Estimating the Dependability's in Constructions

Calin Ciufudean Constantin Filote Adrian Graur George Mahalu

"Stefan cel Mare" University of Suceava, 9 University Str., RO-5800 Romania
calin@eed.usv.ro.

ABSTRACT: In this paper an approach for the throughput evaluation of the construction manufacturing systems is presented. The throughput is evaluated with a heap-based algorithm for the Petri nets model of the construction systems. The Petri nets model is a stochastic one, and the firing rate of the transitions are calculated with Markov chains models of the component subsystems of the manufacturing system. The advantages of this approach are:

- constructing a system level Markov chain (a complex task) is not required;
- it permits to evaluate transient and steady-state performance of alternative designs based on different availability of the system's components;
- the heap based throughput algorithm is simpler than the traditional timed event graph version;
- it introduces the availability of the human factor in the theoretical model of a construction system.

KEYWORDS: Stochastic Petri nets, Markov chains, system availability, heaps of pieces.

1. INTRODUCTION

Construction systems include a set of manual operations, and a set of automatic operations. A major consideration in designing a construction system is its performance. When a machine or other component of the system fails, the system reconfiguration is often less than perfect. The notion of imperfection is called imperfect coverage, and it is defined as probability c that the system successfully reconfigures, when components break down [1]. We assume that when the repair of the failed component is completed it is not as performance as a new one. In this paper a dependability model for evaluating the performance of a construction system is presented. The meaning of dependability is:

- System availability;
- Dependence of the performance of construction system on the performance of its subsystems and components;
- Dependence of designing the stochastic Petri nets model, Markov chains, and special automata over the (max, +) semiring, which compute the height of heaps of pieces (respectively the throughput of the system).

Stochastic Petri nets (SPN) were developed by associating transitions/places with exponentially distributed random time delays [2], [3]. These methods are based on results obtained from the underlying Markov chain for such systems. Extended SPN were developed to allow generally distributed transitions delays in the case of non-concurrent transitions. For concurrent transitions, exponential distribution is required for exact solutions. The underlying models of these PN are semi-Markov processes. Heaps of pieces: In [4], Viennot observed that trace monoids are isomorphic to heap monoids, that is monoids in which the generators are pieces (solid rectangular shaped blocks), and where the concatenation consists of piling up one heap above another. This yields a very intuitive graphical representation of trace monoids. For us, a useful interpretation of a heap model consists of viewing pieces as tasks and slots as resources, where by slots we use the following model [5]. A piece is a solid block, occupying some of the slots, with staircase-shaped upper and lower contours. With an ordered sequence of pieces, we associate a heap by piling up the pieces, starting from a horizontal ground. A piece is only subject to vertical translations and occupies the lowest possible position, provided it is above the ground and the pieces previously piled up.

2. THE STOCHASTIC PETRI NETS MODEL OF A CONSTRUCTION SYSTEM

A SPN is a six-tuple (P,T,I,O,m,F), where:
$P=\{p_1, p_2, \ldots, p_n\}$, $n>0$, is a finite set of places; $T=\{t_1, t_2, \ldots, t_s\}$, $s>0$, is a finite set of transitions with $P\cup T\neq 0$, $P\wedge T=\varnothing$; I: $P\times T\rightarrow N$, is an input function where $N=\{0,1,2,\ldots\}$; O: $P\times T\rightarrow N$, is an

output function; m: P→N, is a marking whose i-th component is the number of tokens in the i-th place. An initial marking is denoted by m_0; F: T→R, is a vector whose component is a firing time delay with an extended distribution function. By extended distribution functions, we mean that exponential distribution functions are allowed for concurrent transitions. Two transitions are said to be concurrent at marking m if and only if firing either does not disable the other. The firing rule for an SPN provides that when two or more transitions are enabled, the transitions whose associated time delay is statistically the minimum fires. According to the transition-firing rule in PN, when a transition t_k has only one input place p_i, and p_i is marked with at least one token, t_k is enabled. The enabled transition can fire. The firing of t_k removes one token from the p_i and then deposits one token into each output place p_j. Let P(i,k) be a probability that transition t_k can fire. The process from the enabling to the firing of t_k requires a time delay, τ_k. This delay τ_k of a transition can be either a constant or an extended random variable in SPN. P(i,k) and M(s) depend on τ_k as well as the current marking and the time delays of other enabled transitions at that marking. M(s) denote the moment generating function, and is defined as follows:

$$M(s) = \int_{-\infty}^{+\infty} e^{st} \cdot f(t) \cdot dt \qquad (1)$$

Where s is an extended parameter, and f(t) is a probability density function of random variable t. Of course, we have: $M(0) = \int_{-\infty}^{+\infty} f(t) \cdot dt = 1$. A transfer function of a stochastic Petri net [4] is defined as the product P(i,k)·M(s), and is:

$$W_k(s) = P(i,k) \cdot M(s) \qquad (2)$$

Transition t_k characterized by P(i,k) and τ_k is expressed by a transition characterized by $W_k(s)$. Three fundamental structures can be reduced into a single transition. The reduction rules can be used to simplify some classes of PN. With these reduction rules we transform PN into finite state machines (in a finite state machine each transition has only one input and output place, and there is one token in such a net). Fig.1, a,b,c depict these reduction rules.

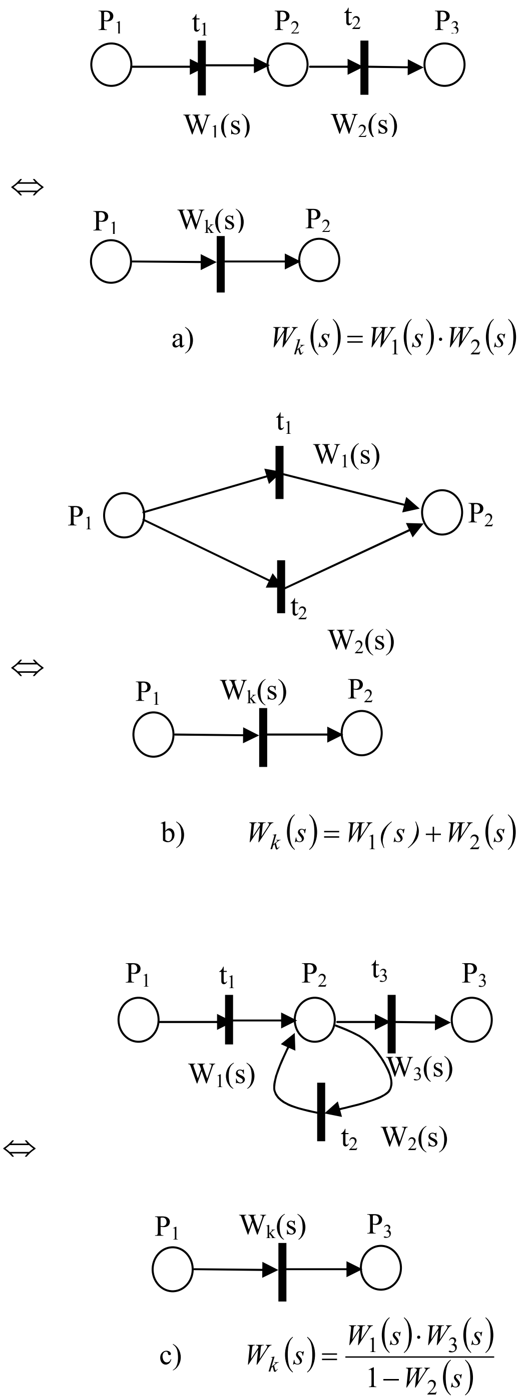

Figure 1. Equivalent transfer functions for three basic structures of PN

The moment generating functions for the state machine PN which models the construction systems represent the availability of the cells (subsystems) which form the PN, and are computed with Markov chains models of the subsystems as shown in the following capitol.

3. AVAILABILITY OF A CONSTRUCTION SYSTEM

We defined above the notion of imperfect coverage, c. We will show the impact of imperfect coverage on the performance of the construction system. We will demonstrate that system availability will be seriously diminished even if this imperfect coverage constitutes a small percentage of the multiple possible flaws of the system. This aspect is generally ignored or overlooked in the current managerial practice. The availability of a system is one probability that should be operational when needed. This availability can be calculated as the sum of all probabilities of operational states of the system. To calculate the availability of a system we need to determine the acceptable levels of functioning degree of the system's states. The availability of the system is considered acceptable when the production capacity of the system can be assured. Considering the big dimensions of a construction system, the multiple interactions among its elements as well as between the system and the environment, in order to simplify the graphs and reduce the amount of calculus we will divide the system into two subsystems. These two subsystems are the following: equipment subsystem (the machine factor) and the man subsystem (the human factor in construction activities). In its turn the equipment system is divided into cells. The Markov chain is built for each cell i, where i=1,2,…,n (n represents the number of cells into which the equipment and human systems are divided) to determine the probability for at least k_i equipment to be operational at a certain moment t, where k_i represents the minimum of well functioning equipment which preserves the cell i operational (for the equipment subsystem), respectively to determine the maximum allowed number of wrong actions of the workers (human subsystem). The availability of the system is given by the probability of the operator doing his duty between k_i operational equipment in cell i and k_i+1 operational equipment in cell i+1, at moment t.

Supposing the levels of the subsystems are statistically independent, the availability of the system is:

$$A(t)=\prod_{i=1}^{n}\left(A_{im}(t)\cdot A_{ih}(t)\right) \qquad (3)$$

Where: $A(t)$ = the availability of the construction system (man-machine system); $A_{im}(t)$ = the availability of the i cell in the equipment system at moment t; $A_{ih}(t)$ = the availability of the cell i in the human subsystem at moment t.

3.1. The equipment system

The expectation of an i cell of the equipment system which includes N_i equipment of the type n_i is to ensure the functioning of at least k_i of the equipment for the system to be operational. To determine the availability of the system including imperfect coverage and faulty repairs for each cell there has been introduced a state of malfunctioning caused either by imperfect coverage or by technical failure. To explain the effect of imperfect coverage of the system we will consider that operation O_1 can be made with one of the equipment M_1, respectively M_2.

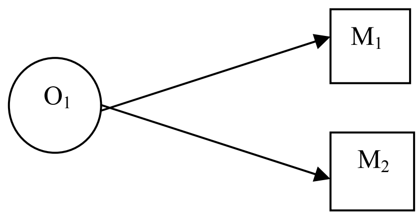

Figure 2. Subsystem consisting of one operator and two machines

If the coverage of the subsystem in Fig.2 is perfect, that is c=1, then operation O_1 is fulfilled as long as at least one of the equipment is functional. If the coverage is imperfect operation O_1 fails with the probability 1-c if one of the equipment M_1 or M_2 breaks down. In other words, if operation O_1 has programmed on equipment M_1 which broke down then the system in Fig.2 fails with the probability 1-c. The Markov chain made for cell i in the equipment subsystem is given in Fig.3. The coverage factor is c_m, the rate of breaking down of a piece of equipment is λ_m (and is exponential), the repairing rate of the equipment is μ_m (which is also exponential), the factor of successful repairing of a piece of equipment is r_m. In state k_i cell i only has k_i operational equipment. The state of cell i change from working state k_i into break down state Fk_i or to imperfect coverage ($1-c_m$), either due to faulty repairing ($1-r_m$). The solution of the Markov chain in Fig.3 is the probability that at least k_i equipment should function in cell i at moment t.

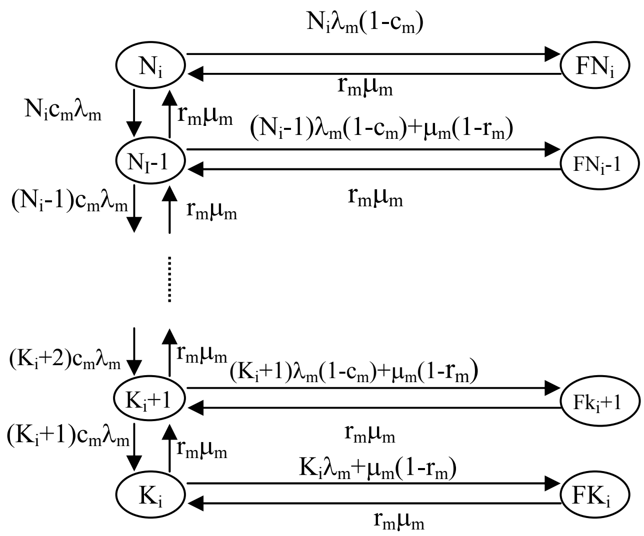

Figure 3. Markov model for cell i in the equipment subsystem

We can calculate this probability according to the following formula:

$$Ai(t)= \sum_{k=k_i}^{N_i} P_{k_i}(t), \quad i=1,2,\dots,n \qquad (4)$$

Where: $A_i(t)$ = the availability of cell i at moment t; $Pk_i(t)$ = probability that, at moment t, cell i should contain k_i operational equipment; N_i = number of M_i equipment in cell i; k_i = minimum number of operational equipment in cell i.

3.2. The human factor subsystem

The expectation from the human factor subsystem is that it should ensure the exploitation of equipment with maximum efficiency and safety. To determine the availability of the operator to be capable of performing his duty at moment t, we build this Markov chain (Fig.4) which models the behavior of the cell i of the human subsystem. In Fig.4, we have:

λ_h = the rate of wrong actions of the operator; μ_h = the rate of correct actions of the operator in case of break down; c_h = the covering factor of problems caused by wrong actions or by unexpected events occurred in the system; r_h = the factor of correcting wrong actions of operators.

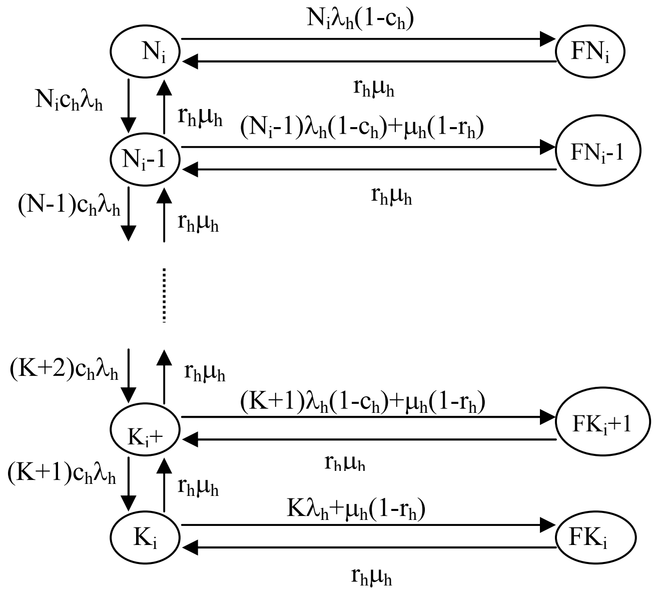

Figure 4. Markov model of cell i corresponding to the human factor subsystem

In Fig.4 the human operator can be in one of the following states of performing his job: state N_i = normal working state in which actions are performed by all N_i operators of cell i; state k_i = working state where actions are performed by k_i operators ($k_i<N_i$); state $F(k_i+u)$ = working state allowing incorrect actions which can cause technological malfunctioning with no serious consequences on the safety of traffic, where $u = 0,\dots,N_i-k_i$; state Fk = state of working incapacity due to wrong actions with serious consequences on traffic safety.

The availability of the human factor due to perform his duties under normal circumstances is:

$$A_{ih}(t) = \sum_{x=j}^{m} P_{x_i}(t), \quad i=1,2,\dots,n \qquad (5)$$

Where: $P_{xi}(t)$ = the probability that the operator is in working state x at moment t, in cell i;
m = total number of working states allowed in the system; j = minimum allowed number of working states.

Attributing supplementary working states to the human factor considerably increases the complexity of the calculus, and furthermore, although the entire system continues to work, certain technological norms are disregarded which leads to low throughput in the construction system.

4. PERFORMANCE EVALUATION OF A CONSTRUCTION SYSTEM

A construction system is specified by the following properties: 1) A finite set R of resources (machines and operators); 2) A finite set T of elementary tasks; 3) For each task $d \in T$, a duration $\tau(d)$ and a single machine cell i, $R(d) \in R$ on which *d* is to be executed; 4) A finite set $B \in T$ of production sequences or jobs. Each job $J = a_1 a_2 \ldots a_k \in \in B$ is composed of a finite number of tasks $a_1, a_2, \ldots, a_k$ to be executed in this order. A job is produced each time the sequence J is completed. This model is equivalent to the one given in [5], where the following algorithm for the performance evaluation of safe jobs (the assumption of safe job is equivalent to state machine Petri net as defined above). The algorithm has the following steps: Input: a job-shop, a pattern of transitions v; 1) Build the heap model, and its associated matrices [5] M(d), $d \in T$; 2) Compute the product of matrices M(v); 3) Compute the (max, +) value of M(v), $\rho(M(v))$, using Karp algorithm, where $\rho(M(v))$ is the (max, +)value of M(v). In [5] it is shown that this algorithm has the complexity $O(|v|(|B|+|R|+(|B|+|R|)^3)$. We notice that this algorithm, in comparison with other algorithms for performance evaluation in discrete event systems, do not need a new time event graph to be build for each new schedule. This is of great advantage for us, because we give to the random variables different values in order to build different scenarios for the construction system optima schedule.

5. CONCLUSIONS

Our work develop heuristics and performance bounds for scheduling, based on heap and automata representation. The performance of a construction system is evaluated, in many scenarios, with a SPN in which a transition can be associated with either a constant or random firing time delay with an exponential distribution, computed with a Markov model which incorporates the notion of imperfect coverage, and imperfect repair factors. An advantage of the Markov model is that the construction of large Markov chains is not required. Another advantage is that it allows performing sensitivity analysis of an entire construction system, as well as of its components. The novelty of this approach is that it incorporates the availability of the human factor. We can generalize the proposed approach, when instead of decomposing the global system in two major subsystems, one can decompose the system into three, four, … subsystems, according to the specific application. We may notice that a large number of subsystems determine an embarrassing growth of the calculus complexity. In this paper we assumed that the failure and repair times were exponential random variables. In real construction systems, the time distributions are arbitrary, which can be handled semi-Markov processes. A state transition may not occur at any time, and the failure/repair time can follow an arbitrary distribution. When a failure/repair event occur, the Markov process representation applies, and the probability of burning a transition to a new state depends only on the current value of state.

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