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Extension and extension state space reduction based on finite automata Petri nets

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Abstract. To improve rationality in renovation of ancient buildings and construction cost of extension engineering, one renovation and extension method of ancient building based on Petri Net BIM technology of finite automation is proposed. First of all, the model is built for construction engineering cost management based on BIM technology and it includes five stages such as design, decision making, construction, tendering and bidding as well as completion; secondly, the model method of Petri Net is used to simplify and optimize constraints and the method of finite automation (Finite automaton, DFA) is used to realize dimensionality reduction for binary input of state space in renovation and extension of ancient buildings and reduce complexity of the model; in the end, simulation experiment is carried out to verify validity of the algorithm.

Key words. Finite automation, Petri Net, BIM technology, Ancient building, Renovation.

1. Introduction

Ancient building is important construction engineering which is left over from specific historical period and it is the wisdom crystallization of Chinese nation for five thousand years which has relatively higher historical value, cultural value and irreproducibility. Meanwhile, it is also the inheritance of traditional culture in our country. Therefore, it is essential to enhance renovation of ancient building.

In construction of renovation engineering for ancient building, we need to stick to the following principles: (1) the principle of not changing original state of ancient building. The cultural relics have characteristics of unsubstitutability and irreproducibility. Therefore, construction of renovation engineering for ancient building, we need to pay special attention to protection of cultural relics so as to keep ancient building in original state. Due to uniqueness, the ancient building has relatively higher historical value and cultural value. Once its original state is changed in

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construction of renovation engineering for ancient building, its historical value and cultural value will be lost. Therefore, in construction of renovation engineering for ancient building, it is necessary to ensure structural features and appearance features of ancient building are not changed. In construction of renovation engineering for ancient building, it is required to prepare the optimal renovation scheme based on original structure of ancient building so as to avoid construction and structures not conforming to ancient building. Meanwhile, it is required to avoid arbitrarily adding and reducing structure and appearance of cultural relics, avoid adopting renovation technology not conforming to design and construction of ancient building and try to conserve all original objects in ancient building in order to keep original state of ancient building to the greatest extent. (2) The principle of sticking to practicability of renovation plan for ancient building. Most of ancient buildings in our country are important construction engineering which is left over in specific historical period. After several years of historical challenges, it shows its imperishable construction technology and has important historical value and cultural value. Therefore, construction of renovation engineering for ancient building is one kind of engineering construction with large scale, significant meaning and higher construction difficulty. Moreover, there is less repeated construction for similar ancient buildings at present and it is difficult to provide effective construction reference for construction of renovation engineering for ancient building. As a result, construction personnel for renovation of ancient building can only summarize all kinds of renovation steps and methods according to practical work experience. In recent years, due to industrious work of countless workers in renovation engineering of ancient building, we have summarized experience in renovation engineering of ancient building, which is operable and practical and can provide valuable reference for construction of renovation engineering in ancient building. Practical renovation plan of ancient building can help construction personnel for renovation engineering of ancient building to know design concept of ancient building and significance in protecting and recovering ancient building. Moreover, it can help construction personnel for renovation engineering of ancient building to carry out research on overall structure of ancient building and guide and normalize construction technology in renovation engineering of ancient building at the same time, which can guarantee smooth implementation of all work in construction of renovation engineering of ancient building, meet renovation requirements of ancient building to the greatest extent and realize renovation of ancient building.

One renovation and extension method of ancient building based on Petri Net BIM technology of finite automation is proposed in the Thesis so as to build the model for construction engineering cost management based on BIM technology, use methods of Petri Net model to simplify and optimize constraints and thus realize dimensionality reduction for binary input of state space in renovation and extension of ancient buildings.

2. Definition of detailed construction cost

2.1. Definition description

Meticulous management on construction cost for renovation and extension of ancient building is namely meticulous management in all stages during renovation and extension of ancient building so as to realize strengthened management on construction cost for renovation and extension of ancient building in stages. In all stages of project implementation, optimal configuration is carried out for resources to effectively avoid the phenomenon of "three excesses". The management on construction cost for renovation and extension of ancient building mainly involves: five stages such as design, decision making, construction, tendering and bidding as well as completion and the construction cost management and relevant entities involved in these five stages are shown in Fig. 1.

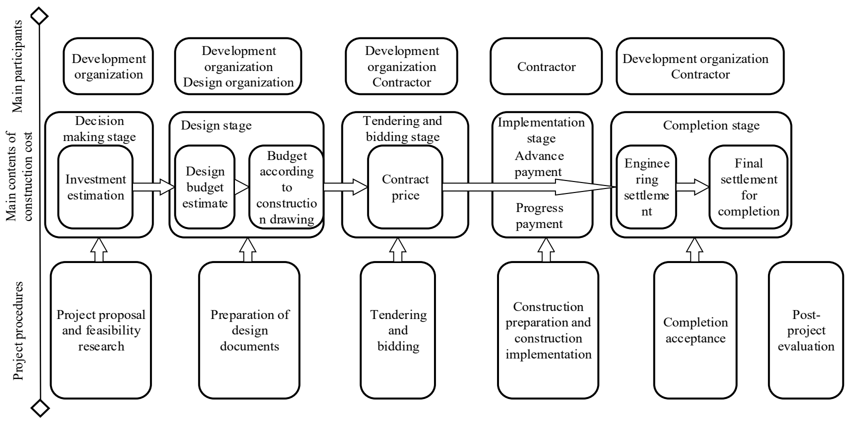

Fig. 1. Management of construction cost for green building

Management of construction cost for detailed engineering in renovation and extension of ancient building is the premise to determine and control reasonable construction cost. To realize reasonable assessment of investment, it is necessary to ensure it is within range of limit control of total construction cost first of all. Especially, in construction cost assessment stage during design, it is required to ensure assessed value of construction cost is much more reasonable than assessed value of construction cost during investment stage. Moreover, the assessed value of construction cost will be influenced by assessed value of construction cost during investment stage. As for management of construction cost for green building, the key to construction cost assessment is to deal with construction cost in tendering and bidding between development organization and contractors. As for management of progress and advance payment in construction project during renovation and extension of ancient building, it is required to refer to practical situation of construction and two key steps in preliminary design of scheme. As for management of settlement for green building projects, it is required not only to summarize construction cost of practical projects but also control construction cost in all engineering stages.

2.2. *Establishment of BIM model and quantification of assessment results*

In the Thesis, renovation and extension project of ancient building is the object engineering and Revit software is used for modeling and then renovation and extension of ancient building in object engineering deemed as research object for environment representation and analysis in the full life circle. After assessment range is determined, it is necessary to define the relationship between BIM element and materials and the type of ancient building is shown in the following table.

Table 1. Correspondence between BIM Elements and Tally

No.	Name of material	Name of model family	Volume
1	FA_ concrete-fine aggregate concrete	100+150	74.168
2	FA_ concrete-rebar	100+150	18.532
3	FA_ concrete-fine aggregate concrete	100+200	19.918
4	FA_ concrete-rebar	100+200	5.974
5	FA_ concrete-rebar	150	0.218
6	FA_ concrete-rebar	FW-150	118.156
7	FA_ concrete-rebar	JT-150	15.142
8	FA_ concrete-rebar	SH-150	290.128

In renovation and extension project of ancient building, after material information of rebar and concrete for ancient building is determined, it is possible to calculate characterization calculation results of various environmental influences on ancient building, which is expressed in functional unit.

(1) Production stage. The output of construction projects in production stage mainly refers to emission of substance and energy which have influences on natural environment and it includes pollution of environment caused by waste water, flue gas and rubbish etc. Influences of environment on life circle of ancient mainly come from production process of ancient building (fine aggregate concrete and rebar). In process of production, the sequence of various environment influences is: GWP>AP>NRE>PED>SFP>EP>ODP>RE. Influences on consumption of nonrenewable resources in production stage of ancient building and demands of primary energy respectively account for more than 80% of the proportion of influences of consumption of nonrenewable resources on life circle of ancient building. Therefore, in selection of life circle, raw materials such as fine aggregate concrete and rebar which have small influences on environment are of great significance to improvement environmental load of ancient building and even all buildings. Production stage of ancient building is the important stage which will cause greenhouse effect and its potential influences on global warming accounts for more than 50% of potential influences on global warming in life circle of ancient building and all greenhouse gases discharged from this is 7929t equivalent value of carbon dioxide. It should be noted that this is the carbon dioxide gas produced by materials used to construct 1323m2 ancient building.

(2) Operation and maintenance stage. In operation and maintenance stage of construction project, it is necessary to enhance recycling and cyclic utilization of rubbish, waste water, flue gas and so on produced in this project. The greenhouse effect produced in maintenance stage reaches 30% of the full life circle and the equivalent value of carbon dioxide discharged from this is about 3650t. The main reason is that plenty of electric energy is consumed in this stage and produced 1kWh electric energy will release lkg carbon dioxide gas which does not include other gases which may cause greenhouse effect. The ozone depletion potential accounts for the largest proportion in environmental influences and the proportion are up to 50%. In this stage, the large proportion of ozone depletion potential in environmental influences is mainly due to increase in NOx, HzO, NzO, CFC and other gaseous substances caused by human activities.

(3) Recycling stage. At the end of life circle of ancient building, the ozone depletion potential and demands of renewable energy are positive value and the rest environmental influences are negative value and the main reason of negative value is that scrap materials of ancient buildings are recycled and used in manufacturing of new building materials, which is named benefits of steel scrap recycling. Therefore, in consideration of environment benefits, recycling and cyclic utilization of scrap materials is of great significance to improve environmental influences and reduce greenhouse effects.

3. Solution of Petri Net based on finite automation

3.1. Conflict between time sequence for renovation and extension of ancient building and Petri Net

Petri Net is one kind of directed weighting bipartite graph [13] consisting of two kinds of nodes and it includes place (Place), transition (Transition), connection (Connection) and token (Token), which are shown in Fig. 2.

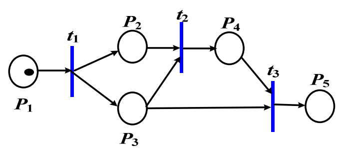

Fig. 2. Model of Petri Net

In above-mentioned model of time sequence, $P = \{p_1, \cdots, p_5\}$ is the place, $t = \{t_1, t_2, t_3\}$ is transition and the dark spot in the figure is token, which are respectively corresponding to region in question, gate and vehicle. Especially, it is thought that the weight of each linking arc belongs to { 0, 1 } and there are no several edges. In this case, the relationship between place and transition can be expressed in event matrix and one nonnegative integer (weight) is distributed for each input (from transition to place) and output arc (from place to transition). Then, incoming matrix of input arc and output arc of each vehicle can be expressed as: $\hat{B}^{+} \in \{0,1\}^{n\times m}$

and $\hat{B}^{-} \in \{0,1\}^{n\times m}$ and it conforms to:

$$\hat{B} = \hat{B}^{+} - \hat{B}^{-}\,. \tag{1}$$

The undirected model of Petri Net for renovation and extension of ancient building can be built based on state-space model expressed in Equation (4). The transition rule of Petri Net can be defined according to the last constraint expressed in Equation (9) and the G_2 can be defined as:

$$G_2 = diag\left(\hat{B}^{-}, \cdots, \hat{B}^{-}\right) \in \boldsymbol{R}^{mS\times mS}\,. \tag{2}$$

It focuses on inclusion relation between constraints so as to reduce number of constraints, and then we can know the following lemma:

Theorem (1): in view that $\hat{x}^{v_s} \in \mathcal{M}$, $\mathcal{M} = \left\{\eta \in \{0,1\}^n \,\middle|\, \mathbf{1}^T \cdot \eta = 1\right\}$, $s = 1, \cdots, S$, $x^{\sum v_s}(0) \in \{0,1\}^n$ and Equation (2) and two equations in Constraint (1) are met, then Equation (7) and the third equation in Constraint (10) are reasonable.

Prove: as for $s = 1, \cdots, S$, $0 \le k \le M-1$, in case the following equation is reasonable:

$$\hat{x}^{v_s}(k+1) = \hat{A}\hat{x}^{v_s}(k) + (\hat{B}^{+} - \hat{B}^{-})\hat{u}^{v_s}(k)\,. \tag{3}$$

Besides, according to two equations in Equation (1), we can know that:

$$0 \le \hat{x}^{v_s}(k) - \hat{B}^{-}\hat{u}^{v_s}(k) \le \hat{A}\hat{x}^{v_s}(k) + (\hat{B}^{+} - \hat{B}^{-})\hat{u}^{v_s}(k)\,. \tag{4}$$

As for $s = 1, \cdots, S$, $0 \le k \le M-1$ and according to Equation (4) and (1), we can know that:

$$\begin{aligned} \mathbf{0} &\le A\hat{x}^{v_s}(k) + (\hat{B}^{+} - \hat{B}^{-})\hat{u}^{v_s}(k) \\ &= \hat{A}_a\hat{x}^{v}(k) + \hat{B}_a\hat{u}^{v}(k) = \hat{x}^{v_s}(k+1) \le \mathbf{1}\,. \end{aligned} \tag{5}$$

According to Equation (3 to 5), we can know that:

$$\begin{aligned} 0 \le \hat{x}^{v_s}(k) - \hat{B}^{-}\hat{u}^{v_s}(k) &\le \hat{A}\hat{x}^{v_s}(k) + (\hat{B}^{+} - \hat{B}^{-})\hat{u}^{v_s}(k) \\ &\le \sum_{s=1}^{S}\{\hat{A}\hat{x}^{v_s}(k) + \hat{B}^{v_s}\hat{u}(k)\}\,. \end{aligned} \tag{6}$$

As for $s = 1, \cdots, S$, $0 \le k \le M-1$ and according to Equation (6), we can know that $0 \le \sum_{s=1}^{S}\left\{\hat{A}\hat{x}^{v_s}(k) + \hat{B}^{v_s}\hat{u}^{v_s}(k)\right\}$ and thus know that:

$$\sum_{s=1}^{S}\hat{u}_{c1}^{v_s}(k) + \hat{u}_{c2}^{v_s}(k) \le 1, \sum_{s=1}^{S}u_{d1}^{v_s}(k) + u_{d2}^{v_s}(k) \le 1\,. \tag{7}$$

As for $0 \le k \le M-1$, $\hat{u}_{c1}^{v_s}$ and $\hat{u}_{c2}^{v_s}$ are gates to intersection area and $u_{d1}^{v_s}$ and $u_{d2}^{v_s}$ are gates to diverging area. If we want to define output gates to intersection area such as $\hat{x}_C^{v_s}$ and $\hat{u}_C^{v_s}$, we can know from Equation (4) that:

$$\hat{x}_C^{v_s}(k+1) = \hat{x}_C^{v_s}(k) + \hat{u}_{c1}^{v_s}(k) + \hat{u}_{c2}^{v_s}(k) - \hat{u}_C^{v_s}(k)\,. \tag{8}$$

As for $0 \le k \le M-1$, we can know from Equation (8) and the third equation in Equation (7) that:

$$\sum_{s=1}^{S} x_C^{v_s}(k+1) \Leftrightarrow \sum_{s=1}^{S} \{x_C^{v_s}(k) + \hat{u}_{c1}^{v_s}(k) + \hat{u}_{c2}^{v_s}(k) - \hat{u}_C^{v_s}(k)\} \le 1\,. \tag{9}$$

Then according to Equation (4) and Equation (1), we can know that:

$$\sum_{s=1}^{S} \{\hat{u}_{d1}^{v_s}(k) + \hat{u}_{d2}^{v_s}(k)\} \le \sum_{s=1}^{S} x_d^{v_s}(k)\,. \tag{10}$$

For this purpose, we can know that Lemma 1 is reasonable. The initial condition of Lemma 1 is $\hat{x}^{v_s}(0)$ and $x^{\sum v_s}(0)$ because two equations in Equation (1) shall be determined in the beginning.

3.2. Method of finite automation

Nodes in finite automation show a discrete-time model of the system dynamics active in discrete time.

Hypothesis 1: a connected digraph is given by finite automation where both ends of each arc are connected to some nodes and there is at least a input arc and at least a output arch in each node. If the Hypothesis is satisfied, then $\mathcal{A}$ should be used for marking.

According to the relation of the input arc and output arc of finite automation as is shown in Fig. 4, the implicit scheme form [14] of the system can be given:

$$E\xi(k+1) = F\xi(k), \xi(k) \in \{0,1\}^{n'+m'}, \xi(0) \in \Xi_0(\delta_0)\,. \tag{11}$$

Where, $\Xi_0(\delta_0) = (\eta \in \{0,1\}^{n'+m'} | 1^T\} \cdot \eta = 1$, $E, F \in \{0,1\}^{n' \times (n'+m')}$, $\mathrm{E}\eta = \delta_0 \in \mathcal{M}_D$, $\mathcal{M}_D = \{\eta \in (0,1\}^{\mathrm{n'}} | 1^{\mathrm{T}} \cdot \eta = 1\}$, then the following theorem can be obtained:

Theorem 2: Given the $\delta_0 \in \mathcal{M}_D$, the implicit system (11) should be considered. It satisfies Hypothesis $\mathcal{A}$. Permutation matrix $P \in (0,1)^{(n'+m') \times (n'+m')}$ satisfies $EP = \left[I_{n'} \tilde{E}\right]$, where $\tilde{E} \in \{0,1\}^{n' \times m'}$. Then, in the transformation of coordinates:

$$\begin{bmatrix} \hat{x}_D \\ \hat{u}_D \end{bmatrix} := \begin{bmatrix} I_{n'} & \tilde{E} \\ O_{m' \times n'} & I_{m'} \end{bmatrix} P^{-1}\xi\,. \tag{12}$$

Implicit system (12) is equivalent to the following state equation:

$$\begin{cases} \hat{x}_D(k+1) = \hat{A}_D\hat{x}_D(k) + \hat{B}_D\hat{u}_D(k)\,, \\ \hat{C}_D\hat{x}_D(k) + \hat{D}_D\hat{u}_D(k) \leq \hat{G}_D\,, \\ \hat{x}_D(k) \in R^{n'}, \hat{u}_D(k) \in \{0,1\}^{m'}\,, \\ \hat{x}_D(0) = \Gamma_D\delta_0, \hat{u}_D(0) \in \{0,1\,.\}^{m'} \end{cases} \tag{13}$$

Where, $\hat{A}_D := \tilde{F}_a$, $\hat{B}_D := -\tilde{F}_a\tilde{E} + \tilde{F}_b$, $\hat{C}_D := -I_{m'}$, $\hat{D}_D := -\tilde{E}$, $\hat{G}_D := \mathbf{0}_{n'}$, $\Gamma_D := \mathbf{I}_{m'}$, $[\tilde{F}_a\tilde{F}_b] := FP$.

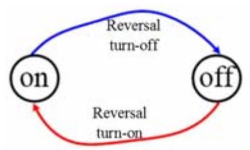

Fig. 3. finite automation

Considering the problem of overlay based shortest path routing, the scheduling model of vehicle of Petri net can be shown as:

$$\begin{cases} \hat{v}^{v_s}(k+1) = \hat{A}\hat{x}^{v_s}(k) + B\hat{u}^{v_s}(k)\,, \\ \hat{C}\hat{x}^{v_s}(k) + D\hat{u}^{v_s}(k) \leq G\,, \\ \hat{x}^{v_s}(k) \in R^n, \hat{u}^{v_s}(k) \in \{0,1\}^m\,, \\ \hat{x}^{v_s}(0) = \hat{x}_0^{v_s}, \hat{u}^{v_s}(0) \in \{0,1\,.\}^m \end{cases} \tag{14}$$

Where, $\hat{A} := I_m$, $\hat{B} := -\hat{B}^- + \hat{B}^+$, $\hat{C} := -I_m$, $\hat{D} := \hat{B}^-$, $G := 0_n$, $\hat{B}^- \in \{0,1\}^{n\times m}$, $\hat{x}_0^{v_s} \in \mathcal{M}$, $\mathcal{M} = \{\eta \in \{0,1\}^n\}$. By considering the discrete dynamics pattern of the vehicle position, the realization of satisfying the route layout and system of Fig. 1 of Hypothesis 1 is corresponding to System Equation (13).

4. Experimental analyzes

4.1. Experimental setup

Engineering plan for the renovation and extension of an ancient building is chosen for the scheduling analysis:

(1) makespan: the overall completion time of construction schedule is the evaluation standard of experimental result;

(2) Number of resource groups ($|R|$): it indicates the available number of resource groups;

(3) Temporal redundancy (TRR); in the actual formulation of construction plan, certain temporal redundancy will be reserved according to the actual executive capacity of the scheduled task of resource group. And the parameter is quantified

by the temporary redundancy (TRR) designed in the experiment. TRR is a preset percentage according to the executive capability of actual task of resource group. It guarantees that the executive time of a task of each resource group is in the internal:

$$[(PFTime_{ti} - PSTime_{ti}) \times (1 - TRR_1), (PFTime_{ti} - PSTime_{ti}) \times (1 - TRR_2)] . \quad (15)$$

Where: TRR_2 indicates the lower limit of temporary redundancy and TRR_1 indicates the upper limit of temporary redundancy; $PSTime_{ti}$ and $PFTime_{ti}$ are respectively the start time and finish time of task node of the formulation of the scheduled plan of original construction. So any executive time of task t_i of any resource group is shown by Equation (16). Therefore, TRR internal determines the limits of acceptable change of the executive capability of any resource group in the heterogeneous resources system and then it can be used to show the degree of heterogeneity of the whole resource model. In addition, it also defines the degree of savable time of any task node under the condition that the number of resource group is sufficient and then the degree of the savable time of the whole construction plan is quantified:

$$EcCost_{rj}(t_i) = (PFTime_{ri} - PSTime_{ri}) \times (1 - rnd), \quad (16)$$

In the equation, $rnd \in [TRR_2, TRR_1]$.

Relevant parameters should be set according to the actual condition of the engineering plan for the renovation and extension of the ancient building formulated by manual work as are shown in Table 2 where the TRR interval is $[0, 5\%]$, the degree of heterogeneity of heterogeneous resources system is $0 \sim 5\%$ and the overall time used for the construction plan of renovation and extension of the ancient building is reduced to between $0 \sim 5\%$.

Table 2. Setting of parameters of simulation experiment

Parameter	Parameter value of the scheduled plan of the east side	Parameter value of the scheduled plan of the west side	(partial) Parameter value of the scheduled plan of the overall
Number of resource groups	3	4	5
TRR interval [0, 5%]	[0, 5%]	[0, 5%]	
Number of tasks	17	54	51

4.2. Simulation experiment and analyzes

The detailed experimental result is shown in Table 3 and Fig. 4. By analyzing the data of experimental result, we can find that the optimization of the scheduled plan (which is the construction period formulated by manual work, the engineering project of the renovation and extension of the ancient building is fully completed) of the original construction is achieved by effectively using resource group by MCEFT optimization algorithm, where the scheduled plan of the east side is reduced by 45 days, accounting for 4.25 % of that of the original plan; the scheduled plan of the west side is reduced by 69 days, accounting for 4.47% of that of the original plan; the construction time of the overall scheduled plan (partial) is reduced by 69 days, accounting for 3.81% of that of the original plan. The total reduction of construction time is 173 days, accounting for 4.13% (the optimization range is preset not to exceed 5%) of that of the original plan. The total cost of the engineering is about RMB 862992.6 thousand yuan, which also means that compared with that of the original plan, the overall cost can be saved averagely 3541.6 thousand yuan.

Table 3. Experimental result of optimization simulation (unit: 10 days)

Scheduled plan of construction	Completion time of original plan	Completion time after optimized by MCEFT	Reduced construction time by MCEFT	Percentage % of reduced time
Scheduling plan of the est side construction	106	101.5	4.5	4.25
Scheduling plan of the west side construction	132	126.1	5.9	4.47
Scheduling plan (partial) of the overall construction	181	174.1	6.9	3.81

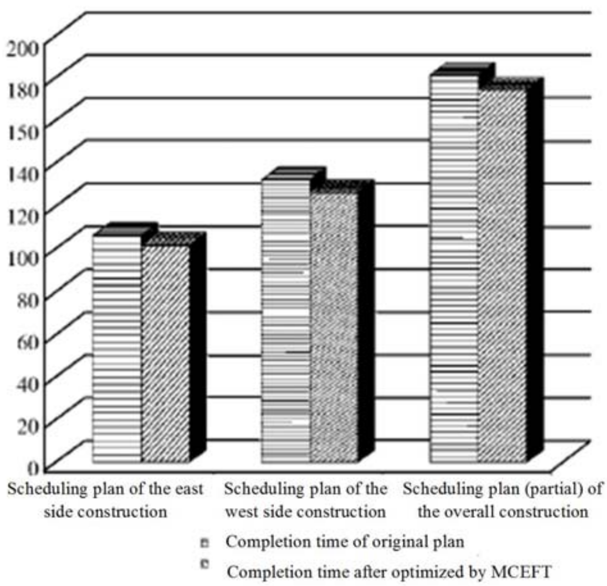

Fig. 4. Experimental result histogram of optimization simulation

At the same time, in order to verify the influence of parallel algorithm on the execution time of algorithm, we here make a contrast of the computation time of the algorithm that is added with parallel algorithm and not added with parallel algorithm to verify the advantage of proposed algorithm in computational efficiency. The experimental result is shown in Table 4.

Table 4. Contrast of computational efficiency

Index	Added with parallel computation	Not added with parallel computation
Computation time	5.63s	25.97s

From the data of Table 4, we can know that the used time is just 5.63s after added with parallel computation in the computational efficiency index while the computation time of algorithm not added with parallel computation is 25.97s. The computational efficiency after added with parallel computation is increased by 80%, showing the efficiency advantage of parallel computation.

5. Conclusions

The method of the renovation and extension of an ancient building based on Petri net BIM technology of finite automation is proposed in the Thesis. The model of construction cost management is constructed based on BIM technology and the constraint of optimization is simplified by using Petri net model method. The dimensional reduction of the binary input of the state space of the renovation and extension of the ancient building is achieved by using finite automation (DFA) and the complexity of the model is reduced. The experimental result indicates that the method can effectively improve the reasonability of the renovation and extension cost of the ancient building.

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