Modeling resource management in the building design process by information constraint Petri nets

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Abstract: The effect of resource management on the building design process directly influences the development cycle time and success of construction projects. This paper presents the information constraints net (ICN) to represent the complex information constraint relations among design activities involved in the building design process. An algorithm is developed to transform the information constraints throughout the ICN into a Petri nets model. A resource management model is developed using the ICN to simulate and optimize resource allocation in the design process. An example is provided to justify the proposed model through a simulation analysis of the CPN Tools platform in the detailed structural design. The result demonstrates that the proposed approach can obtain the resource management and optimization needed for shortening the development cycle and optimal allocation of resources.

Keywords: Resource management, Building design, Information constraint net, Petri nets, Simulation

1. Introduction

Building design is complex and interactive process, involving many stakeholders from multiple disciplines. The design process is constrained in several ways, including time, resources and process precedence relationships. Of these, the resource constraint is a key factor directly influencing the construction project development cycle and economic benefits [1-3]. The establishment of a process model that accurately describes the main constraint relationships in the design process is thus crucial for resource management and optimization.

Existing resource management simulation and optimization methods are used for complex systems, mainly through discrete event optimization algorithms, to obtain optimal or near-optimal results. Discrete event simulation (DES) [4,5] and heuristic algorithms [6,7] are the commonly used simulation tools for resource management modeling. Zhang and Li [8] have presented an optimization methodology that integrates DES with a heuristic algorithm. This optimizes dynamic resource allocation for construction scheduling. Joglekar and Ford [9] propose the use of a Resource Allocation Policy Matrix as a means of describing resource allocation policies in dynamic systems - using system dynamics and control theoretic models. Park [10] also proposes a model-based dynamic approach for construction resource management to identify the dynamics of construction progress and the tradeoff with resource coverage.

The use of Petri nets is a discrete systematic approach which can effectively model parallel and asynchronous variables. Based on graph theory, this method provides both mathematical formulas and graphical representation, and demonstrates the advantages of process modeling [11-14]. Cheng et al. [15] have developed a colored Petri net model for the virtual construction of earthmoving operations. This describes the dynamic changes of workflow and information flow in the construction process and the dynamic constraint relations between equipment and the construction environment. Julia et al. [16] propose an approach based on a p-time Petri net model with hybrid resources to solve the real time scheduling problems of workflow management systems. Here, hybrid resource allocation mechanisms are modeled by a hybrid Petri net with discrete transitions in order to identify the optimal sequence of activities under time constraints. Kiritsis and Porchet [17] propose a Petri net based approach for dynamic process planning and sequencing. Their model clarifies the type of precedence relation constraints, represents dynamically the process planning procedure, produces and simulates all possible process-planning solutions, and provides alternative optimized solutions heuristically. Information constraint is the important factor influencing process modeling. Research has been conducted to take advantages of the intuitive expressions and systematic descriptions that Petri nets offer, and represent constraint relations. Zhang et al. [18] use timed Petri nets to simulate production sequencing in a flexible assembly system. In this case, the constraints involved include precedence relations, working space that limits concurrent operations, and variations in process time. Heish [19] have developed a cooperation mechanism for multi-agent systems with Petri nets under conditions of resource contention. Aalst [20] and Liu et al. [21] propose a transforming method between a bill of materials (BOM) and process model. However, because of the simple constraint relationship that exists among the various parts of a BOM, it is difficult to represent the complex design information constraint relations among building design tasks.

Discrete event optimization methods, such as Tabu search [22,23], the Genetic Algorithm [24-26], and Simulated Annealing [27,28], have been used for process modeling. However, the difficulty in building an objective function makes it impractical to optimize dynamic allocation policies. These methods lack a clear description of the process itself, and fail to accurately express informational constraint relations. Heuristic approaches generally consider each activity separately and only one activity is determined each time, which results in a waste of resources [1,29,30]. Research in the field of process modeling with Petri nets provides modular and flexible modeling solutions through color, time, and hierarchy extensions to Petri nets. Nevertheless, they cannot satisfy the requirements for modeling the interactive and complicated nature of the building design process and its many stakeholders. Moreover, the correlations and constraints of multiple conditions in the design process are not considered by any of these methods.

In this study, an information constraint Petri net is proposed to represent the information constraint relations among the activities involved in the building design process. An algorithm is developed to transform the information constraints throughout ~~thought~~ the information constraint net, for the Petri nets model. A resource management model is developed using the information constraint Petri net to simulate and optimize resource allocation in the design process. The use of the model is illustrated through the CPN Tools platform in a case study concerning the detailed structural design of a building.

2. Description of the building design process

2.1 The building design process

The detailed structural design of a building involves producing the design output plan, carrying out structural calculations, designing the foundation and frame structures, designing the external walls and roof structures, and designing complementary structures [31]. Each part of the process is influenced by many constraints, such as the global design, conditions of contract, geotechnical information and the external environment. Fig. 1 illustrates the workflow and information constraint relations in the detailed structural design work.

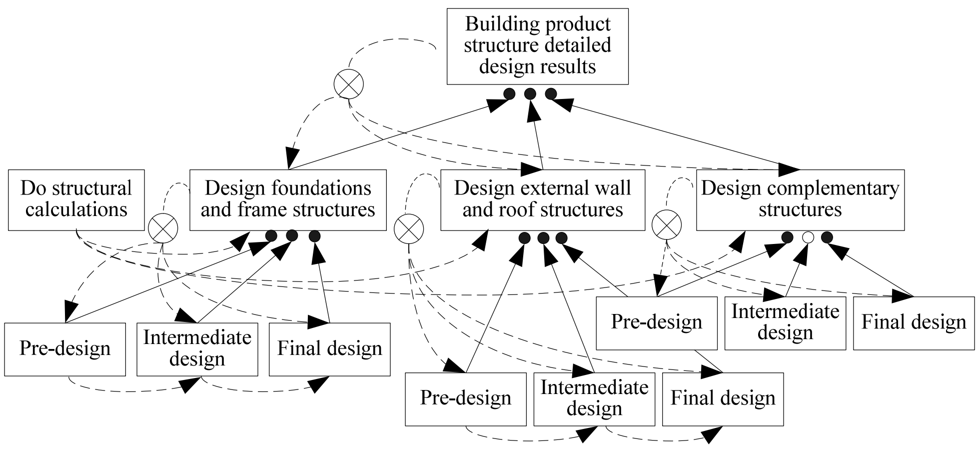

Fig. 1. Workflow and information constraint relations in detailed structural design

2.2 The building design information constraint net

The internal constraint relations of product design information affect quality and efficiency of the building design process. The concept of a product design information constraint relation net (ICN) is introduced in order to express the design information constraint relations (widely existing among design activities),. Each node in the ICN denotes a design task and every task transforms the input information to the succeeding node.

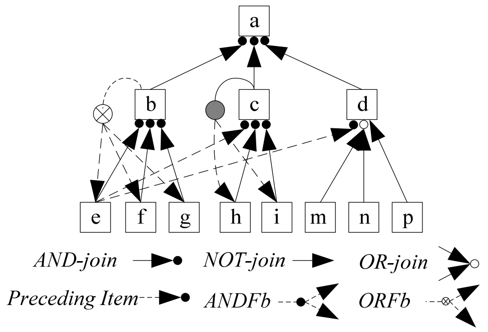

Fig. 2. A design information constraint net of task *a*

As shown in Fig. 2, executing design task *a* needs the design information concerning task *b*, task *c* and task *d*. Therefore, before starting task *a*, task *b*, *c* and *d* must be completed. An arrow and a solid dot denote an *AND-join* relation in the information. Similarly, task *b* needs the information concerning task *e*, *f* and *g*, task *c* of *h* and *i* and task *d* of *m* or *n* and perhaps also *p*. The *OR-join* relation is denoted by more than two arrows and a hollow dot. The *NOT-join* relation is denoted by an arrow. Task *e* is the preceding design activity of task *c* and *d*. The *preceding item* relation is represented by a dashed line and a solid dot. The information conceernig any task *e*, *f* and *g* can influence task *b*. The *OrFeedback* relation can be expressed by several dashes and a "X" mark hollow dot. Task *h* and *i* can together affect task *c*. The *ANDFeedback* relation can also be expressed by several dashed lines and a solid dot. The ICN of task *a* is established through labeling the above constraint relations and attaching necessary information such as the completion time.

3. Resource management model of the building design process based on an information constraint Petri net

3.1 Definition of an information construction net

Definition 1. Information constraint net (ICN)

$ICN = (V, R_V, E)$, where:

(1) Finite set $V = (v_1, v_2, \ldots, v_n)$ is the set of nodes in the net. Order pair (v_i, v_j) is the side of ICN indicating the information flow from v_j to v_i.
(2) Color set R = (*And-join*, *Or-join*, *Not-join*, *pre*, *AndFb*, *OrFb*). Relation R refers to information relations of *And-join*, *Or-join*, *Not-join*, *precedence* relation, *And-Feedback*, *Or-Feedback*. R_V is the constraint relation set of random side (v_i, v_j) .
(3) E denotes the task's execution time corresponding with the nodes. It is a triangular fuzzy number [*EF*, *MF*, *LF*] [32]. *EF* refers to the minimum completion time, *MF* refers to the most likely completion time and *LF* refers to the maximum completion time.

If v_0 is the final task, there is no information output except the feedback relation line connection. If there is information output for random node v_i, v_i is the middle task needed by downstream tasks.

Definition 2. For relation R and for random node v_i, $R(v_i,)$ denotes the node set with relation R set which points to node v_i. For example, *And-join* denotes the required set for node c.

The following two deductions can be made from the definition of ICN.
Deduction 1: There is no orphaned node in ICN, that is $\forall v_i \in V$, $\forall v_j \in V$, $st\ v_i \in R(v_j)$.
Deduction 2: There is no node that only belongs to preceding constraints in ICN and a preceding node must have a parent node with the required relation, that is $\forall v_i, v_j \in V$, if $v_i \in pre(v_j)$, then $\exists v_k \in V$, so that $And\text{-}join(vk) \cup Not\text{-}join(vk)$

Definition 3. For an ICN, it denotes a relation R for a random node, $\widehat{v} = \{x \in V \mid (v, x) \in V\}$, $\widehat{v} = \{x \in V \mid (x, v) \in V\}$.

It can be concluded from the formalized definition of an ICN that it is a directed information relation constraint net that indicates the design information constraint relations among design activities in a design process.

3.2 Resource management model for the building design process

In this paper, the concept of a fuzzy time colored workflow net (FTCWF-net) is introduced to extend the workflow net modeling methodology. This offers an improvement on the Petri net, to accommodate time uncertainties and the integration, complexity and dynamics of the product design process. In addition, it can effectively support resource analysis, optimization and the simulation of the design process.

Definition 4. Fuzzy timed colored workflow net (FTCWF-net)
A FTCWF-net is a 5-tuple:
FTCWF-net = $\{P, T, F, D, M_0\}$, where:
(1) WF-net = $\{P, T, F, M_0\}$ is a basic workflow net system, but the firing of transition T can be instantaneous (instantaneous transition), or it can last for some time (fuzzy time transition);
(2) D is a triangular fuzzy number $[a, b, c]$, which indicates the firing time of the corresponding transition: letter a denotes the minimum completion time, letter b denotes the most likely completion time and letter c denotes the maximum completion time.

Definition 5. Resource management model for the building design process
The resource management model for the building design process is a 10-tuple: RMMBPDP $=\{R, P, T, F, D, M_0, C, G, I, S\}$, where:
(1) R is a multi-set of token color, see definition 6;
(2) the meanings of P, T, F, D, M_0 are the same as definition 4;
(3) C is a color function, defined from P into R;
(4) G is a guard function, defined from T into expressions such that $\forall t \in T$:$[Type(G(t) = Boolean \square Type(Var\ (G(t))) \subseteq R]$;
(5) I is an initialization function, defined from P into closed expressions such that
$\forall p \in P$:$[Type(I(p) = C(p(a)_{MS}]$. $P(a)$ is the place of the $N(a)$. MS is the multi-set;
(6) $S(S \in [0,1])$ is the firing possibility of transition T when it conflicts with other transitions. S = 1 when there is no conflict.

Definition 6. Token color multi-set

R is a multi-set that expresses token color based on object oriented $R = \{ID, OR, B, i, e, Res\}$, where:

ID is the only identification of token in the system

OR is the activity type of token. The value is *ON* or *OFF* is decided by the predecessor activity for expressing the synchronousness or asynchronousness of the activity

B is the boolean value of tokens, $B \in BOOL$

i is the iteration number

e is the timestamp

Res is the subset of the resource characteristics.

3.3 Transforming algorithm for the information constraint net

The transforming algorithm from ICN to information constraint Petri net is presented based on the ICN and information flow view. Each node of the ICN corresponds to a place or transition of the FTCWF-net, which represents a design task in the model or design information captured from an external source. The algorithm is clarified in the following steps:

Step 1: Construct a fuzzy timed workflow net $PN = \{P, T, F, D, M_0\}$, where $P = \{start_{v0}, end_{v0}\}$, $T = \{v_0\}$, $F = \{(start_{v0}, v_0), (end_{v0}, v_0)\}$, and $V = V - v_0$.

Step 2: Choose a subnet $N = (P, T, F, D)$. If $V = \phi$, then go to step 4; else choose a node $v \in V$ in the net. If $\breve{v} = \phi$, then re-mark label *v* as $perf_v$, go to step 1; else go to step 3.

Step 3: Add transitions $prep_v$ and $perf_v$ respectively before and after transition *v*. Transition *v* is replaced by subnet. The description method of transition and place depends on relation *R*.

If $x \in \breve{c}$ and $R(x, c) = mand$, then $P_{end} = end_x$, $P_{start} = start_x$, $F = (start_x, x) \cup (x, end_x)$, $T = x$;

If $y \in \breve{c}$ and $R(x, c) = cho$, $R(y, c) = cho$, then $P_{end} = end_{(x,y)}$, $P_{start} = start_{(x,y)}$, $T = \{x, y\}$,

$F = (start_{(x,y)}, x) \cup (x, end_{(x,y)}) \cup (start_{(x,y)}, y) \cup (x, end_{(x,y)})$.

If $x \in \breve{c}$ and $R(x,c) = opt$, then $F = (start_x, x) \cup (x, end_x) \cup (start_x, skip_x)$; $P_{end} = end_x$, $P_{start} = start_x$, $T = \{x, skip_x\}$;

If $x \in \breve{c}$ and $R(x,c) = pre$, then $F = (perf_x, prep_{(x,y)}) \cup (prep_{(x,y)}, perf_c)$, $T = \phi$, $P = prep_{(x,y)}$.

Traverse each node of *c*, go to step 2.

Step 4: Add feedback relation line. For random node v needs to be reviewed, that is $R(v, x_1) = R(v, x_2) = AndFb$ or *OrFb*, add place $submit_v$ and transition $check_v$ before the place end_v, and add place $iterate_v$ and logic transition *t* after the transition $check_v$ so that a new workflow net model is generated. $P = P \cup \{submit_v, iterate_v\}$, $T = T \cup \{check_v, t\}$, $F = F \cup \{(perf_v, submit_v), (submit_v, check_v), (perf_v, iterate_v), (check_v, end_v), (iterate_v, t), (t, start_{x1}), (t, start_{x2})\} \setminus (perf_v, end_v)$.

Traverse each node that has a feedback relationship in the net.

Step 5: Delete the transition *perp* with only one input and output place, together with its input place and output place. Complete the workflow model.

Step 6: Add the corresponding fuzzy time parameters to each transition *perf*, that is $D_i = E_i$.

3.4 Establishment procedures of the resource management model based on the information constraint Petri net

Under constraints of time, design information, and resources, the resource management model for the building design process based on information constraint Petri net is developed based on the above definitions and transforming algorithm. The detailed steps are as follows.

Step 1: Decompose the tasks of the building design project into several design sub tasks. Establish the top layer ICN according to the design information constraint relationship of each design sub task.
Step 2: Establish ICN_1, ICN_2, …, ICN_n, , for all the design sub tasks.
Step 3: Connect all the ICN_i ($i \in n$) according to the corresponding constraint relationships to constitute a general ICN for the building design process.
Step 4: Transform the ICN_i ($i \in n$) to design sub task process models W_1, W_2, …W_n, based on the FTCWF-net according to the transformation algorithm from ICN to FTCWF-net.
Step 5: Connect all the W_i ($i \in n$) models according to the corresponding constraint relationships in the general ICN. Add two transitions T_{in} and T_{end} for concurrent design activities as input control transition of P_i and output control transition of P_0. P_i in the W_i ($i \in n$) model is set to the input place of T_{in}, and P_0 is set to the output place of T_{end}.
Step 6: Set the initial value of P_i in all W_i workflow net models to zero. Set the initial value of P_i in the general workflow net to 1.The initial markings in other positions are unchanged.
Step 7: Connect the simulation system clock model and resource allocation manager model through Res and transition t5 so that the system time can be timed to the total model by the resource token.
Step 8: Connect the input place and output place in the resource allocation manager sub model and system clock simulator model respectively to the design activity transitions via arcs.
Step 9: Define the fuzzy time function and initial parameters for simulation referring to the practical design activities. Validate the model structure and performance and prepare for simulation.

4. Case modeling and simulation optimization

4.1 Case study and data acquisition

This case study is of a high-rise residential project located in Jilin, China, constructed by China Overseas Holdings Limited. The project covers an area of 36,768.78m^2. The building area totals 188,792 m^2. Data was collected through interviews with project managers and designers from the design company. Data statistics from previous similar projects were also considered as part of the data source.

The building design process involves many uncertainties. Of these, the main ones concern the duration of designing specific tasks, the amount of resources required by sub design tasks, the probability of a design adjustment caused by changes in the design requirement, modifications of the design task itself, and the probability that corresponding design modifications are required due to related design information. Based on the actual data statistics and analysis from twenty-one similar projects designed by China Overseas Holdings Limited within two years, the distribution of the parameters is similar to the fuzzy triangular function. Therefore, this study applies the fuzzy triangular probability function to model the uncertainties in the structural design activities involved.

4.2 Model establishment and simulation

The resource management model for the detailed structural design of the building wqs developed based on an information constraint Petri net according to Section 2.1 and 3.4. The model was implemented and simulated utilizing CPNTools, a public domain program developed by Aarhus University. Fig. 3, 4, and 5 show the key structures of the model. Screenshots illustrate the simulation process.

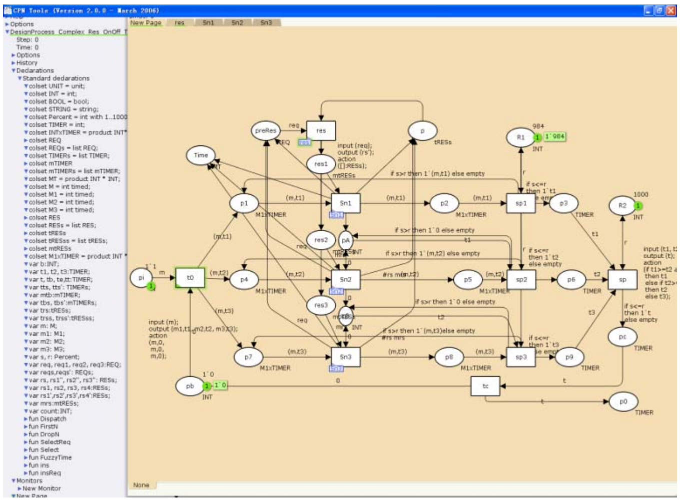

Fig. 3. Resource model for the detailed structural design based on the information constraint Petri net (Top layer)

The top layer of the resource allocation model is illustrated in Fig. 3. The transitions *Sn1*, *Sn2* and *Sn3* with rectangle tags at the bottom left corner are substitute transitions respectively representing the structural calculation design task subnet, foundation and frame structure design task subnet and external wall and roof structure design task subnet. The transition *res*, with a rectangle tag at the bottom left corner, is also a substitute transition, and corresponds with the resource allocation subnet in Fig.4.

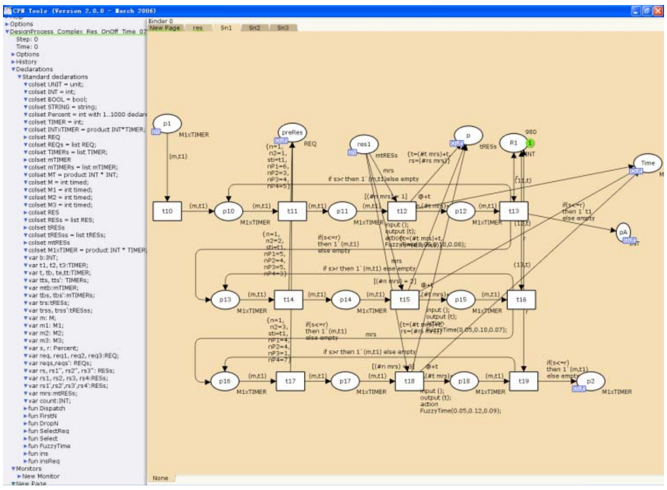

Fig. 4. Resource model subnet layer

The subnet layer of the resource model is illustrated in Fig. 4. This corresponds with the structural calculation design task subnet showing the structural design process. The place *p1* in the model is the design task input place in the subnet. The place *p2* is the output place. They are joined with the top layer of the model. The place *preRes* is an activity resource request; the place *res1* denotes the resource allocation; the place *p* denotes the resource return; and the place *Time* represents time. Each of these is connected with the resource layer.

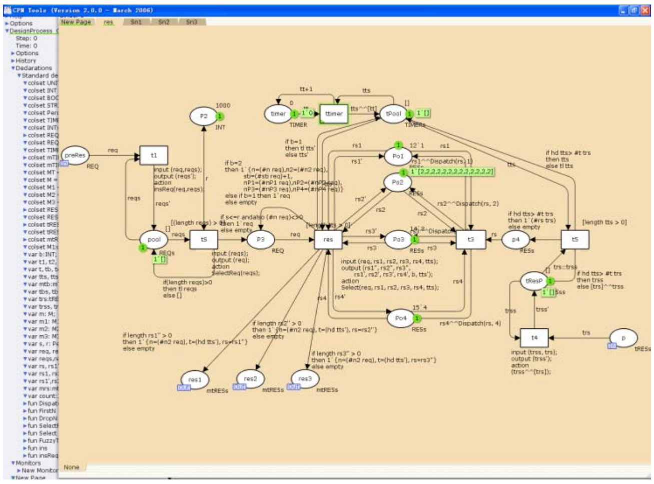

Fig. 5. Resource layer of the resource model

Fig.5 shows the subnet in the resource management layer. This is the core of the resource management model, which controls resource allocation, monitors changes in activity time, and simulates resource utilization and competition. All resource allocations are managed by the subnet. In the subnet, the place *preRes* represents resource requests and the places *Po1*, *Po2*, *Po3*, and *Po4* represent four resource pools of four kinds of resources. The places *res1*, *res2*, and *res3* represent output resource pools allocated to design activities 1, 2 and 3, respectively. The place *p* denotes resource return orders after the completion of design activities. The transition *t1* denotes the check for resource requests from the activities (Input: requirement requests of activity resourc; Output: requirement requests of activity resourc after being checked). The transition *res* indicates that the resource is allocated to the corresponding resource request output pool according to the resource requests of design activities (Input: requirement requests of activity resources after being checked; Output: the allocated resources according to the resource requests). The transition *t3* indicates that the resource is released by the design activities and returned to the corresponding resource pool (Input: resources returned; Output: resources after being classified).

Tables 1, 2, 3 and 4 introduce the captions of the places and transitions of the proposed model for the structural design process respectively. Table 1 indicates the legend of the places in ~~of~~ the model presented in the top layer. Table 2 indicates the legend of the transitions in the top layer. Table 3 indicates the legend of the places in ~~of~~ the model presented in the subnet layer. Table 4 indicates the legend of the transitions in the subnet layer.

Table 1

Legend of the places of the model presented in the top layer

Places	Meanings
pi	structural design tasks
p1	design tasks of structural calculation
p2	preliminary design results of structural calculations
res1	resource pool 1
preRes	request requirements of design resources
Time	system time
p	return requirements of design resources
p3	structural calculation results after being checked
res2	resource pool 2
res3	resource pool 3
p4	design tasks of foundations and frame structures

p5	preliminary design results of foundations and frame structures
p6	design results of foundations and frame structures after being checked
p7	design tasks of external wall and roof structures
P8	preliminary design results of external wall and roof structures
P9	design results of external wall and roof structures after being checked
pc	preliminary design results of building product structure
po	final design results of building product structure

Table 2

Legend of the transitions of the model presented in the top layer

Transitions	Meanings
t0	task allocation of structural design
Sn1	structural calculation of design subnet
Sn2	design subnet of foundation and frame structures
Sn3	design subnet of external wall and roof structures
res	resource allocation
sp1	check for structural calculations
sp2	check for foundation and frame structures design
sp3	check for external wall and roof structures design
sp	combination of various design results

Table 3

Legend of the places of the model presented in the subnet layer

Places	Meanings
p1	structural calculations design tasks
p	return requirements of design resources
preRes	request requirements of design resources
res1	resource pool 1
p11	preliminary-phase design tasks of structural calculations
p12	structural calculations results in preliminary-phase
p14	middle-phase design tasks of structural calculations
p15	structural calculations results in middle-phase
p17	post-phase design tasks of structural calculations
p18	structural calculations results in post-phase
Time	system time
p2	design results of structural calculations

Table 4

Legend of the transitions of the model presented in the subnet layer

Transitions	Meanings
t10	design task allocation of structural calculations
t11	resource apply in structural calculations pre-design
t12	preliminary-phase design of structural calculations
t13	check of results in structural calculations pre-design
t14	resource apply in structural calculations intermediate design

t15	middle-phase design of structural calculations
t16	check of results in structural calculations intermediate design
t17	resource apply in structural calculations final design
t18	post-phase design of structural calculations
t19	check of results in structural calculations final design

4.3 Analysis of simulation results and resource management optimization

4.3.1 *Analysis of simulation results*

1 Model structure analysis

A standard state space report is generated through a system syntax structure test and structure analysis to the resource model by the state space tools of CPN Tools. The boundedness, liveness and impartiality of the model are shown ~~showed~~ in the report (the contents are omitted here for brevity), which establishes the correctness of the structure of the resource model.

2. Run-time analysis

10,000 simulations were conducted from the initial parameters in Table 5,. The simulation results show that the shortest completion time for design activities is 36.2 days, the longest completion time is 84.3 days, and average time of a given resource condition is 50.8 days. Table 6 provides the results when all the design duration simulation data are arranged from small to large, with the percentage corresponding to the right hand side denoting the average of the simulation data for that percentage. For example, the duration values are 43.03, 46.42, 48.31, 49.10, 50.24, 50.96, 51.95, 54.00 and 60.01 days respectively, with a corresponding cumulative probability of 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90%, respectively. The standard deviation is 4.52 days. As shown in Fig. 6, the accuracy rate and stability improves as the number of simulations increases.

Table 5

Resource list for the detailed structural design process

Resource category	Total number	The amount of resource needed by each design sub-activity								
		t11	t12	t13	t21	t22	t23	t31	t32	t33
R1	12	6	5	4	3	5	5	5	5	3
R2	13	3	4	4	5	6	3	4	7	3
R3	14	4	5	1	7	4	3	6	4	5
R4	15	5	3	7	2	4	4	3	5	5
Time（Day）		8	7	9	6	7	10	8	9	7

Table 6

Ccumulative probability data statistics for the detailed design process time

Number of tests	10%	20%	30%	40%	50%	60%	70%	80%	90%
1000	42.53	45.73	47.52	48.12	50.96	51.73	52.82	54.82	60.73
2000	42.65	46.52	47.56	48.49	49.37	51.46	52.35	54.79	60.68
3000	42.82	46.38	48.01	48.52	50.13	51.32	52.28	54.68	60.17
4000	43.13	46.49	47.92	48.87	50.01	51.29	52.22	54.37	60.65
5000	42.86	46.15	48.37	49.03	50.24	51.34	52.23	53.76	60.21
6000	43.09	46.49	48.46	49.18	50.47	51.35	52.24	53.81	59.87
7000	42.87	46.38	48.52	49.27	50.25	51.28	52.25	53.77	59.78

8000	43.18	46.54	48.65	49.44	50.12	51.27	52.27	53.51	59.63
9000	43.28	46.41	48.87	49.53	50.27	51.25	52.26	53.33	59.33
10000	43.85	46.92	49.12	49.72	50.16	51.26	52.27	53.15	59.07

Note: **% denotes the data average of 1% that locates in the i^{th}% after the experiment data is arranged from small to large order.

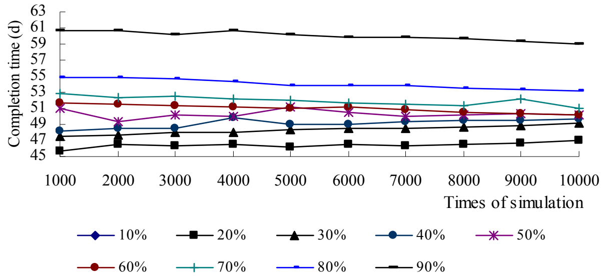

Fig. 6. Accumulative probability data analysis for building detailed design process time

3. Analysis of resource utilization

Under the simulated conditions, the resource utilization efficiencies for R1 are 54.72%, R2 is 47.53%, R3 is 42.41% and R4 is 40.80% respectively.

4.3.2 Resource management optimization

Based on the above simulation results, the corresponding resource demand varies with the time constraint conditions. Thus, the design process completion time and resource utilization efficiency can be affected by changing the resource allocation ratio to obtain the optimal resource allocation in specific situations - the goal of resource management optimization in this case is the most economical resource allocation when the average design duration is within 60 days.

The dynamic programming algorithm [33] is adopted to statistically analyze the simulation results of system time when each type of resource changes independently. The relationship curve for the resource number and system time is shown in Fig. 7. This indicates that the resource allocation alternatives can be obtained if the design duration is within 60 days. When all the alternatives are simulated, the best one is that which satisfies the time conditions in addition to using minimum resources. After 10,000 iterations, it was found that when the resource allocation for R1 is 10, R2, R3 and R4 ares 11, 10, and 11 respectively, the average task completion time is 59.2 days and the resource utilization ratio for R1, R2, R3 and R4 is 51.44%, 52.79%, 46.14%, and 52.35% respectively. This program is therefore optimal, as it has the least amount of resource consumption of all the alternatives.

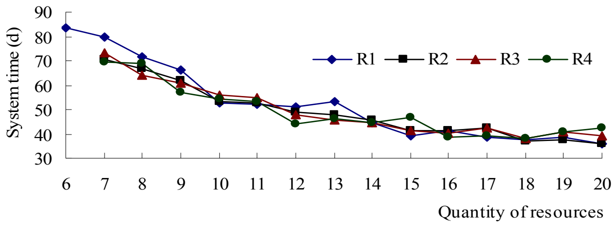

Fig. 7. Relationship curve for resource amount and system time

4.4 Model validation

The actual labor allocation in this case for R1 to R4 is 10, 11, 10 and 11 respectively, with a design completion time of 67 days. Using the proposed model and same resource allocation to analyze, the average task completion time is 65.3

days (10,000 simulations). The simulation deviation is 2.54%, which is more accurate than the completion time predicted by the project manager. Through interviews with the designers and project managers, the operation process of the model simulation and settings of parameters was verified. Three factors result in the model's deviations:

1. In the management of the design process, designer allocation and scheduling are conducted based on the experiences of project managers and lack systematic and quantitative methods. This results in unstable project management quality, as well as a large deviation range of estimates of the design task completion time.

2. The work efficiency of the designers in the model is the average value based on previous statistics. The separate efficiency value for each designer is not analyzed. However, one designer in this case has worked less than three years, which resulted in a simulation time that is less than the actual completion time.

3. The design process was interrupted twice due to waiting for the owner's modification requirements. Restarting the work generally results in the reduction of efficiency, which is one of the reasons that the simulation design duration is less than the actual duration.

5. Conclusion

This paper presented an information constraint Petri net for resource management modeling and simulation of the building design process. This approach can satisfy the practical demands of design management for dynamic discrete systems, and also can realize the objectives of minimizing the overall development cycle time of construction projects and the rational allocation of resources. Taking a the detailed structural design of a building as an example, a resource management model was established. The CPN Tools platform was used for simulation. Through the analysis of the model structure, run-time, resource utilization efficiency and the relationship between the quantity of resources and system time, the expected completion time and resource allocation solutions under an arbitrary pre-supposed duration can be found. In validating the model, the key factors influencing the deviation between the model and the actual situation were identified.

This approach can be used to select and evaluate the program plans for different design projects. The optimal plan with the highest efficiency and shortest duration can be selected under conditions of resource constraints. Further research being pursued by the authors includes the joint use of the proposed model with optimization algorithms in order to minimize the total duration of the product design process. In addition, extensions of the modeling to other stages in the design process and construction stage are anticipated in the future.

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