ICCEPM 2017
The 7th International Conference on Construction Engineering and Project Management
Oct. 27-30, 2017, Chengdu, China

Analysis on Tower Crane Selection in Precast Concretes Structures and its Connection with Precast Rate

Jingjing Guo [1], Yan Fu [1,2]*, Kang Wang [1], Zhenyu Peng[3]

[1] *School of Construction Management and Real Estate, Chongqing University, Chongqing 400045, China.*
[2] *Research Center of Construction industrialization and Innovation, Chongqing University, Chongqing 400045, China*
[3] *School of Civil Engineering, Chongqing University, Chongqing 400045, China.*

Corresponding author: Yan Fu
E-mail address:fuyan1981@foxmail.com.

Abstract: With the acceleration of construction industrialization, the buildings that China has adopted the construction of industrialization technology are increasing day by day, and Precast Concrete (PC) Structure technology is one of the main technologies of construction industrialization. Compared with the traditional cast-in-place concrete structure, PC structure is more conducive to shorten the construction period, reduce the number of construction workers and the site construction waste. Nevertheless, PC structure improves the requirements of hoisting machinery in the construction site, and the lay-out and selection of hoisting machinery become an important factor influencing the construction cost. The paper regards the typical tower crane in China as the research object, and establishes the time optimization model for the lifting scheme. The influence of the different precast rate on the selection of the tower crane is analyzed. This paper obtains the time variation of the tower crane under different precast rate, provides a theoretical basis for the design of precast concrete structures under the influence of assembly construction, and lays the foundation for the selection of tower crane under the precast rate.
Key words: Precast Concrete (PC), tower crane, selection, precast rate

1. INTRODUCTION

Precast construction process usually refers to the prefabrication production at a particular plant, and creates part of the component that can be used directly for the final assembly [1]. In Western and Eastern Europe, the prefabricated buildings in a large number of public buildings, new towns and other construction has made some development [2, 3]. In the United States, the current assembly of residential construction accounted for 7% of residential and the prefabrication level has reached 15% and 8% in Asia [3,4]. In most countries, prefabricated construction in the construction process, greatly improves the efficiency, production and saves labor. Meanwhile, it can also reduce the construction costs [4].

In high-rise construction, the use of construction machinery is often a major cost, and the tower crane is the most expensive type in the construction equipment [5, 6, 7]. With the development of the assembly of high-rise concrete construction, relative to the traditional concrete cast-in-place construction, tower crane utilization will be greatly improved. The operating efficiency of the crane not only controls the rhythm of the vertical construction, but also concerns the construction cost and safety. Therefore, the selection of tower crane type and location has become one of the focuses of the construction of high-rise building.

The optimization of the tower crane selection began in 1999. P. Zhang et al. proposed that the lifting radius of the tower crane depends on the lifting capacity of the tower crane, and then by restricting the "Feasible Area" of the tower crane in the case where the component position and the material stacking position are known, they could get the possible position of the tower crane [8]. Subsequent studies are entirely based on P. Zhang's research. In the visualization of the tower crane arrangement, J. Irizarry et al. further improved the method by using BIM and GIS, so that the tower crane can be optimized from the 3D perspective [9]. Other researchers have optimized the tower arrangement through different algorithms. C. M. Tang [10] and M.A. Abdelmegid [11] proposed to use genetic algorithm to determine transport time and cost of the tower crane point, supply point and demand point; M. A.Hussein et al. proposed the optimization algorithm that avoids the conflict of work in the automation and mechanized construction sites by addressing the spatial arrangement in the hoisting process [12]; C. Huang et al. used mixed-integer-linear programming (MILP) to reduce the operating costs of the tower crane and improve the tower crane operating efficiency [13]; L.C.Lien further proposed the particle bee algorithm to solve the tower crane location and stocking area optimization problem [14]; J.Wang used BIM technology and firefly algorithm to study the automatic arrangement of the tower crane [15].

In these studies, scholars mainly analyzed the hoisting scheme through the consideration of material stocking position, building shape and field distribution, hoisting time, tower crane number and coverage of the lifting, but did not consider the precast rate Z. Nadoushani and other researchers have studied different precast locations and found that different precast locations have a significant effect on the location and type of the tower [16]. However, at present, especially in China, the precast rate is still at a low level. The method that components are considered precast cannot be consistent with the actual situation. On the other hand, for different precast rates and precast schemes, the corresponding component weight is not the same, but the effect on tower efficiency is not known.

Therefore, based on the existing research, this paper studies the efficiency of the lifting scheme under the conditions of different precast rates and precast schemes of PC components in the concrete building. Moreover, this research discusses the influence of different precast rate on the hoisting scheme selection. By combining with the actual engineering case, and under different precast rate conditions, the parameters of the selected tower crane could be imported into the construction of the preferred algorithm, then calculate the corresponding hoisting time, and get the appropriate model of the best position. Thus could compare the lifting efficiency of the tower under different precast rates, and finally obtain the relationship between the lifting scheme and the precast rate.

2. OPTIMIZATION OF LIFTING SCEHME

Assumptions:

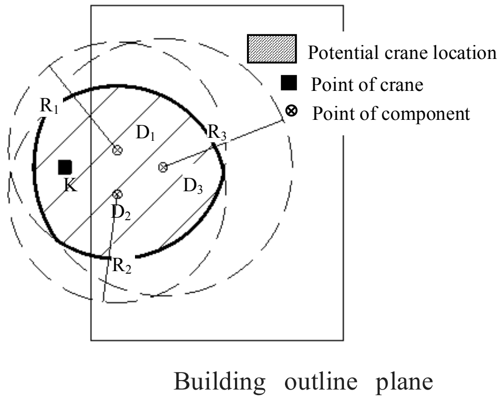
i. The relationship between the total time required for lifting the crane T_t and the lifting time of the PC component T_{tn} is $T_t \cdot \alpha = T_{tn}$($0 \le \alpha \le 1$);

ii. The venue layout does not consider other obstacles, such as terrain, roads, surrounding obstacles and so on;

iii. Field components have been stacked according the hoisting sequence.

2.1 Potential crane and supply location

As shown in Fig.1, D_1, D_2 are demand point of a certain type of parts (such as external walls), D_3 is demand point of another certain type of parts (such as columns); R_1, R_2, R_3 are respectively the limit distance $\rho_{D,max}^{K}$ that the same type of tower crane lift successfully the two same parts of the two most distant and most heaviest parts of this type. Assuming M_1=M_2>M_3, the longer the jib, the smaller the maximum weight that can be lifted. So $R_1 = R_2 < R_3$. If the tower crane is centered on the range of the limit circle, and it means that the tower crane can be successfully lifted the component. The overlapping parts of the different limit ranges are all possible positions K for the hoisting of the various parts. Similarly, for the material stacking position, there are $R_{k1(2)}^{s} < R_{k3}^{s}$, as shown in the shadow overlap in Fig.2.



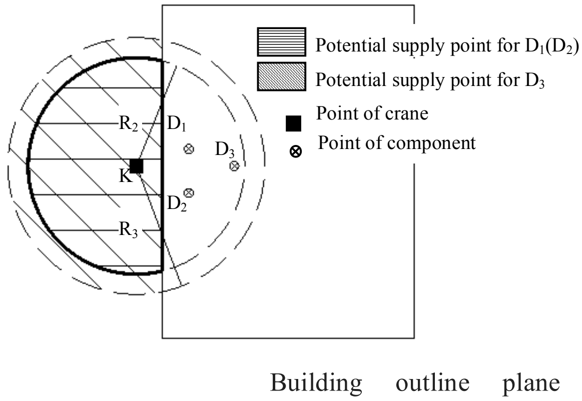
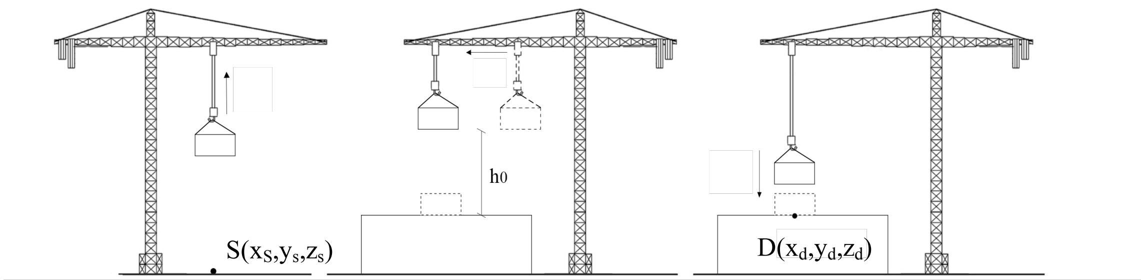


Fig.1. Possible crane location **Fig.2.** Possible supply location

2.2 Total time of lifting scheme



(a) (b) (c)

Fig. 3. Movement process of tower crane

Tower crane's lifting movement is shown in Fig.3. When the demand point is transporting, the movement of the tower crane can be divided into two parts: horizontal movement (Fig. (b)) and vertical movement (Fig. (a) and Fig. (c)).

2.2.1 Horizontal movement

When transported from the material stacking point $S(x_s, y_s, z_s)$to the demand point $D(x_d, y_d, z_d)$, the movement in the horizontal direction can be divided into the translation of the crab and the rotation of the jib (Fig. 3).

Eq. (1) - (3) calculate the horizontal distance from the supply point to the demand point:

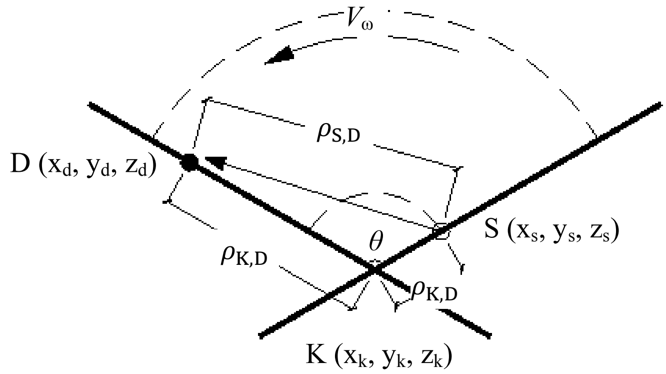


Fig.4. Horizontal operation process

$$\rho_{K,D} = \sqrt{(x_d - x_k)^2 + (y_d - y_k)^2} \tag{1}$$

$$\rho_{K,S} = \sqrt{(x_s - x_k)^2 + (y_s - y_k)^2} \tag{2}$$

$$\rho_{S,D} = \sqrt{(x_d - x_s)^2 + (y_d - y_s)^2} \tag{3}$$

In the process of horizontal movement, the calculation of the crab traversing time *Tr* is expressed by the Eq. (4). According to the cosine formula, the time expression of the time *Tω* required for the rotation of jib is expressed by Eq. (5), P. Zhang and other researchers calculated theT_ω [9], mistakenly calculated cosine formula into a negative number.

$$T_r = \frac{|\rho_{K,D} - \rho_{K,S}|}{v_r} \tag{4}$$

$$T_\omega = \frac{1}{v_\omega} \arccos\left(\frac{{\rho_{K,D}}^2 + {\rho_{K,S}}^2 - {\rho_{S,D}}^2}{2 \cdot \rho_{K,D} \cdot \rho_{K,S}}\right) \tag{5}$$

$$0 \leq \arccos(\theta) \leq \pi$$

Where T_ω= time for trolley movement; T_r= time for jib rotation; v_ω= slewing speed of jib (rad/min); and v_r= radial speed of trolley (m/min).

The total time required for horizontal movement can be calculated by combining (4) and (5), as shown in Eq. (6).

$$T_h = T_r + T_\omega \tag{6}$$

2.2.2 Vertical movement

As shown in Fig.3, vertical movement can be divided into two parts. The first part is a vertical lifting movement (as shown in Fig. (a)) and the other is a vertical descent movement (as shown in Fig. (c)). In regard to the lifting process, a certain safety height $h_0$shall be set at the top of the demand point to ensure that there is no collision with the building during the lifting process, as in Eq. (7). Thus, compared to previous studies, this paper increases the time T_{v2} used in the descending phase of vertical movement, as shown in Eq. (8).

$$T_{v_1} = \frac{|z_d - z_s| + h_0}{v_h} \tag{7}$$

$$T_{v_2} = \frac{h_0}{v_h} \tag{8}$$

Where v_h = hoisting speed of hook (m/min)

2.2.3 Total travel time of crane

The calculation of the total time $T_{i,j,l}^{o}(x_s, y_s)$ for a single component hoisting is shown in Eq. (9). Where μ_k represents the level of difficulty with which the operator operates the different towers at point K, ranging from 0.1 to 10.0, and different demand points and material stacking points have different values. δ is a parameter deciding the point $D(x_d, y_d, z_d)$ is precast or not, where 0 represents not precast, and 1 refers to precast.

$$T_{i,j.l}^{o}(x_s, y_s) = \delta \cdot \mu_k \cdot (T_{v_1} + T_h + T_{v_2}) \tag{9}$$

Where i refers to the order of lifting component, j refers to the floor of the demand point, l represents the floor of the demand point.

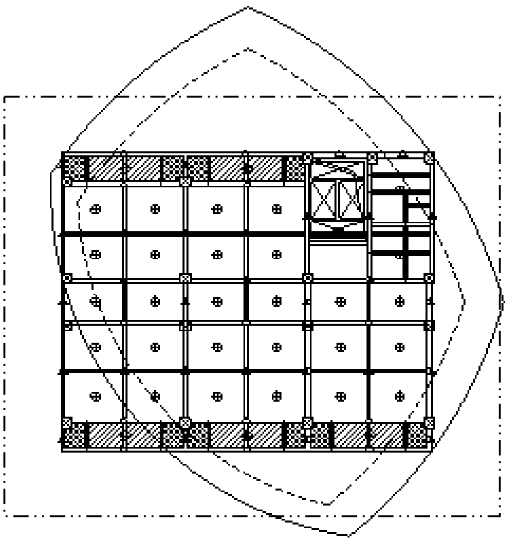
In this paper, Eq. (1) - (9) calculate the total travel time of a demand point. In addition, taking into account the entire hoisting process, due to the existence of unloading time T^u and waiting time T^w, the total time required for lifting scheme T_{t_n} is defined as T_{t_n}(10).

$$T_{t_n} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{l=1}^{L} T_{ijl}^{o} + T^u + T^w \tag{10}$$

Where I refers to the total number of the components belonging to the same type, J refers to the total number of the floor, L represents the total number of type of the component.

3. CASE STUDY

This case is the construction (Phase II) project of Chongqing Jianzhu College in China; the project uses the attached tower crane. Three different tower cranes are respectively QTZ63, QTZ80 and QTZ125, and the lifting capacity of the three kinds of tower cranes increased in turn. The paper is based on 14 different precast schemes, has the experiment in turn, calculates the time of the corresponding lifting scheme, and analyzes the relationship between the time and the precast rate.



Note: Since the QTZ125 has the highest lifting capacity, it can be deposited in every point on the attachment route. Where the numbers after "QTZ" refer to the max load moment (unit: kN·m) of that type of tower.

Fig.5. Layout of the building considered in the case study

Based on the "*Shanghai Municipal Commission of Housing and Urban-Rural Development on the Assembly of Precast Rate of Construction Unit and the Assembly Rate Calculation Rules (Trial)*", the concrete structure of the assembly structure of the monomer

$$\text{Single building precast rate} = \frac{\text{Concrete volume of precast parts}}{\text{Cast−in−place parts+Concrete volume of precast parts}} \times 100\%$$

In this case, the types of quasi-precast components are respectively stairs, columns, beams and floors, through the combination of components to determine the different precast schemes. Corresponding demand point of every precast component is (x_d, y_d, z_d). Because the tower crane is the attached tower crane, taking tower crane tower distance from the building d1 is 4m. According to the performance parameters of different tower cranes, deduce the relationship between the limit distance $\rho_{D,max}^{K}$ and the weight of each precast part m, and the relationship between the load-lifting speed and the weight of each precast part m. Putting the weight of corresponding parts into the curve can be obtained for the limit radius R and the rise speed vh of each corresponding part. In this case, the position of the part supply point is assumed to be the position where the transport vehicle is docked, and the position of the tower crane d2 is taken as 8m. The connection with the tower crane position is always perpendicular to the building wall. The tower crane position range is shown in Fig.6.

Therefore, this experiment is programmed by python. By importing into the performance parameters of the tower crane and the position and weight of the components of different precast schemes, the position of the crane with the shortest lifting time in the scheme is selected as the optimal position of the tower crane. Analyzing the case by importing the shortest time that tower crane used under different precast rates, the results are shown in Table 1.

Table 1. Lifting time of different tower crane in different precast rate

Program Number	Precast Rate(%)	Prefabricated Part	Prefabricated Weight(t)	Lifting Time (min)		
				QTZ63	QTZ80	QTZ125
1	3.29	S	115.70	23.757	22.866	19.527
2	20.45	C	718.25	257.903	242.491	226.605
3	23.74	S, C	833.95	286.922	282.880	267.765
4	31.16	F	1094.28	438.216	431.237	400.803
5	34.45	S, F	1209.98	489.594	482.229	455.333
6	34.47	B	1210.63	608.900	599.454	564.530
7	37.76	S, B	1326.33	656.920	647.991	614.836
8	51.61	C, F	1812.53	699.873	687.983	627.408
9	54.90	S, C, F	1928.23	747.497	737.108	685.432
10	54.92	C, B	1928.88	870.562	855.410	791.135
11	58.21	S, C, B	2044.58	914.823	902.870	849.159
12	65.63	B, F	2304.90	1047.674	1032.066	965.333
13	68.92	S, B, F	2420.60	1102.381	1084.979	1023.357
14	89.37	S, C, B, F	3138.85	1360.300	1341.404	1249.962

Note：S refers to stairs, C refers to columns, F refers to floors, B refers to beams.

4. DISCUSSION

4.1 The precast rate and the hoisting time are approximate linear correlation. The hoisting time and efficiency of the tower crane depend on the weight, quantity and position of the precast components.

From the experimental results, as shown in Fig. 6, the overall hoisting time of the tower crane increases with the precast rate, which is linear correlation. However, at the same precast rate, there was a significant fluctuation in the hoisting time of the same tower crane. For example, when the precast rate is about 35%, the lifting time of the tower crane had two different hoisting times for two different precast combinations. And the different precast cast combinations depend on the weight, position and quantity of the precast components.

The same precast rate corresponds to a combination of multiple precast components. According to the "*Shanghai Municipal Commission of Housing and Urban-Rural Development on the Assembly of Precast Rate of Construction Unit and the Assembly Rate Calculation Rules (Trial)*", for the ordinary frame shear structure, the same precast rate can correspond to different precast form, precast ratio and precast combinations. In this case, the precast rate among the individual precast beams, precast stairs and plates are almost equal. Therefore, we can not only explore its relationship with the lifting time, efficiency through the study of the precast rate.

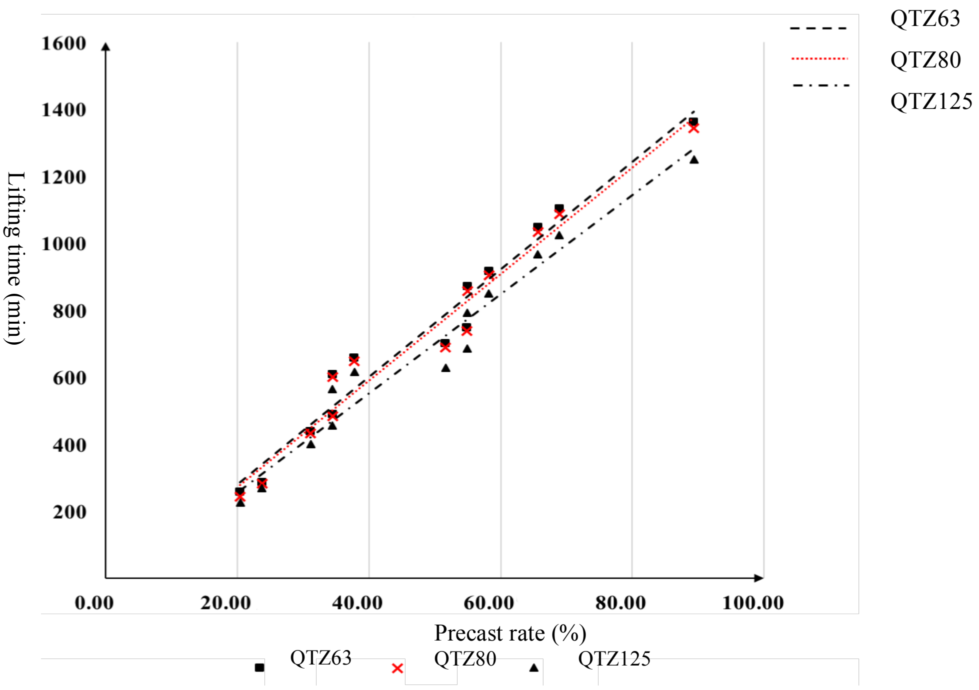


Fig.6. The lifting time of different precast rates

Since the time calculation of the hoisting program does not take into account other objects except the precast components, so the hoisting time should be 0 when the precast rate is 0%. Therefore, the modified fitting function should be calculated as follows:

C63: $T = 1605.2e$ $R^2 = 0.96572$

C80: $T = 1588.8e$ $R^2 = 0.96548$

C125: $T = 1478.9e$ $R^2 = 0.95956$

When the precast rate e = 100%, the total time of hoisting is numerically equal to the slope of the fitting function. Therefore, under full prefabrication in this case, the hoisting time of C63 should be 1605.2min, and the lifting time of C80 should be 1588.8min, and C125 lifting time should be 1478.9min. And the fitting time can be used to calculate the lifting time required for different tower cranes under different precast rates.

4.2 The relationship between lifting time of tower crane with precast rate, and with combination of precast components

Lifting a single component time of the tower crane is:

$$T^0_{i,j,l}(x_s, y_s) = T_v + T_h \tag{11}$$

where $T_v = T_{v1} + T_{v1} = \dfrac{H}{v_h}$, $H = |z_d - z_s| + 2h_0$

So the total lifting time is:

$$T = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{l=1}^{L}(T_{i,j,l} + T_h) + T^u + T^w \tag{12}$$

And the precast rate is the proportion of the material used in the precast part to the amount of material used in the corresponding component. Assuming that the density of the precast member is constant (the density ρ of the precast concrete is 2600kg/m^3), so the precast rate has the expression:

$$e=\frac{V_p}{V}=\frac{m_p}{M} \quad (13)$$

where $$m_p=\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{l=1}^{L}m_{i,j,l}$$

Where V_p represents the volume of the precast part of the concrete, V represents the sum of the volume of the precast and cast-in-place concrete, m_p represents the concrete weight of the precast part, V represents the sum of the precast and cast-in part concrete weight, $m_{i,j,l}$ represents the weight of a single component.

The lifting speed of the crane is linear with the weight of the hanging member, and load-lifting speed of a tower crane v_h can be set as follows:

$$v_h=-a\cdot m_{i,j,l}+b \quad (14)$$

So

$$eaM=IJL\cdot b-\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{l=1}^{L}(\frac{H}{T_{i,j,l}-T_h})=n\cdot b-\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{l=1}^{L}(\frac{H}{T_{i,j,l}-T_h}) \quad (15)$$

Where n refers to the total amount of prefabricated components.

Therefore,

i. When the precast rate rises, no matter how the precast scheme is combined, $\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{l=1}^{l}T_{i,j,l}$ will rise, so the lifting time as a whole increases with the precast rate.

ii. If the precast rate e is constant, when the number of precast components (n) increases, and the weight of a single precast component ($m_{i,j,1}$) decreases, the corresponding v_h of each component will increase, and $T_{i,j,l}$ will decrease. As the number (n) increases, the total time of hoisting (T) exists the situation of rise, decline and invariance. So T will fluctuate at that point. If the number of precast components (n) decreases, the weight of a single precast component ($m_{i,j,1}$) rises, so the T can still fluctuate up and down at the corresponding precast rate.

5. CONCLUSION

In this paper, the precast scheme with different precast rates is formed by combining the different PC components under the premise of optimizing the position of the tower crane and the material stacking, and adding the parameters to judge whether the components are precast in the time calculation of the lifting scheme, and the relationship between the precast rate and the time and efficiency of the lifting scheme is explored. After several experiments, it was found that the time and efficiency of the lifting scheme had an approximate linear correlation with the precast rate of the precast scheme, and related to the quantity and weight of the precast components that determined the size of the precast rate. Through mathematical analysis, when the precast combination changes, tower crane hoisting time will fluctuate within the same precast rate.

The results of this study supply and improve the research of other scholars on the tower crane, and further analyze the influencing factors of the precast rate. It is found that although the improvement of the precast rate will bring about the lifting time and efficiency of the crane. But this influence and the precast rate behind the combination of lifting programs exist in direct relationship. Therefore, based on the optimization of the lifting scheme, at the time of fabricated building design, the designer can improve the combination of the precast scheme by calculating the calculation method proposed in this paper, and then calculate the approximate hoisting time of corresponding precast rate to save construction duration and cost.

ACKNOWLEGEMENTS

The support of the Fundamental Research Funds for the Central Universities (Project No.106112016CDJXY030002) is gratefully acknowledged.

REFERENCES

1. Sparksman, G., Groak, S., Gibb, A., & Neale, R. 1999. Standardisation and pre-assembly: Adding value to construction projects. *CIRIA Report*, *176*.
2. Warszawski, A. 1999. Industrialized and Automated Building Systems: E and FN Spoon.
3. Traynor, T. (2002). Total housing even in 2001 at 2.219 million. *Automated Builder*, *39*(1).
4. Gibb, A. G. 1999. *Off-site fabrication: prefabrication, pre-assembly and modularisation*. John Wiley & Sons.
5. Hasan, S., Bouferguene, A., Al-Hussein, M., Gillis, P., &Telyas, A. 2013.Productivity and CO 2 emission analysis for tower crane utilization on high-rise building projects. *Automation in Construction*, 31, 255-264.
6. MoussaviNadoushani, Z. S., Hammad, A. W., &Akbarnezhad, A. 2016.Location Optimization of Tower Crane and Allocation of Material Supply Points in a Construction Site Considering Operating and Rental Costs. *Journal of Construction Engineering and Management*, 143(1), 04016089.
7. Tam, C. M., & Tong, T. K. 2003. GA-ANN model for optimizing the locations of tower crane and supply points for high-rise public housing construction. *Construction Management and Economics*, 21(3), 257-266.
8. Zhang, P., Harris, F. C., Olomolaiye, P. O., & Holt, G. D. 1999. Location optimization for a group of tower cranes. *Journal of construction engineering and management*, 125(2), 115-122.
9. Irizarry, J., & Karan, E. P. 2012. Optimizing location of tower cranes on construction sites through GIS and BIM integration. *Journal of information technology in construction* (ITcon), 17(23), 351-366.
10. Abdelmegid, M. A., Shawki, K. M., & Abdel-Khalek, H. 2015. GA optimization model for solving tower crane location problem in construction sites. *Alexandria Engineering Journal*, 54(3), 519-526.
11. Marzouk, M., &Abubakr, A. 2016.Decision support for tower crane selection with building information models and genetic algorithms. *Automation in Construction*, 61, 1-15.
12. Al-Hussein, M., Alkass, S., &Moselhi, O. 2005. Optimization algorithm for selection and on site location of mobile cranes. *Journal of construction engineering and management*, 131(5), 579-590.
13. Huang, C., Wong, C. K., &Tam, C. M. 2011. Optimization of tower crane and material supply locations in a high-rise building site by mixed-integer linear programming. *Automation in Construction*, 20(5), 571-580.
14. Lien, L. C., & Cheng, M. Y. 2014. Particle bee algorithm for tower crane layout with material quantity supply and demand optimization. *Automation in Construction*, 45, 25-32.
15. Wang, J., Zhang, X., Shou, W., Wang, X., Xu, B., Kim, M. J., & Wu, P. 2015. A BIM-based approach for automated tower crane layout planning. *Automation in Construction*, 59, 168-178.
16. Moussavi Nadoushani, Z. S., Hammad, A. W., & Akbarnezhad, A. 2016. Location Optimization of Tower Crane and Allocation of Material Supply Points in a Construction Site Considering Operating and Rental Costs. *Journal of Construction Engineering and Management*, *143*(1), 04016089.