Agent-based Mobile Robotic Cell Using Object Oriented & Queuing Petri Net Methods in Distribution Manufacturing System

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Abstract

In this paper, we deal with the problem of modeling of agent-based robot manufacturing cell. Its role is becoming increasingly important in automated manufacturing systems. For Object Oriented & Queueing Petri Nets (OO&QPNs), an extended formalism for the combined quantitative and qualitative analysis of different systems is used for structure and performance analysis of mobile robotic cell. In the case study, the OO&QPN model of a mobile robotic cell is represented and analyzed, considering multi-class parts, non-preemptive priority and alternative routing. Finally, the comparison of performance values between Shortest Process Time (SPT) rule and First Come First Serve (FCFS) rule is suggested. In general, SPT rule is most suitable for parts that have shorter processing time than others.

1. Introduction

Because of increased competition in the world market, product-oriented manufacturing enterprises are being forced to seek more advanced technologies to earn profits. Product life cycle and the cycle time for new product development are becoming shorter while batch sizes are smaller and will decrease further as products become more durable, reusable, upgradable, and configurable. At the same time, the variety of products is increasing and manufacturing industry must be flexible, adaptable, and agile to respond to the fast pace of product changes.

Although traditional mass production and fixed automation are still being used for many products, as more companies enter into the market, both their market share and profits will be harder to maintain. In the coming decades, major changes in manufacturing will occur due to globalization, telecommunications advances, computer technology, limited natural resources, and environmental and other concerns. Mass production and mass consumption are no longer valid answers for the growing problems of the world economy. Thus discrete manufacturing industries will have to change their strategies to compete in the new world economy.

Agile manufacturing, concurrent engineering, enterprise integration, and responsive manufacturing systems are emerging as new technologies which might reflect the rapid changes in manufacturing environment. These new ideas will be based on the most advanced technologies now available such as CAD, automated process planning, CNC machine tools technologies, robots, computerized production planning and scheduling, JIT production, FMSs, and so on. Among the above technologies, process planning has become the main subject of interest for both the academia and the discrete manufacturing industries over the last three decades. Although process planning has been interpreted mainly in the context of the machining process, it is now a more complex concept including inspection and assembly as a part of an integrated process planning in a computer-integrated manufacturing environment.

There are various factors which might impact process planning, such as the innovation and invention of new technologies, customer's order changes, promotion of competitors, different problems with single source suppliers, etc. These factors may improve or endanger the viability of the manufacturing system. Therefore, designing process planning of manufacturing systems which can cope with the environment becomes an issue. It is believed that flexibility and adaptability are the issues that should be considered in the design, planning, and control of process planning of manufacturing systems. The concept of hierarchical planning which is also referred to as the distribution structure, can be considered because it enables one to classify the process plan into the abstract plan, the refined plan, and the detailed plan. In the meantime, due to the advent of information technologies, it is easy for decision makers to send and receive operational instructions on the hierarchy layers. The distribution of decision makers unfortunately brings other management problems: coordination and collaboration. Recent agent research identifies a research direction to solve the above problems.

In this paper, we suggest an extended methodology called Object Oriented & Queueing Petri-Nets (OO&QPNs) which is the combination of Object Oriented Design (OOD) methodology and QPNs approaches. It will enable the system analyst to integrate the agent-based manufacturing system modeling and performance analysis. For the definition of OO&QPNs, we first unfold the concept of generalized stochastic petri-net and objectize each node using multi-set concepts in place, predicate in arc, and colored function in transition. Using this methodology in modeling mobile robotic cell, we represent the two types of autonomous agents in this research: control agents and operating agents in which the former is suitable for the tasks such as routing and dispatching in a controller of the mobile robotic cell, and the latter is compatible with the role of PLC and sensors performing job management, load/unload and deadlock avoidance.

2. Intelligent Agent Systems For Mobile Robotic Cell

In recent automated manufacturing systems, industrial robots play an important role in some workstations that are exposed to hazardous working conditions, repetitive work cycle, and difficult handling. Many different production tasks have been achieved by robot arms - the most common form, with the robot's capacity to be programmed. Major applications of industrial robots involve material transfer, machine loading/unloading, welding, and painting. Machine loading/unloading applications are most popular and their configuration is frequently called robotic cells in automated manufacturing areas.

It is important that the equipment in robotic cells be organized into an efficient layout. Robotic cell layout can be classified into three basic types: robot-centered cell, in-line robot cell, and mobile robot cell. Robot-centered cell, which is most common, is used when one industrial robot is located at the approximate center of the workcell with other pieces of equipment around it. In-line robot cell is an arrangement in which one or more robots are located along an in-line conveyor or other material transport systems. Its layout recalls typical transfer lines. The third category of robot cell is the mobile robot cell presented in Figure 1. In this arrangement, the robot is provided with a means of being transported within the cell to perform various tasks at different locations.

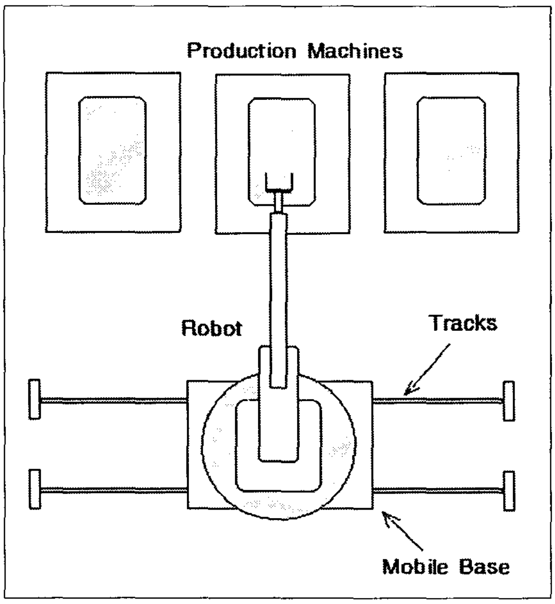

Figure 1. Mobile robotic cell layout

The mobile robot is appropriate in installations where the robot must service more than one workstation. With workstation robots, either a floor-mounted or overhead rail system is used. Each workstation can include local buffers in this cell. Various tasks may also be processed, in this case, flexible control activities for efficient production have to be performed by computer controlled systems. The mobile robotic cell, therefore, can be operated more flexibly than other types of cells, in which control activities must accept tasks (or parts) priority, alternative routing, efficient buffer and tool management, realtime scheduling, etc..

Only a few studies in the robot cell have been reported in the literature. It is the main reason why robotic cells are used mostly in workstations that deal with relatively hazardous and monotonous works. Nevertheless some researchers have developed many models and various solutions. Baumann et al.(1981), Bedinit et al.(1979), Kondoleon(1979), and Sethi et al.(1992) concentrated on deriving models to analyze and determine robotic cell utilization or to optimize the work cycle of robots. In studies of multi-robot cells, Nof and Hama(1989) and Seidmann et al.(1985) present predictive models for describing the productive capacity and operational analysis models, respectively. Develzic(1990) proposes a knowledge-based system approach for the strategic control of robots in flexible manufacturing cells, and related studies of this topic are so widespread. Kim and Langston(1987) have dealt with mobile robot movements, which is restricted to a single track that connects a series of workstations.

In the analysis of computer integrated manufacturing systems such as the mobile robotic cell, it is very important to understand and investigate data processing components from order receipt, through design and production to product shipment, as well as to consider the material processing components. The research related to the automation of material processing components has been extensively exploited for many years in the industrial and mechanical engineering areas, but the research on automated data processing as distributed systems in robotic cells is limited. Therefore, it is necessary to find a method that to coordinate data processing activities and to extract necessary information scattered at several physically distributed data systems. Figure 2 depicts this architecture which shows inputs, outputs, and sub-system interactions. In Figure 2, two kinds of autonomous agents are suggested: control agent and operation agent.

The functions of control agent involves the mapping of geometric, physical and operational information of an assembly to the corresponding capabilities of the

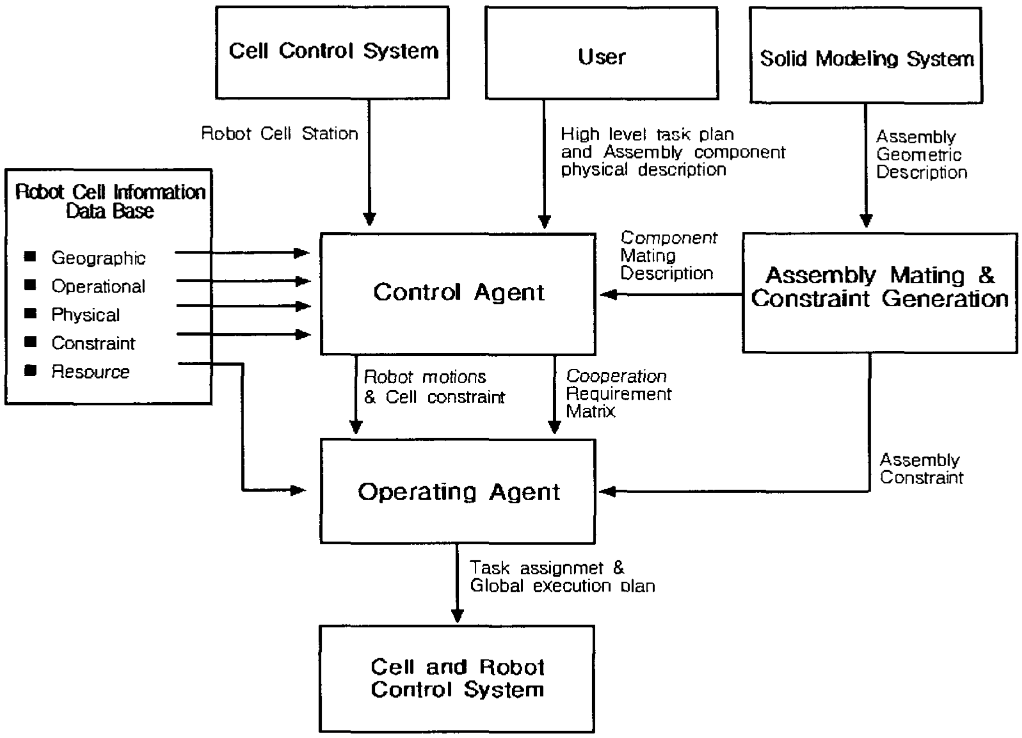

Figure 2. Intelligent agent systems for mobile robotic cell Architecture showing inputs, outputs, and sub-system interactions

robots; generating assembly, robot, and cell constraints, and the operating agent assigning tasks to single robots(or multi robots) based on their capabilities, and generating a consistent and coordinated global plan to accomplish the cooperative task.

In this study, we are interested in the efficient operation of agent-based mobile robot cell that includes multi-class of parts, different batch sizes, part priority, alternative routing, and different capacity of each machine on parts. To analyze this model, we use Object Oriented & Queueing Petri Net (OO&QPN), which is one type Petry-Nets widely accepted as a formalism for describing concurrent systems. The OO&QPN modeling for agent-based robotic cell can objectize each activity of agent and evaluate performance measures under different alternatives.

3. Object Oriented & Queueing Petri Nets

Queueing Networks (QNs) and Petri

Nets (PNs) are well known formalism for the description and analysis of a variety of systems. PNs are used for qualitative analysis whereas QNs are employed for performance evaluation (quantitative analysis). But there are certain specific deficiencies in both areas: PNs have difficulties in describing scheduling strategies in a compact manner, while QNs are weak at describing sophisticated synchronization aspects. To overcome these insufficiencies, many researchers have proposed different formalism such as GSPNs, CGSPNs, Extended QNs, etc.. The introduction of a new version of the Queueing Petri Nets(QPN) formalism also aims at eliminating these difficulties, which was first proposed by Balbo, Bruell, and Ghanta(1986) as Integrated Queueing Petri Net(IQP). Now the formalism for the integrated specification of qualitative and quantitative aspects of a system leads to new possibilities in system analysis.

On the other hand, data processing among distributed systems is based on the concept of object-oriented programming. Therefore, the modeling representation of the agent-based robotic cell including distributed systems can transform the design of model into object-oriented programming which is constituted by object model, dynamic model, and functional model. A number of studies are suggested on the aim of integrating petri-nets approaches and object-oriented programming, but these researches concentrated on technology development of object-oriented programming. Thus we suggest integrated tools as more analytical views. Based on the definitions of OO&QPNs and node representation in Figure 3, we propose OO&QPNs modeling for agent-based mobile robotic cell in Figure 4.

Definition : An Object Oriented & Queueing Petri Net (OO&QPN) is a 4-tuple (QPN, P_{IN}, Connector, Predicate) where QPNs is again a 4-tuple (CPN, Q, M0, W).

1. $CPN = (P, T, C, I^-, I^+)$ is the underlying Coloured Petri net, where

· $P=\{p_1, p_2, \ldots, p_n\}$, $n>0$, is a set of place

· $T=\{t_1, t_2, \ldots, t_m\}$, $m>0$, is a set of transition.

$$P \cup T \neq \Psi \text{ and } P \cap T = \Psi$$

· $C(p_i)$ and $C(t_j)$ are sets of colours, with place $p_i \in P$ and transition $t_j \in T$, given by

$$C(p_i)=\{a_{i1}, a_{i2}, \ldots\ldots, a_{iu_i}\}; \quad u_i=|C(p_i)|$$

$$C(t_j)=\{b_{j1}, b_{j2}, \ldots\ldots, b_{jv_j}\}; \quad v_j=|C(t_j)|$$

$$i = 1, 2, \ldots, n; \; j = 1, 2, \ldots, m$$

· $I^-(p, t) : C(p)\times C(t) \rightarrow \mathbf{N}$ is an input function,

and $I^+(t, p) : C(p)\times C(t) \rightarrow \mathbf{N}$ is an output function.

2. $Q = (\overline{Q}_1, \overline{Q}_2, (q_1, \ldots q_{|P|}))$ where

· $\overline{Q_1} \subseteq P$ is the set of timed queueing places,

· $\overline{Q_2} \subseteq P$ is the set of immediate queueing places.

· $q_i = \begin{cases} QU(p_i) & \text{if } p_i \in \overline{Q}_1 \cup \overline{Q}_2 \\ 0 & otherwise \end{cases}$

· A Queueing(QU) is a 4-tuple $QU(p)$ = {$ST(p)$, $TR(p)$, $AC(p)$, $TN(p)$}

· $ST(p)$ specifies the feasible states of a queue, and especially $0 \in ST(p)$ denotes the empty queue. Note that $ST(p)$ might be infinite.

· $TR(p)$: $(ST(p) \times CN(p)) \times (ST(p) \times CN(p)) \rightarrow R_0^+$.

where $CN(p)$ = $[C(p) \rightarrow N_0]$ is the set of all functions f: $C(p) \rightarrow N_0$. This real value can be interpreted as the rate of a negative exponential distribution for the description of service times in case of a timed queueing place or as a weight, if p is an immediate queueing place.

Their weights will be exploited for calculating probabilities of transition from vanishing states of the QPN's stochastic process.

· $AC(p)$: $ST(p) \times C(p) \rightarrow ST(p)$ specifying the next state of the queue after arrival of a token of a colour $\in C(p)$.

· $TN(p)$: $ST(p) \times C(p) \rightarrow N_0$ specifying the number of tokens in the queue. Note that, given $s \in ST(p)$, $TN(p)(s)$ is a function of $CN(p)$

3. M_0 is the initial marking.

A marking of a CPN is a function M defined on P such that for $p \in P$, then $M(p)$: $C(p) \rightarrow$ N. Let M denote the current marking of a CPN. The marking M is an $(n \times 1)$ vector with components $M(p_i)$, where $M(p_i)$ represents the marking of place p_i, $M(p_i)$ is represented by the formal sum of colors:

$$M(p_i) = \sum_{h=1}^{u_i} n_{ih}\, a_{ih}$$

where n_{ih} is the number of tokens of color a_{ih} in place p_i. Thus $M(p_i)(a_{ih}) = n_{ih}$ denotes the number of tokens of color a_{ih} in place p_i in current marking.

4.

$W = (\overline{W}_1, \overline{W}_2, (w_1, . . . , w_{|T|}))$

where

· $\overline{W_1} \in T$ is the set of timed transitions,

· $\overline{W_2} \in T$ is the set of immediate transitions, $T = \overline{W_1} \cup \overline{W_2}$, $\overline{W_1} \cap \overline{W_2} = \phi$ and

· $w_i \in [C(t_i) \rightarrow R^+], \forall t_i \in T, b_{jv_j} \in C(t_i)$.

$w_i(c)$ is interpreted as the rate of a negative exponential distribution specifying the firing delay, if transition t_i is a timed transition, or a weight specifying the relative firing frequency, or if transition t_i is an immediate one.

5. P_{IN} : Instance Place

6. Connector = { P_{CN}, T_{CN} }

· $T_{CN} = \langle t_1 \rangle \cap \langle t_2 \rangle \cap . . . \cap \langle t_m \rangle$

· P_{CN} : IN($P \times T_{CN}$) or OUT($P \times T_{CN}$)

where $\langle t_m \rangle$= t-invariant

7. Predicate = { $IN_{Predicate}$, $OUT_{Predicate}$ }

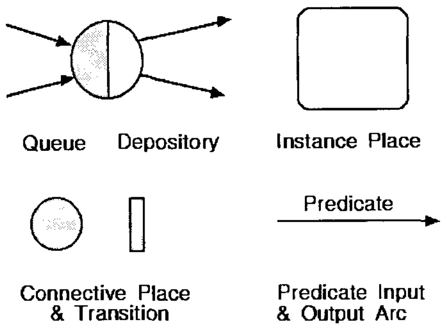

Figure 3. Node Representation of OO&QPNs

4. Robotic Cells Modeling and Analysis

In this section, we deal with the problem of modeling and analysis for mobile robotic cell, which is arranged by three-machine robotic cell. Each machine has rotary indexing buffer, and incoming part is guided by index conveyor.

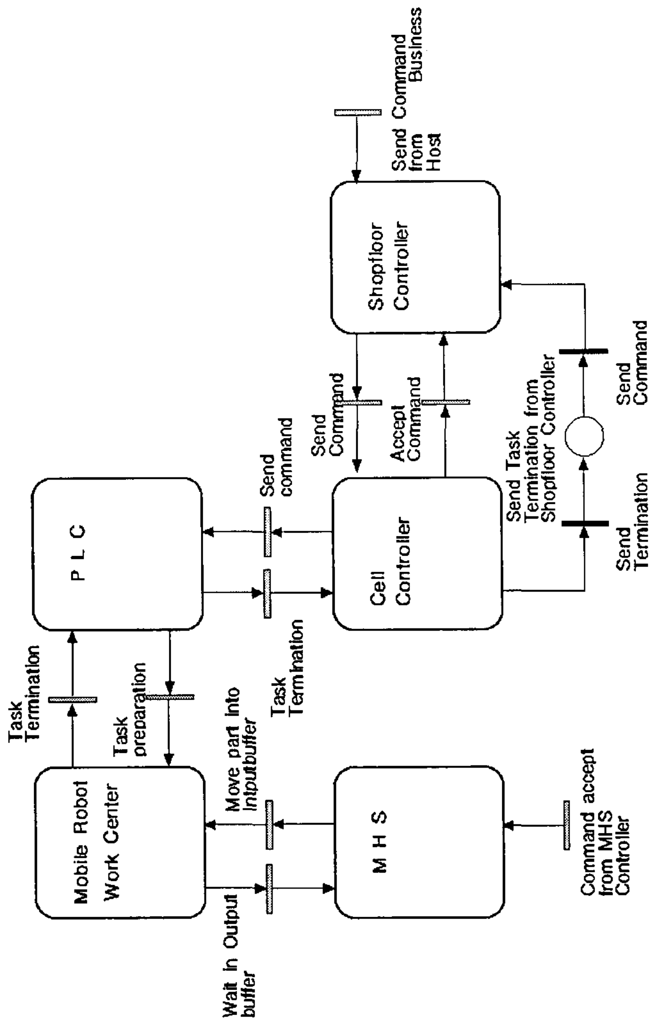

Figure 4. OO&QPNs modeling for agent based mobile robotic cell

Three-class of parts can be processed in this work cell. Batch size of each part and service rate at each machine are different depending on the type of part. Alternative routing strategy is also accepted. In this case, part type 2 and 3 is designed to have route flexibility, therefore parts of these types will define machines to be operated at next stage. In this model each machine is designed to follow specific scheduling strategy. Non-preemptive priority is also considered. Shortest Process Time is accepted as the dispatching rule. The comparison of performance measurement between SPT and FCFS is presented to Table 3.

Table 1 and Figure 5 are given as QPN modeling of mobile robotic cell and description of the QPN model of Figure 5 in Table 2.

Table 1. Mobile robotic cell capacity and route for each part type.

	Part type	Robot	Production machines		
			M1	M2	M3
Service Rate (per min)	1	3	12	6	8
	2	5	10	8	6
	3	6	14	4	6
The number of visits	1	4	1	1	1
	2*	3	1	0.43	0.57
	3**	3	1	0.60	0.40

*, ** Probability of alternative route with part types 2 and 3

$$P(M_{22}) = \mu_{22} / \sum_{i=2}^{3} \mu_{i2},\ P(M_{32}) = \mu_{32} / \sum_{i=2}^{3} \mu_{i2}$$

$$P(M_{32}) = \mu_{32} / \sum_{i=2}^{3} \mu_{i3},\ P(M_{33}) = \mu_{33} / \sum_{i=2}^{3} \mu_{i3}$$

Table 2. Description of the QPN model of Figure 4

■ Place & Transition

P_1 = Job j : Available fresh jobs. (j = 1, 2, 3)

P_2 = Robot : Available robot.

P_3 = Machine i : Available machines. (i = 1, 2 ,3)

P_4 = Job j + Robot

: Transportation of job j by robot.

P_5 = Buffer k : Available buffers. (k = 1, 2, 3)

P_6 = Queued place : Processing in progress.

t_1 = Transition indicating robot's loading.

t_2 = Transition indicating robot's unloading.

t_3 = Transition indicating start of processing.

t_4 = Transition indicating finishing of processing.

■ Color sets

C(Job j) = { J_1, J_2, J_3 }

C(Robot) = { Robot }

C(Machine i) = { M_1, M_2, M_3 }

C(Job j + Robot) = C(Job j) × C(Robot)

C(Buffer k) = C(Job j)

C(Queued place) = C(Job j) × C(Machine i)

$C(t_1) = C(t_2)$ = C(Job j + Robot)

$C(t_3) = C(t_4)$ = C(Queued place)

■ The number of tokens of colour a_{ih} in place p_i

$M(P_1)(J_1) = 4$, $M(P_1)(J_2) = 3$, $M(P_1)(J_3) = 5$

■ Rates / Weights (referred to Table 1)

■ Queued place

ST(p) = The set of all sequences of elements of C(p)

TR(p)((v, f_p),(w, f_r)) = μ_s (the service rate of a color-i token)

if $f_r = f_q + \delta_s\ \exists s \in C(p)$,

$v_I \in ST(p)$: $v = sv_I$ & $w = v_I$

AC(p)(v, s) = sv

TN(p)(v, s) = 1 + TN(p)(v_I, s) if $\exists v_I \in ST(p)$: $v = sv_I$

Table 3. Performance values for the QPN model

Part type	Throughput Time (minute)			Production Rate (per minute)
	M_1	M_2	M_3	
1	0.246 (0.310)*	0.106 (0.110)	0.050 (0.060)	1.92
2	0.178 (0.280)	0.143 (0.100)	0.101 (0.060)	1.69
3	0.377 (0.350)	0.0704 (0.080)	0.101 (0.100)	2.69

* ( ) is a case of FCFS

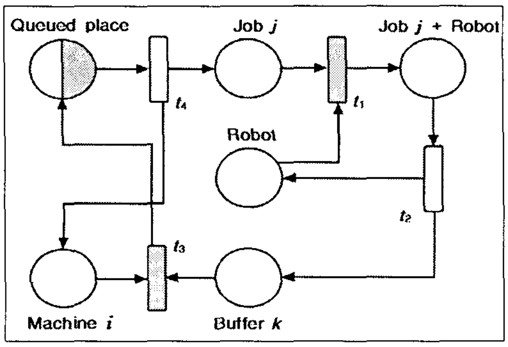

Figure 5. QPN modeling of Mobile Robotic Cell

5. Results

In this paper, we carried out the modeling of three machine mobile robotic cells using QPN, and confirmed that explicit differences between scheduling strategies exist as shown in Table 3. The three machine mobile robotic cells used involve different operation time with machines and robot, various batch size, non-preemptive priority rule and route flexibility. But it doesn't consider the time difference for loading and unloading of different parts, different travel time between machines, multi-robotic processing in larger workstations, roles of agent oriented knowledge based on the level of computer control systems. These issues can be good subjects for the next study.

The introduction of a new formalism of Petri Net is also suggested in the paper. QPN, a methodology capable of quantitative and qualitative analysis, will be used by many researchers in this field, if the remaining problems such as the development of relevant software, unification of Petri Net notation etc., is solved. Therefore, it might be a promising area for future research.

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