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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 constraint 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 net 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.

1. Introduction

Building design is a 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 advantage 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] has 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)

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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 the information constraint net, for the Petri net 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.

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.

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 tasks *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 tasks *c* and *d*. The *preceding item* relation is represented by a dashed line and a solid dot. The information concerning any tasks *e*, *f* and *g* can influence task *b*. The *OrFeedback* relation can be expressed by several dashes and a "X" mark hollow dot. Tasks *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 $R = (And\text{-}join, Or\text{-}join, Not\text{-}join, pre, AndFb, OrFb)$. 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.

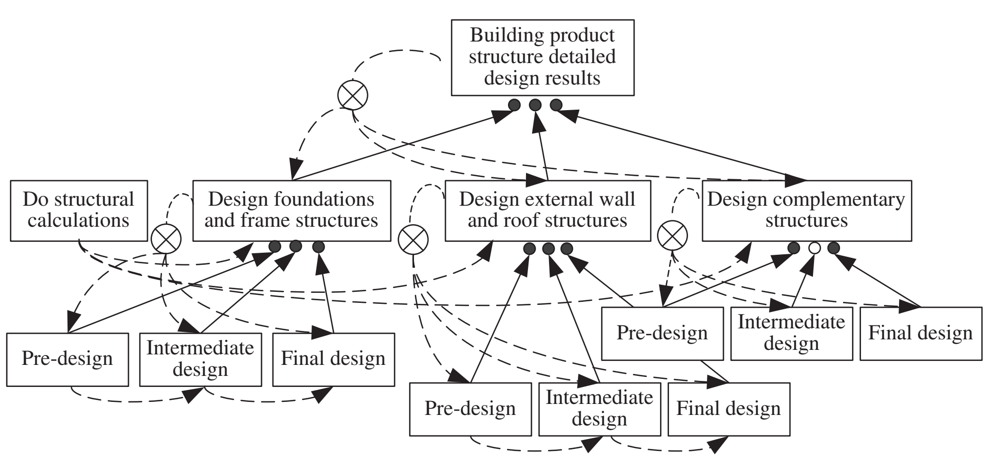

Fig. 1. Workflow and information constraint relations in detailed structural design.