A simple example is used to introduce the basic net elements and their attributes. The paper then describes several common structures useful in construction system modeling. This is followed by a discussion of timed PNs, colored PNs, priorities, probabilities, and queuing disciplines that assist in modeling specific characteristics of construction systems.

Two illustrative examples are then presented. The advantages and disadvantages of PNs in modeling and simulation of construction operations as well as potential enhancements of the method to make the networks more user friendly are discussed.

PETRI NET APPROACH

C. A. Petri introduced his networks in 1962. Since then many advances have been made in both theory and application. PNs have been developed by simulation researchers for general simulation applications. As a result, the names of the network components are simulation terms and may be unfamiliar to constructors. To ease the transition, a simple construction operation is used as an example.

Fig. 1(a) is a graphical PN model of crane-hoisting materials from the ground to the work face. This network is made up of a number of connected symbols, each with the following attributes:

1. Circles (places) represent states of being. In construction, these are often states of readiness. The crane moves through the following states of readiness: crane ready to attach, ready to lift, ready to detach, and ready to return.
2. Squares (transitions) are actions that change the state of the system. Attach the load, lift and swing, detach the load, and crane return are transitions.
3. Black dots (tokens) are the resources of the operation. In this case the tokens are the materials being hoisted and the crane doing the hoisting.
4. Arrows (directed arcs) indicate the direction the resources (tokens) move when an action (transition) takes place. In Petri net jargon, transitions are said to ''fire'' as their action takes place.

The location of the materials and crane (tokens) in the network at any point in time is referred to as the ''marking'' of the net at that instant. In this example we start with two tokens, the crane and the materials to be lifted, both in their respective circles (places). At this point the transition ''attach the load'' is enabled and ready to fire. The firing of the transition moves the tokens from ''crane ready'' and ''materials to be lifted''

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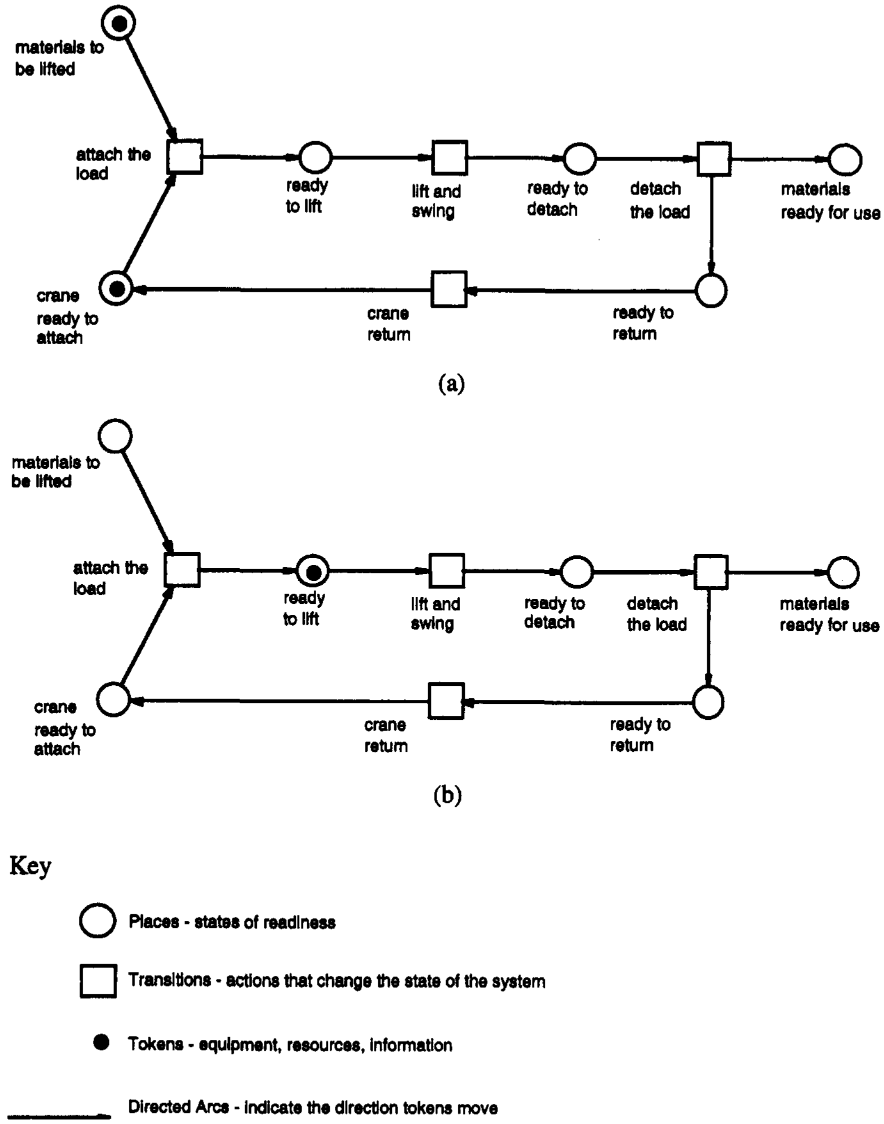

FIG. 1. PN Model of Crane Hoisting Materials

(the input places), and puts a single token in the place "ready to lift" (the output place). The result of this first transition firing is shown in Fig. 1(b). Transitions continue to fire when enabled until the supply of tokens is exhausted.

Mathematical Definition

In this section a basic introduction to PNs is given. The reader is referred to Peterson (1981), Resig (1985) and Viswanadham and Narahari (1992) for a more thorough treatment. A PN, in its most basic form, is a four tuple defined as:

$$PN = \langle P, T, \mathrm{IN}, \mathrm{OUT} \rangle \text{ where} \quad (1)$$

$$P = \{p_1, p_2, p_3, \ldots, p_n\} \text{ the set of } n \text{ places} \quad (2)$$

$$T = \{t_1, t_2, t_3, \ldots, t_m\} \text{ the set of } m \text{ transitions} \quad (3)$$

$IN = (P \times T) \rightarrow N$ is an input function that defines directed arcs from places to transitions (4)

$OUT = (P \times T) \rightarrow N$ is an output function of directed arcs from transitions to places (5)

The directed arcs can be weighted to indicate the number of tokens that are transferred to or from a place on the firing of a transition.

Properties of Petri Nets

PNs exhibit a number of important properties that are useful in determining the behavior of the modeled system. These properties may also prove useful in analyzing construction systems at the planning stage. A list of the properties, along with descriptions, are given as follows (Peterson 1981; Cossins and Ferreira 1992):

1. Safeness—a place is safe if the number of tokens in that place never exceeds one. A PN is safe if all its places are safe. The crane places in the foregoing example must be safe as there is only one crane. Safeness can be used to check the logic of the net.
2. Boundedness—a place is k-bounded if the number of tokens in it cannot exceed k. For example, if a storage area on a site can only store three precast units, it would be necessary for the place representing the storage area to be three-bounded.
3. Conservativeness—a net is strictly conservative if the number of tokens within it remains constant. This concept is useful when tokens represent resources. Sometimes, however, tokens represent counters or other nonresource items. Under these circumstances it might not matter if tokens are created or destroyed. To provide the benefit of conservativeness without this problem, one can

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consider the net conservative only for tokens representing resources. This problem can also be overcome by using colored tokens.

4. Liveness—a transition is live if it is able to fire and is not deadlocked. If a transition is live it is not necessarily enabled, but is potentially enabled under some attainable marking. This property can be used as a check on the logic of the system. If all transitions are live, given the correct conditions, they can fire and the stage change represented by the transition can occur.
5. Reachability—under the marking μ, if it is possible to obtain the marking μ', μ' is said to be reachable. In Fig. 1, the fact that the marking of one token in "ready to lift" is reachable from the initial marking means the logic of the transition is correct.

These properties are not all applicable to all forms of PNs. The properties and associated techniques for their determination are fully treated by several researchers [e.g., Viswanadham and Narahari (1987, 1992)].

Basic PNs are useful in investigating qualitative or logical properties of dynamic systems, such as boundedness and liveness.

PETRI NET CONSTRUCTS USEFUL IN CONSTRUCTION PROCESS MODELING

There are typical structures that are common in construction. In this section we identify several PN constructs (Viswanadham and Narahari 1992) that represent particular characteristics of construction activities. The constructs are illustrated in Fig. 2 as follows:

Fig. 2(a). Sequential execution—transition t_2 can fire only after the firing of t_1. This imposes a precedence constraint that is typical of some construction activities. The construct can also be used to model causal relationships between activities. For example, concrete cannot be placed until the reinforcement is fixed and the framework is completed.

Fig. 2(b). Conflict—transitions t_1, t_2, and t_3 are in conflict. All are enabled but firing of any leads to the others being disabled. Such situations arise when a resource is being shared between a number of activities. The conflict can be resolved by assigning probabilities or priorities to the transitions. An example of such a conflict occurs when a single tower crane is needed to carry out two separate tasks simultaneously. Performance of one task stops the other task being undertaken at that time.

Fig. 2(c). Concurrency—transitions t_1, t_2, and t_3 are concurrent. This construct allows us to represent construction activities that proceed in parallel.

Fig. 2(d). Synchronization—when several resources and pieces of equipment need to be available for an activity to proceed this type of construct can be used. The activity can proceed only when a token arrives in the place without a token, thereby synchronizing the firing of t_1 to the token arrival. An example of synchronization occurs in Fig. 1 where the places "materials to be lifted" and "crane ready to attach" each have a token and therefore enable the transition "attach the load" to occur.

Fig. 2(e). Merging—this structure arises when several materials arrive for use at the same activity. For example, the constituent materials of concrete arrive at the concrete mixer for mixing.

Fig. 2(f). Confusion—this is the situation when conflict and concurrency exist together. In construction this sometimes occurs when resources are shared. It can be resolved by associating priorities or probabilities with the relevant transitions.

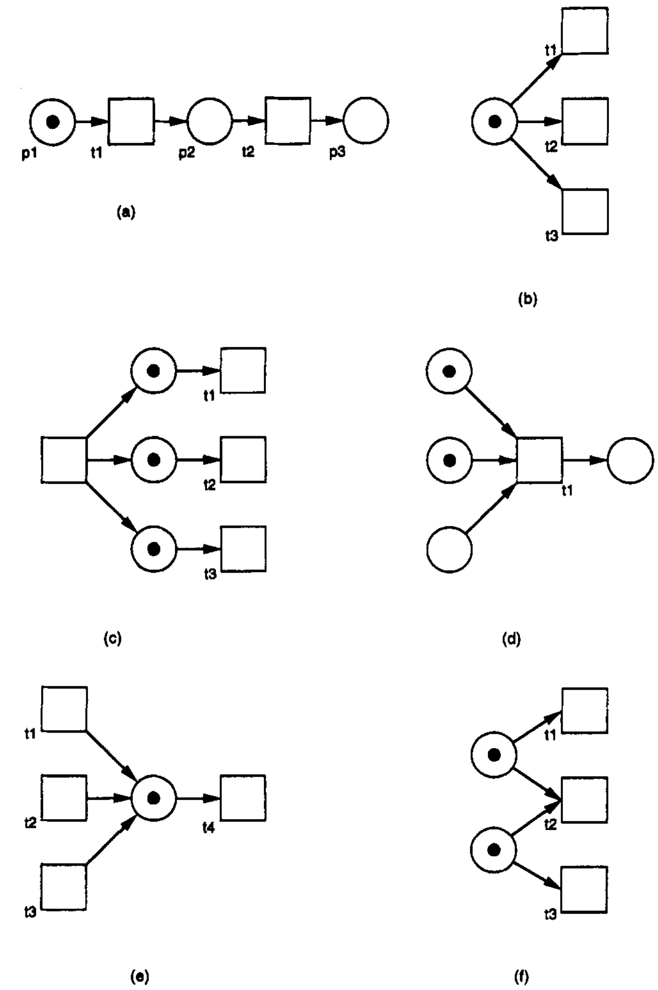

FIG. 2. Typical PN Constructs Useful in Construction Modeling: (a) Sequential Execution; (b) Conflict; (c) Concurrency; (d) Synchronization; (e) Merging; (f) Confusion

It is possible to build a logic model of most construction systems using a combination of these basic PN constructs. However, for quantitative modeling and analysis of construction systems the concepts of time and decision branching need to be added to basic PNs.

Time Petri Nets (TPN)

To effectively model construction systems we need to be able to associate times with transitions (activities). This means that the transition will, when all the input conditions are met, take t time units for the firing process to deposit tokens in the output places [for a full description of the development of TPNs see: Viswanadham and Narahari (1992), Ravi Raju and Krishnaiah Chetty (1993), Venkatesh et al. (1994), Lin and Lee (1994)]. The time delay can be deterministic or represented by any distribution function. It is also possible to associate time with other PN elements, but here we will consider time to be associated only with transitions.

Extended Transitions

Extended transitions allow the modeler to put decision branches into the net. When tokens pass an extended transition a decision must be made according to a given condition within the transition. The extensions to basic transitions that we use in construction modeling are probabilistic transitions and priority transitions. These extensions are necessary when two or more transitions are in conflict, that is, they both are enabled.

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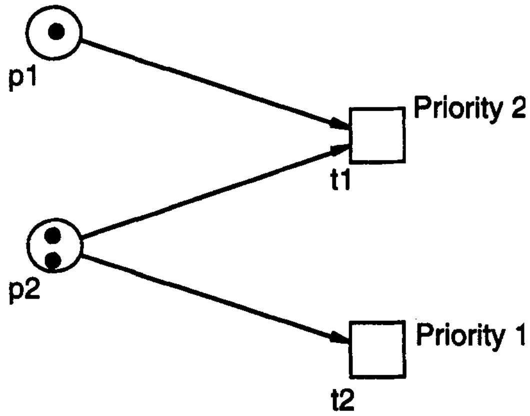

FIG. 3. Example of Use of Extended Transitions

It is possible to give transitions a priority order for firing in such situations. For example, in Fig. 3 transitions t_1 and t_2 are in conflict. If we associate a higher priority with t_2 and a lower one with t_1, and assuming there is an adequate number of tokens in the places (as shown in the figure), the transitions will fire in priority order. If there is an inadequate number of tokens in the places the firing of a higher priority transition may preclude the firing of a lower priority transition.

When several transitions have the same priority and are in conflict it is possible to associate a probability with each that will determine which transition will fire first. For example, in Fig. 3 t_1 and t_2 are in conflict. We can associate a probability of 0.3 with t_1 and a probability of 0.7 with t_2; t_2 will then fire first on 70% of the occasions that the two transitions are in conflict.

Colored Petri Nets (CPNs)

CPNs are extensions of PNs with identical modeling power but with increased graphical conciseness (Cossins and Ferreira 1992). CPNs allow different attributes (colors) to be associated with tokens and for different colored tokens to be handled differently by the PN elements. For many modeling problems in construction it is necessary to distinguish between different information, material, and resource flows. CPNs allow us to do this. Colored tokens are useful when several tasks need to share a scarce resource. For example, a crane lifting different materials on a construction site: each material can be represented by a different color token and handled differently by the crane. Materials, based on their color, could be delivered to different processes or locations on the site. CPNs are also useful for modeling heterogeneous queuing situations in construction, in cases where equipment fleet are made up of different types of equipment [see, e.g., McCahill and Bernold (1993)]. In this situation nondeterministic timed transitions can, if required, have different time distributions associated with different colored tokens.

Colored PNs are defined formally as a quintuple (Viswanadham and Narahari 1987; Kasturia et al. 1988; Cossins and Ferreira 1992)

$$CPN = \langle P, T, C, IN, OUT \rangle \text{ where} \quad (6)$$

$$P = \{p_1, p_2, p_3, \ldots, p_n\} \text{ the set of } n \text{ places} \quad (7)$$

$$T = \{t_1, t_2, \ldots, t_m\} \text{ the set of } m \text{ transitions} \quad (8)$$

where $C(p)$ and $C(t)$ = set of colors associated with place $p \in P$ and $t \in T$.

$$C(p_i) = \{a_{i1}, a_{i2}, a_{i3} \ldots, a_{iu_i}\} \text{ where } i = 1, 2, 3, \ldots, n$$

$$\text{and } u_i = |C(p_i)| \quad (9)$$

$$C(t_j) = \{b_{j1}, a_{j2}, a_{j3} \ldots, b_{jv_j}\} \text{ where } j = 1, 2, 3, \ldots, m$$

$$\text{and } v_j = |C(t_j)| \quad (10)$$

where a and b = associated colors.

$$IN(p, t)\text{: } C(p) \times C((t) \rightarrow N \quad (11)$$

is an input function and

$$OUT(p, t)\text{: } C(p) \times C(t) \rightarrow N \quad (12)$$

is an output function where N = set of all nonnegative integers. The input arc from a place p_i, with respect to the color a_{ih}, to a transition t_j, with respect to the color b_{jk}, is denoted by the scalar $IN(a_{ih}, b_{jk})$ for some h and k. Similarly, an output arc is denoted by the scalar $OUT(a_{ih}, b_{jk})$.

The firing rules for a CPN are as follows (Kasturia et al. 1988):

1. A transition fires if an only if the token colors marking the input places are members of the color set associated with the transition.
2. When a transition fires, the token colors defined by the input function, $IN(p, t)$ are removed from the input places.
3. Similarly the color sets of the output places as defined by the output function, $OUT(p, t)$, are marked.
4. Colors associated with functions are allowed to change across transitions.

Queuing Disciplines for Places

This extension to basic PNs allows queues of tokens that form at places to be governed by a queuing discipline. Such a facility is important in modeling some construction systems when resources are shared or where it is necessary to distinguish between queue members (if the queue members have different attributes) and process them accordingly. An example occurs in many earthmoving systems when first-in-first-out queues are used for loading and different capacity trucks take different times to be loaded.

EXAMPLE 1

This example demonstrates that a PN-based model produces results very similar to microcyclone when used for simulating the same construction system. The concrete placement operation is described in detail in Halpin and Riggs (1992) and used as an example to demonstrate the capabilities of the microcyclone system. Accordingly, the same example is used here to show the reliability of PNs on a classical construction simulation example. Basically, the example involves the dry batching of concrete materials into a truck at a batch plant location approximately 2 mi from the jobsite. Five batches are transported in each truck to the site where they are dumped individually and sequentially into the skip of a concrete mixer and mixed. After each batch is mixed it is dumped into a concrete bucket and lifted by crane to the placement location, where it is dumped, spread, vibrated, and finished by a concrete placement crew.

The graphical PN model of the system is shown in Fig. 4. The process begins with four trucks in the truck queue place. A truck leaves the queue and the five batch partitions in the truck are counted. A weighted arc places five counter tokens (each representing a batch in the following place). When a batch is available the truck partition is loaded. This process is repeated five times until the truck is fully loaded. The fully loaded condition is represented by a marking of five on the place "truck loaded." The truck then begins the haul cycle. On reaching the mixer, providing the mixer is available, the

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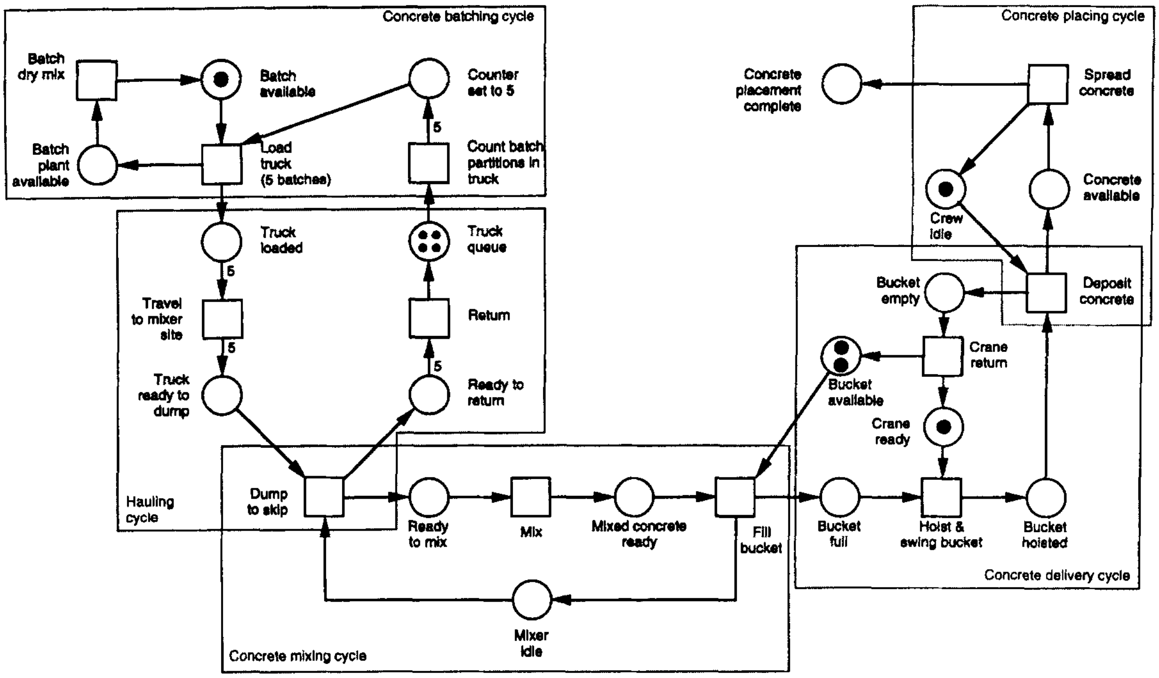

FIG. 4. PN Model of Concrete Placement Operation

batches are dumped sequentially into it. On completion of the mixing the concrete is placed in a one of two buckets for lifting to the worksite. When the crane is available it lifts the bucket to the worksite for placement by the concrete placement crew.

The Visual Simnet program (Garbe, unpublished manual, 1995) was used to run the numerical model of PN. The resources used in the simulation and the duration of the activities are identical to those used by Halpin and Riggs (1992) and are given in Table 1. One hundred cycles of dumping and placement of concrete were simulated using both microcyclone and the PN numerical model. The time for 100 cycles was 569.75 min using both PN and microcyclone. Results obtained indicate good agreement within the limits of numerical accuracy reported by each program. A summary of the results is given in Tables 2 and 3. This example shows that PNs can reliably model construction processes and produce results similar to microcyclone.

EXAMPLE 2

This example illustrates several powerful features of PNs not available in other construction simulation programs. This example makes use of colored tokens, probabilistic transitions, and queuing priorities in modeling an earthmoving system.

The system modeled here is loosely based on a subsystem

TABLE 1. Resources Available and Activity Durations for Example 1

Resources (1)	Number (2)	Activity (3)	Duration (min) (4)
Batch plant	1	Load truck	5
Trucks	4	Travel to mixer site	10
Concrete mixer	1	Dump to skip	1
Concrete buckets	2	Mix	3
Crane	1	Return	8
Work crew	1	Fill bucket	0.5
—	—	Hoist and swing bucket	0.25
—	—	Deposit concrete	0.3
—	—	Crane return	0.2
—	—	Spread concrete	5

TABLE 2. Comparison of Activity (Transition) Utilization for Example 1

	Microcyclone Simulation			Petri Net Simulation	
Activity (1)	Service time (min) (2)	Average number of units at work task (3)	Utilization (4)	Average number of units at work task (5)	Utilization (6)
Load truck	5	0.99	0.992	1.0	1.0
Travel to mixer site	10	0.39	0.386	0.386	0.386
Dump to skip	1	0.18	0.181	0.1818	0.182
Mix	3	0.28	0.281	0.2808	0.281
Return	8	0.54	0.542	0.5418	0.542
Fill bucket	0.5	0.09	0.090	0.0901	0.090
Hoist and swing bucket	0.25	0.04	0.044	0.0446	0.045
Deposit concrete	0.3	0.05	0.053	0.0531	0.053
Crane return	0.2	0.04	0.035	0.0354	0.035
Spread concrete	5	0.88	0.878	0.8777	0.878

of the earthwork construction system used in a civil works contract for the New Hong Kong International Airport. The main aim of the example is to demonstrate the capability of extended PN models in representing complex construction systems.

The initial stage of the civil works contract involved the expansion of a small existing island by dredging and land-based earthmoving, into a 1,248 ha island, 4.5 km end to end and 3.5 km at its widest point. The fill for the land-based part of the contract was provided by leveling the existing island and importing excavated material from other parts of Hong Kong. The land-based part of the contract was one of the world's largest earthmoving operations, involving approximately 100,000,000 m^3 of material in 31 months (Allwood 1993). As part of the contract the Provisional Airport Authority (the client) supplied approximately one-third of the equipment needed for earthmoving operations. This included four Demag H285 loaders, 17 trucks (Cat 785), and other drill and blast equipment. The civil works contract was split into two subcontracts. The supplied equipment was divided between the two subcontractors. The subcontractors then added to the supplied equipment to meet their operational requirements. One subcontractor did this with a mixed fleet of trucks, including

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TABLE 3. Comparison of Queue Information for Example 1

Queue (1)	Microcyclone Simulation Average wait (2)	Microcyclone Simulation Average queue length (3)	Petri Net Simulation Average wait (4)	Petri Net Simulation Average queue length (5)
Batch available	0	0	0	0
Mixed concrete ready	0.56	0.1	0.56	0.101
Mixer idle	0.47	0.1	0.4767	0.085
Bucket full	3.84	0.7	3.783	0.679
Bucket hoisted	4.31	0.8	4.25	0.755
Crane ready	0.59	0.1	0.593	0.104
Bucket available	1.83	0.3	1.867	0.327
Crew idle	0.39	0.1	0.396	0.070
Truck ready to dump	16.45	3.2	16.166	3.12
Truck queue	40.37	8.5	40.133	8.45

Cat 777 and Cat 785 trucks, while the other chose to use a fleet of Cat 785 trucks. Allwood (1993) gives a description of the systems used. The subcontractors also used different loader truck combinations and operating policies. There are a number of aspects of the operation that could be investigated using PN simulation, including economic analysis of different truck loader combinations and the effect on production of different operating policies; however, it is beyond the scope of this paper. For the purposes of this paper we will model a one-loader truck fleet combination that was utilized as part of the earthmoving process.

The objective of this example is to demonstrate that PNs can usefully model earthmoving systems and to compare the production performance of a mixed truck fleet and a homogeneous truck fleet. The method of excavation used at the new Hong Kong International Airport site was drill and blast. Material was then loaded into trucks using excavators. Based on the quality of the excavated material it was hauled to one of three fill locations: A, B, and C. Generally, trucks of two capacities were used on the site: Cat 777 trucks with capacity 30, 33, and 35 m^3 of material types A, B, and C, respectively; and Cat 785 trucks with capacity 50, 55, and 60 m^3 of material types A, B, and C, respectively. The loader used in this example is a Demag H285 with an 18 m^3 rock bucket. The loader required two to three bucket loads to fill the Cat 777 trucks and three to four bucket loads to fill the Cat 785 trucks.

The PN model of the load, haul, dump operations is shown in Fig. 5. To model some of the important characteristics of the construction operation it was necessary to include the following aspects of the PN model:

1. Different types of trucks needed to be allowed to work together in a truck fleet. The model needed to include different characteristics of the trucks, including capacities and performance characteristics.
2. Three separate load destinations had to be available for the excavated material. The probabilities of loading each type of material had to be included in the model.
3. The model needed to include the possibility of breakdown of trucks on both the haul and return legs of the operation.
4. Nondeterministic times for loading, hauling, and returning.

Inclusion of these aspects requires colored tokens to represent the different truck models. In the example we have included two types of trucks, however, it is possible to model each truck individually if required. Breakdown probabilities are associated with each type of truck to model the situation in which one type of truck is more reliable than another. First-in-first-out queuing is used at the loader, the dump site, and when repairing breakdowns. Details of the initial markings of places in the PN are given in Table 4. Transition information including the distribution of durations and the probability of activation when conflict arises are given in Table 5. Durations of transitions are based on information obtained from the subcontractors and collected on site.

Results of simulation with three different truck fleet combinations are given in Table 6. Daily production averages are based on two 11-hour shifts per day. Transient effects are ignored in this analysis. The results indicate that roughly equivalent daily production can be obtained with each of the truck

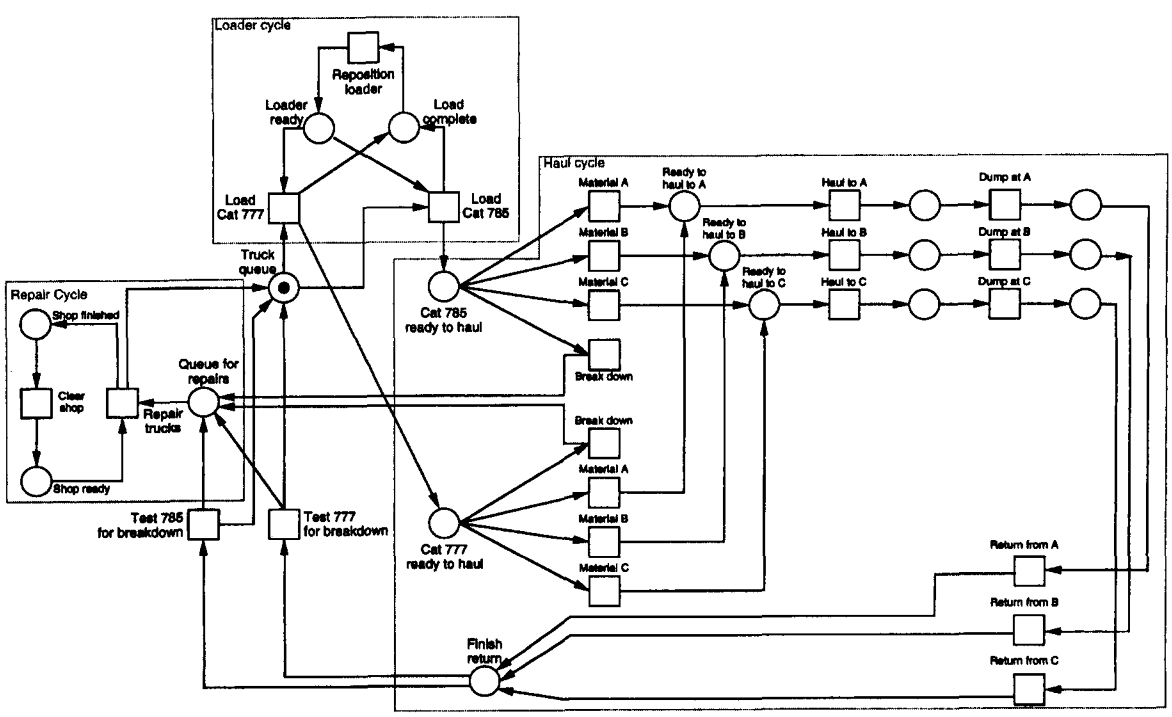

FIG. 5. PN Model of Earthmoving Operation

TABLE 4. Transition (Activity) Information for Example 2

Transition (1)	Probability (2)	Duration (min) (3)	Distribution type (4)
Reposition loader	1	Minimum 0.5, maximum 1.5, mode 1	Triangular
Load Cat777	1	Minimum 1, maximum 2, mode 1.5	Triangular
Material A	0.449	0	Constant
Material B	0.300	0	Constant
Material C	0.250	0	Constant
Breakdown	0.001	0	Constant
Load Cat785	1	Minimum 2, maximum 3, mode 2.5	Triangular
Material A	0.449	0	Constant
Material B	0.300	0	Constant
Material C	0.250	0	Constant
Breakdown	0.001	0	Constant
Haul to A	1	Mean 4.0, SD 0.7	Normal
Haul to B	1	Mean 3.0, SD 0.5	Normal
Haul to C	1	Mean 5.0, SD 0.9	Normal
Return from A	1	Mean 2.4, SD 0.4	Normal
Return from B	1	Mean 1.8, SD 0.3	Normal
Return from C	1	Mean 3.0, SD 0.5	Normal
Test Cat777 for breakdown	1	0	Constant
Breakdown probability Cat777	0.001	0	Constant
Test Cat785 for breakdown	1	0	Constant
Breakdown probability Cat785	0.001	0	Constant
Repair trucks	1	Mean 240, SD 60	Normal
Clear shop	1	0	Constant
Reposition loader	1	0	Constant

Note: SD stands for standard deviation.

TABLE 5. Queue Information for Example 2

Place name (1)	Initial marking (2)	Queueing discipline (3)
Loader ready	1	FIFO
Truck queue	Case 1: 4-777, 3-785 Case 2: 8-777 Case 3: 5-785	FIFO
Shop ready	2	FIFO

TABLE 6. Summary of Results for Example 2

Truck fleet (1)	Average queue length (2)	Average wait (min) (3)	Average Daily Quantity at Dump Sites (m³) A (4)	B (5)	C (6)
Five—Cat785 trucks	1.4	4.95	9,161	6,865	5,994
Three—Cat785 and Four—Cat777 trucks	2.89	8.5	8,475	6,406	5,447
Eight—Cat777 trucks	3.3	8.25	7,744	5,719	5,025

fleets modeled. This example indicates that the PN model can provide production rates, cycle times, and equipment utilization information that, along with production costs and economic information regarding the equipment, could be used by contractors to determine the optimum earthmoving system. The extended PN model of the process effectively represents the earthmoving process and handles the heterogeneous queues, nondeterministic transitions, different load destinations, and breakdown probabilities.

COMMENT

These examples demonstrate how PN models can be effectively used for both qualitative and quantitative modeling and analysis of construction operations. The graphical nature of the models make them relatively easy to understand and to communicate to others, and their ease of conversion into algebraic form means analysis is straightforward. PNs are capable of modeling phenomena present in construction operations including nondeterministic activity times, attaching priorities to particular activities, probabilistic branching, and queuing disciplines. The use of colored PNs, demonstrated in Example 2, gives further capability for the user to differentiate between different types of equipment, information, and resource flows. In Example 2, the colored PNs allow the simulation model to account for the different truck capacities; they could also allow for different loader characteristics or different repair shop performance if required. This feature is of particular use when modeling more complex construction operations and is not available in microcyclone and ithink(Stella). The other feature of the PN modeling system, which it is not possible to demonstrate in this paper, is its ability to animate the graphical model of the simulation. This feature is useful when debugging the simulation model and also in improving the construction process design. The modeling power of PNs when combined with their simplicity make them a powerful and accessible tool for construction engineers for the modeling and simulation of construction systems.

The disadvantages of PNs in the construction context include the terminology of the modeling system and the fact that most software tools are not aimed at construction users. Potential improvements could include provision of a construction-terminology-based interface. Another improvement to the enhanced stochastic PN modeling system presented in this paper would involve making transition behavior variable and dependent on token attributes and elapsed time. This would mean that PNs would be equivalent to a purpose-written discrete event simulation in this regard, but with the advantage of the graphical model of the system. For example, in the earthmoving system described earlier, breakdown probabilities could be related not only to the type of truck, but also to the number of hours of operation since the last overhaul. Travel times could also be varied with the truck or road conditions. Work on these enhancements to the present system is presently under way. These improvements will enable construction personnel to benefit from the simplicity and power of PN modeling and contribute to the development of a simulation modeling framework for construction advocated by Halpin (1993).

CONCLUSION

This paper introduces an extended stochastic petri net approach to the modeling of construction systems. Extended stochastic PNs can handle many of the characteristics common in construction systems such as priorities, probabilistic branching, multiple resource sharing, queuing disciplines, and the need to identify, differentiate, and allow interaction between different entities in the system. PNs are a tool for modeling discrete event dynamic systems that provide a feasible alternative to existing construction simulation systems. The power and flexibility of PNs make them attractive for use in both logical and quantitative modeling of construction processes. The further enhancement suggested in this paper should lead to PNs becoming a more useful modeling and analysis tool for construction practitioners.

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