# An Algorithm for Optimizing the Location of Attached Tower Crane and Material Supply Point with BIM

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**Abstract**

Attached tower crane is globally used in the high-rise construction to transport components vertically and horizontally. To reduce cost and improve overall efficiency, the tower crane should be well located to move heavy materials. This paper proposes an optimization algorithm to identify the optimal type and location of attached tower crane with proper location of material supply point. The algorithm concerns four main models:1) tower crane location generation model to define alternative type and area for allocating crane.2) supply point location model for selecting all potential area to establish supply point.3) tower crane optimization model to get the ideal location of tower crane and supply point. 4) 4D simulation model to evaluate and visualize the optimal layout scheme through BIM. Then, a practical case, in China, is described in order to demonstrate the outputs obtained by the optimization algorithm. Later, three typical situations of construction site are discussed based on the case. The results reveal the rule that the trolley sliding movement is weightier than the jib rotation movement when considering the optimal layout scheme.

**Keywords –**

Attached Tower Crane; Optimal Algorithm; Site Layout; BIM

## 1 Introduction

Construction site layout planning is a tough task that has to be determined at the early stages of construction, and suitable site layout can significantly improve the construction efficiency [1]. Equipment cost might be in the range of 10% to 40% of overall construction cost [2]. Therefore, having an optimal layout of equipment (e.g. tower crane) and material supply point will be conducive to shorten schedule period and reduce cost [3].

As for types of construction equipment, tower crane is the most prominent construction machinery in the construction market, not only for their large size, but also because they played a prominent role in transporting components vertically and horizontally [4]. In addition, tower crane is the most expansive type among these construction equipment types [5].

With the accretion of population during urbanization process, the number of high-building is increasing especially in China and this phenomenon leads to the widespread uses of attached tower crane. The crane, allocated close to the building boundary, significantly improves the lifting capacity of cranes. Therefore, the selection and allocation of attached tower crane has been the main concern of the construction of high-rise building.

## 2 Literature Review

Current study has put forward a lot of different ways to find the optimal position of tower crane, which is mainly based on simulation and mathematical algorithms. Based on achieving minimal collision of tower cranes, Zhang et al. [6] proposed the method of calculating hoist travel time firstly which laid the foundation for later study. C. Huang et al. [7] improved the equation by adding not only formulas to calculate vertical transporting time but also a parameter $\alpha$ to reveal the location specific effect in different construction sites. Subsequent study completed simulating the hoisting process and separated into load mode and unload mode [7]. In 2017, Justin K. W. Yeoh et al. [8] took multiple stages and the concept time into account to a better solution.

Most of previous researches prefer using mathematical algorithms to allocate optimal layout planning. C. M. Tam et.al [9] applied genetic algorithm to optimizing supply point and tower crane location. Later, GA-ANN model, combined genetic algorithms and artificial neural networks, was introduced to solve
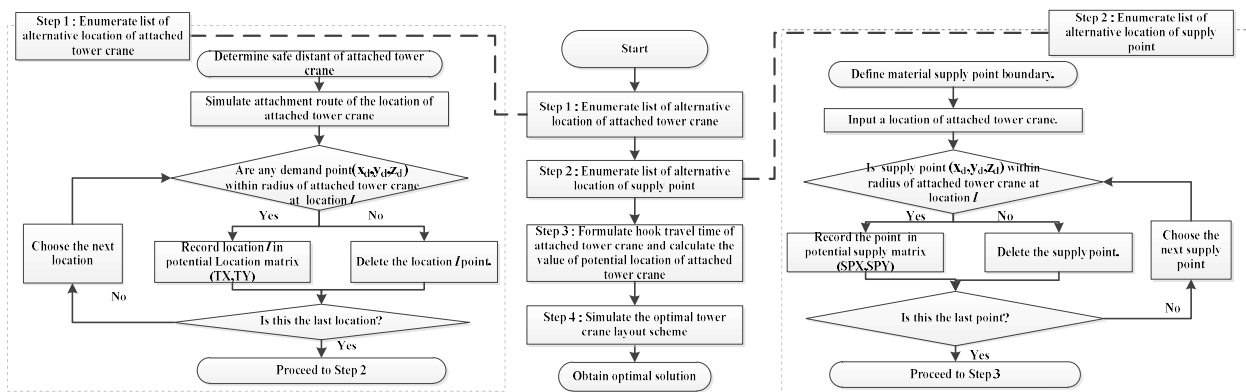
Figure 1. Flowchart of attached tower crane optimization

the same problem [10]. Another modern application for the problem, involving mixed-integer linear programing technique, was introduced by Huang et al. [11]. With increasing focus on construction layout planning, Javier Irizarry et.al. [12] applied geographic information system (GIS) and building information modeling (BIM) to solve the problem which visualize the potential conflicts. And Particle Bee Algorithm (PBA), combined particle swarm optimization (PSO) and bee algorithm (BA), involved to get the optimization location of demand points and supply points [13]. Then, Jun Wang et.al [14] used firefly algorithm for generate optimal layout planning and BIM technology to input data and visualize layout scheme. Mohamed Marzouk et.al. [15] developed a decision model for tower crane selection and location based on BIM and GA.

In previous study, scholars mainly discussed material demand point, supply point, location and lift capacity of tower crane that based on the object of minimal operating time, cost and collision between tower cranes. Practically, tower crane with high lift capacity means using less time to transport the same quantity components than lower ones. However, this also leads to increased costs which is proportional to the rent time. Thus, it is essential to select the suitable type and optimal construction layout planning in different construction which is the purpose of this paper

# 3 Attached Tower Crane Optimization Model

Finding optimal tower crane scheme involves four steps as shown in Figure 1. Firstly, a tower crane location generation model is introduced to produce all alternative tower crane location. Secondly, a supply point location model is generated, finding all potential material supply point. The next is an optimization model to search optimal exact location of tower crane

and supply point. Finally, the outputs are evaluated and visualised through BIM.

## 3.1 Module A: Tower Crane Location Generation Model

To illustrate the constraint of selecting and locating tower crane, several analogies has been drawn on from the previous study. As shown in Figure 2, D1 and D2 represent two demand points where need the same type of components, while the component in D3 is lighter than that in D1, which means M1=M2>M3. And R1, R2 and R3 stand for the radiuses of the maximum area to ensure the crane lift the load of the demand points respectively. Ideally, each crane has its own fixed lift capacity and the radius of the component is inversely proportional to the component mass. The lighter the component is, the further the jib is, which leads to R1=R2<R3. In order to insure the crane to deliver all components to demand points, the crane has to be positioned in the overlapping region.

According for the attributes of attached tower crane, the crane needs a safe and short distance to be located and operated. This distance can be obtained by practical experience. Therefore, attached tower crane should be located in the junction of the overlapping region and attachment route.

## 3.2 Module B: Supply Point Location Model

Comparing with the tower crane location generation model discussing above, supply point location also has two limiting factors. On accounting for the distance between attached tower crane and the building, the supply point lays behind the crane. Another factor is similar to the principle discussed above. Each potential crane location can have its alternative supply area, as shown in Figure 3.
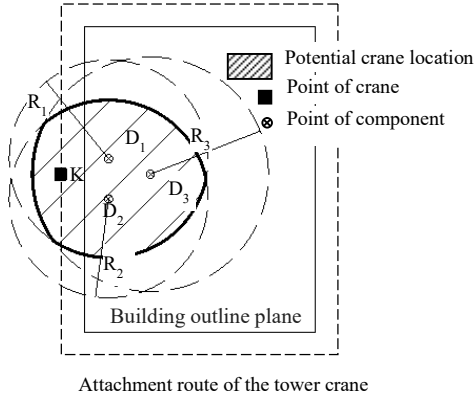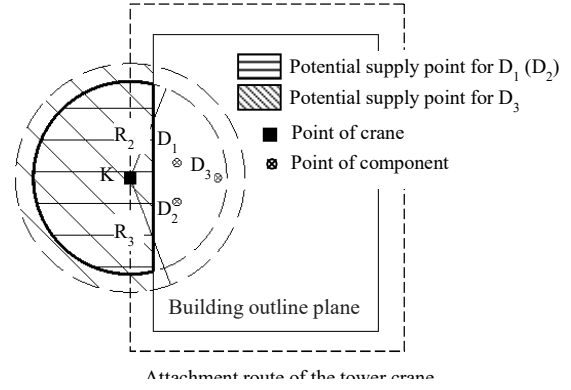
Figure 2. Possible crane location



Figure 3. Possible supply point location

## 3.3 Module C: Tower Crane Optimization Model

Attached tower crane lift components in supply point S ($x_s$, $y_s$, $z_s$), transporting it to demand point D ($x_d$, $y_d$, $z_d$). This movement process of attached tower crane is consist of vertical movement and horizontal movement. On the other hand, the hoisting process can be divided in two main situations: (i)With load (ii) Unload.

### 3.3.1 Vertical Movement of Attached Tower Crane

Vertical movement can be separated into two parts, the vertical lift movement and descent movement. In order to avoid the collision between the components and building, there is a safe height $h_0$ above demand point. Eq. (1) and (2) calculate the travel time of vertical lift movement and descent movement respectively where $v_{h1}$ represents hoisting speed of hook (m/min). When attached tower crane is back to supply point for starting the next delivery, the crane is under unload condition. The different between with load and unload is the velocity of hook.

$$T_{v_1} = \frac{|z_d - z_s| + h_0}{v_{h1}} \quad (1)$$

$$T_{v_2} = \frac{h_0}{v_{h1}} \quad (2)$$

### 3.3.2 Horizontal Movement of Attached Tower Crane

As mentioned in Zhang et al. [6] model, the horizontal movement contains two motions: (i) linear motion of the trolley;(ii) the rotation of the jib. Figure 5 shows the relationships among location of the crane, demand point and supply point, including the radial and tangential movements of the crane jib. The relationships can be calculate using Eq. (3) - (7).

$$\rho_D^K = \sqrt{(x_d - x_k)^2 + (y_d - y_k)^2} \quad (3)$$

$$\rho_S^K = \sqrt{(x_s - x_k)^2 + (y_s - y_k)^2} \quad (4)$$

$$\rho_S^D = \sqrt{(x_d - x_s)^2 + (y_d - y_s)^2} \quad (5)$$

$$T_\omega = \frac{1}{v_\omega} \arccos\left(\frac{\left(\rho_S^D\right)^2 - \left(\rho_D^K\right)^2 - \left(\rho_S^K\right)^2}{-2 \cdot \rho_D^K \cdot \rho_S^K}\right) \quad (6)$$

$$T_r = \frac{|\rho_D^K - \rho_S^K|}{v_r} \quad (7)$$

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

Where $T_\omega$= time for trolley movement; $T_r$= time for jib rotation; $v_\omega$= slewing speed of jib (rad/min); and $v_r$= radial speed of trolley (m/min).

Practically, the movement of the jib rotation and the trolley sliding runs simultaneously to transport component efficiency. The parameter α represents the degree of synchronization between the movement of jib rotation and trolley sliding. The assignment of α is between 0 and 1 that stand for full simultaneous movement and full consecutive movement. The parameter $\beta_r$ and $\beta_\omega$ represent the first movement of the
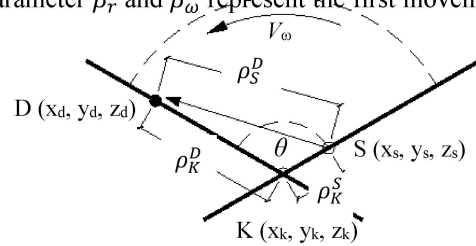


Figure 4. Horizontal operation process

$$T_h = \alpha[\beta_r T_r + \beta_\omega T_\omega] + max\{(1 - \alpha)[\beta_r T_r + \beta_\omega T_\omega], \beta_\omega T_r + \beta_r T_\omega\} \quad (6)$$

When $\alpha$=1，$\beta_r$=1，$\beta_\omega$=1，or $\alpha$=0，$\beta_r$=1, $\beta_\omega$=0, or $\alpha$=0，$\beta_r$=0, $\beta_\omega$=1, the results of Eq. (6) are same as the results of that of Zhang [6].

### 3.3.3 Total Travel Time of Attached Tower Crane

In the same consideration of parameter $\alpha$, the parameter $\gamma$ is added to express the degree of synchronization between the vertical lift movement and horizontal movement. Furthermore, the hook travel time is determined by many factors such as site conditions and the proficiency of operators. Hence this paper adds the parameter $\mu_k$ to reveal the degree of difficulty in alternative crane location K for the operator to manipulate ranging from 0.1 to 10.0, which may be diverse in different combination of demand and supply points.

$$T_{i,j,l}^o(x_s, y_s) = \mu_k\{\gamma T_{v_1} + max\{(1 - \gamma)T_{v_1}, T_h\} + T_{v_2}\} \qquad (9)$$

In conclusion, Eq. (1) - (9) define the calculation of hook travel time when delivering a single component. Besides, in practical, there would be loading time, unloading time and waiting time during the whole process of hoisting. Therefore, the total time of a building hoisting scheme could be defined as Eq. (10).

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

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

### 3.4 Module D: 4D Simulation Model

Owing to the abstract outputs from above model, it is tough for site manager to fully understand the result and make wise decisions. Furthermore, conflicts and restrictions in spaces are difficult to display in 2D or 3D layout planning. Hence, the purpose of developing this 4D simulation model is to evaluate the credibility of the mathematical model outputs and space restrictions.

The inputs of this model come from three parts: 1) the outputs of tower crane optimization model including the location of attached tower crane and supply point with proper type of the crane.2) the coordinates of demand point and material comsumption.3) model library concerns 3D building model, construction schedule and 3D construction site model. The outputs of this model are the final layout scheme which will be implemented in reality.

## 4 Case Study

The proposed optimization model was used in the construction of a 23-story single apartment in Chongqing, China. The high-rise building is a footprint of 34.8 X 11.7m using attached tower crane. In addition, the types of the cranes used in this case are QTZ63, QTZ80 and QTZ125, and the numbers after "QTZ" means the max load moment of that type of tower (unit: KN/m). According to practical experience, the distance between the building boundary and tower crane is assume to be 4 meters which is the same between the location of tower crane and material supply points, as shown in Figure 5. Owing to the significant shape of attached tower crane and components, the possible position of tower crane and supply points is described in one-dimensional coordinate as particle distribution.

The results of module A, produced by MATLAB, displays in Figure 6. QTZ63 and QTZ80 are only able to deliver components to cover all demand points in part of the attachment route, while QTZ125 has potential location in all of the route. Depending on whether the attachment route, the situation can be divided into two parts: (i)full-filled which achieves the object; (ii) part-filled which attached tower crane locates in part of the attachment route. Practically, tower crane and material supply points locate on the basis of the experience that the tower crane should satisfied the farthest demand point with the heaviest component. And the full-filled situation simulates this realistic scenario. Thus, QTZ125 is the optimal type of attached tower crane in this project using practical experience. Meanwhile, QTZ63 and QTZ80 are another choice based on this mathematical model. As shown in Table 3, choosing
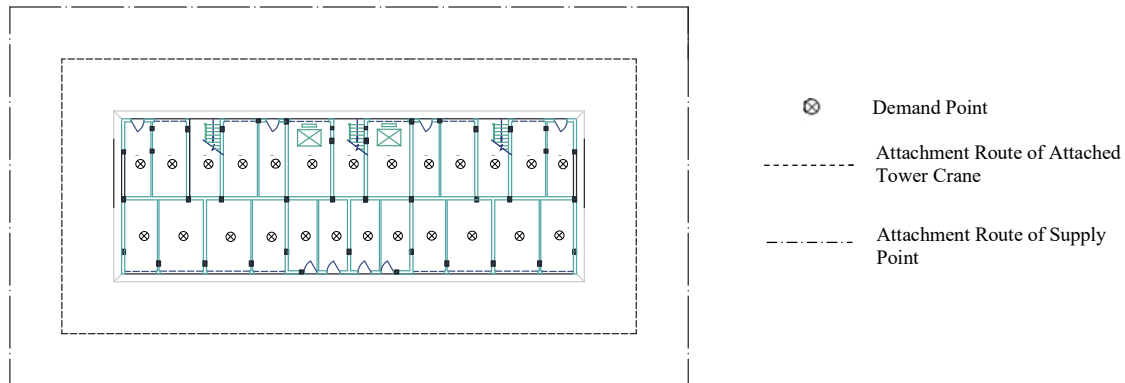


Figure 5. Site layout of case study

QTZ63 is a better solution that reduced the total cost of QTZ125 by 42.57%. Finally, the outputs are proved feasible in practice by Module D, and display in Figure 7.

Table 1 Coordinates of demand points and weight of the section to be transported (Standard floor)

| Prefabricated Part | Demand Point | Coordinate | | | Weight of the section to be transported(t) |
|---|---|---|---|---|---|
| | | X | Y | Z | |
| Beam | D1 | 18.10 | 19.57 | 18.00 | 2.75 |
| Floor | D2 | 21.20 | 19.57 | 18.00 | 3.25 |
| Floor | D3 | 24.85 | 19.57 | 18.00 | 3.25 |
| Beam | D4 | 27.94 | 19.57 | 18.00 | 2.75 |
| Column | D5 | 30.55 | 19.57 | 18.00 | 2.50 |
| Column | D6 | 32.89 | 19.57 | 18.00 | 2.5 |
| Column | D7 | 35.35 | 19.57 | 18.00 | 2.5 |
| Column | D8 | 37.69 | 19.57 | 18.00 | 2.5 |
| Beam | D9 | 40.30 | 19.57 | 18.00 | 2.75 |
| Floor | D10 | 43.39 | 19.57 | 18.00 | 3.25 |
| Floor | D11 | 47.04 | 19.57 | 18.00 | 3.25 |
| Beam | D12 | 50.14 | 19.57 | 18.00 | 2.75 |
| Floor | D13 | 50.01 | 25.54 | 18.00 | 2.25 |
| Floor | D14 | 47.60 | 25.54 | 18.00 | 2.75 |
| Stair, Beam | D15 | 45.10 | 25.54 | 18.00 | 3.25 |
| Beam | D16 | 42.37 | 25.54 | 18.00 | 2.75 |
| Column | D17 | 39.93 | 25.54 | 18.00 | 2.5 |
| Floor, Beam | D18 | 37.06 | 25.54 | 18.00 | 3.75 |
| Stair, Beam | D19 | 34.12 | 25.54 | 18.00 | 3.25 |
| Floor, Beam | D20 | 30.95 | 25.54 | 18.00 | 3.75 |
| Column | D21 | 28.07 | 25.54 | 18.00 | 2.5 |
| Beam | D22 | 25.63 | 25.54 | 18.00 | 2.75 |
| Stair, Beam | D23 | 22.90 | 25.54 | 18.00 | 3.25 |
| Floor | D24 | 20.40 | 25.54 | 18.00 | 2.75 |
| Floor | D25 | 17.99 | 25.54 | 18.00 | 2.25 |

Table 2: The value of parameters used in the optimization model

| Parameter | Unit | Type of Attached Tower Crane | | |
|---|---|---|---|---|
| | | QTZ63 | QTZ80 | QTZ125 |
| $v_h$ | m/min | 41.6 | 43.3 | 51.4 |
| $v_{r1}$ | m/min | 25 | 25 | 25 |
| $v_\omega$ | r/min | 0.7 | 0.7 | 0.7 |
| $v_{r2}$ | m/min | 40 | 58 | 58 |
| $h_0$ | m | 3 | 3 | 3 |
| $\alpha$ | / | 0.5 | 0.5 | 0.5 |
| $\beta_r$ | / | 1 | 1 | 1 |
| $\beta_\omega$ | / | 0 | 0 | 0 |
| $\gamma$ | / | 0.5 | 0.5 | 0.5 |



---------- QTZ63
———— QTZ80
—·—·—· Attachment route

Note: QTZ125 is able to locate on any position of the attachment route due to its huge lift capacity.
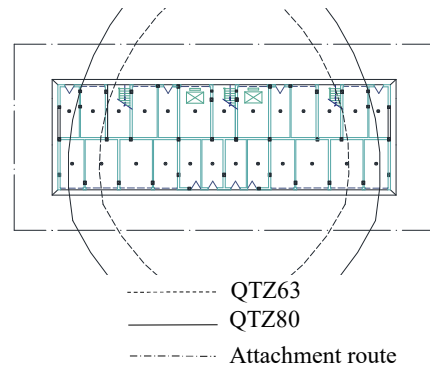
Figure 6. Possible attached tower crane location

Table 3: Optimized total costs of attached tower crane on site using the proposed model

| Results | Attached tower crane | | |
|---|---|---|---|
| | QTZ63 | QTZ80 | QTZ125 |
| Total material transporting time(min) | 4215 | 4103 | 3910 |
| Installation and dismantle costs(RMB) | 39800 | 46200 | 74800 |
| Foundation costs (RMB) | 20250 | 24502.5 | 29160 |
| Rental costs(RMB/d) | 600 | 700 | 1200 |
| Total cost(RMB) | 65318.75 | 76686.04 | 113735 |
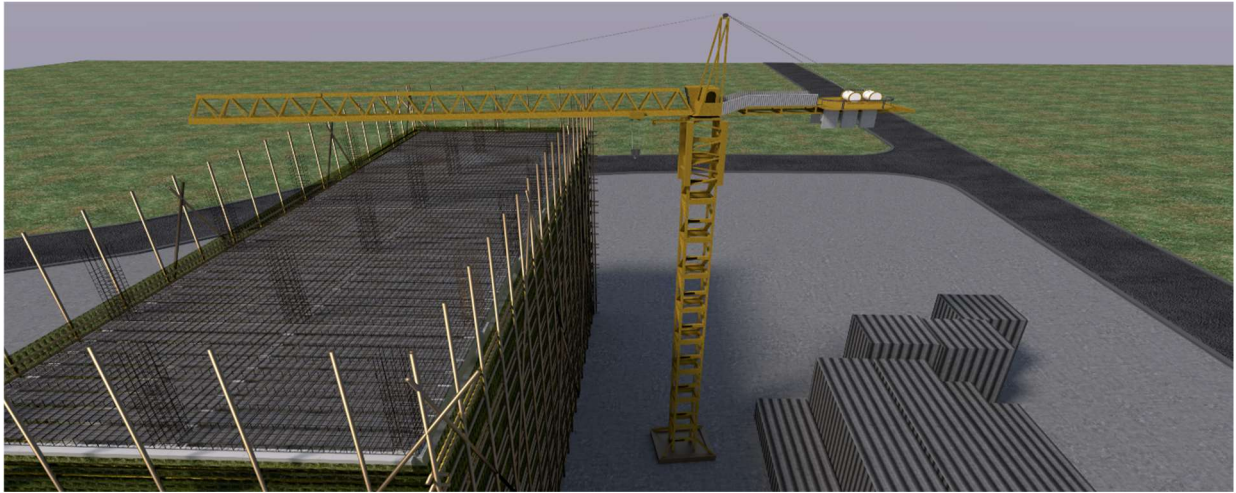


Figure 7. Simulation of the optimal scheme

## 5    Discussion

Each project has its individualism optimal layout planning because of the different constraint among the construction site. Exploring the main influencing factors and the changing rule of time in different situations is helpful to find the optimal layout planning. Practically, the supply point may be fixed in one position on account for the other facilities layout (e.g. steel cut machine), or there is no constraint of the allocation of supply point and tower crane. The experiments are based on the full-filled mode that is able to reveal the all-round output of the layout. In addition, the mass of the demand point distribution is symmetrical in left and right.

**Situation I: Material supply point is right behind attached tower crane.**

As shown in Figure 8 (a), the filled black pentacle refers to the optimal location of attached tower crane in the center of top attachment route. The line chart shown in Figure 8 (b) is the total delivering time of each attached tower crane location, and when the crane lays on the bottom and top of the attachment route, the total time will be shorter than that it in the right and left. The reason is that the high-mass component distributing mainly on the top line of demand points, so the distance to all demand points gets the minimal travel time.
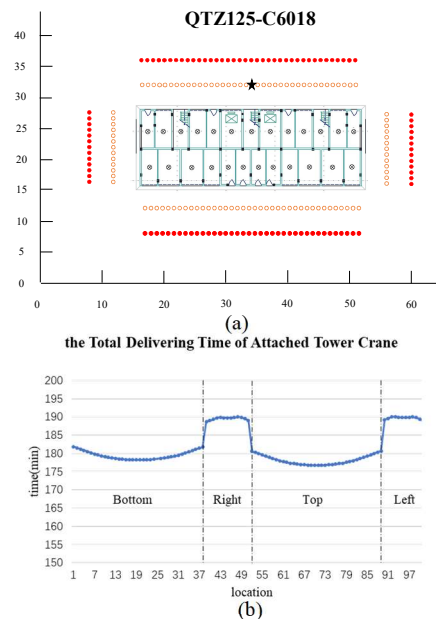


Figure 8 Results of situation I

**Situation II: under no extra constraint when define the location of attached tower crane and supply point.**

For this part, the layout planning reaches a state of relative ideal that may achieve in the early planning stage. As illustrated in Figure 9, the green triangle refers to the optimal metirial supply point when the tower

crane located on the black filled pentacle. In addition, the left green triangle is corresponding to the left black pentacle.
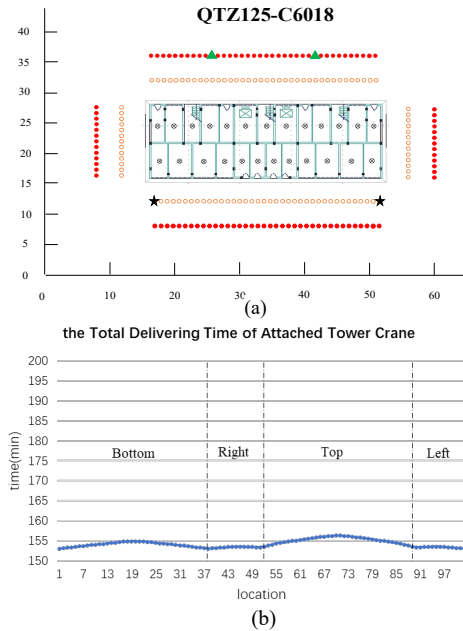


(a)



(b)

Figure 9 Results of situation II

**Situation III: Supply point is fixed.**

In order to comprehensive discuss this situation, this part is divided into three typical conditions:

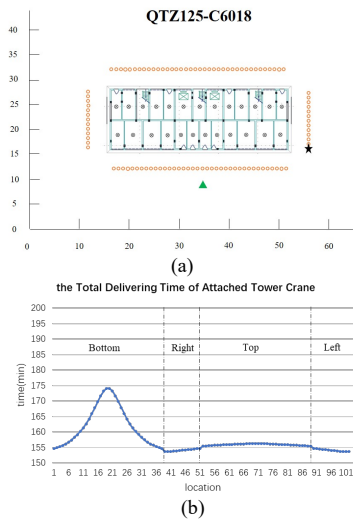1.  fixed the supply point in the center at the bottom of attachment route;
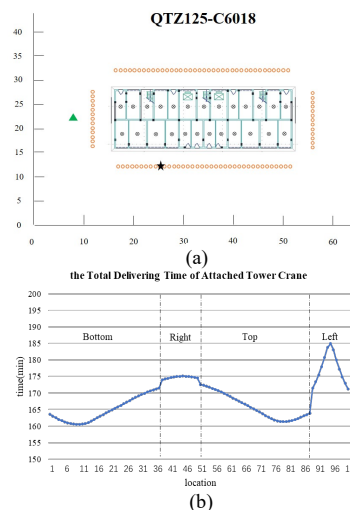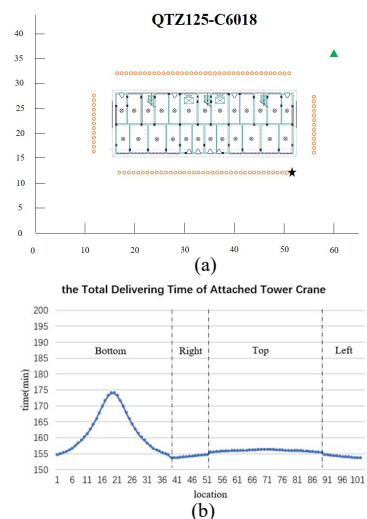
2.  fixed the supply point in the center at the left of attachment route

3.  fixed the supply point in the angular point of the attachment rout

As shown in Figure 10-12, the optimal location of attached tower crane usually locates in another side of the attachment route, but not so far from the fixed supply point. The fixed supply point plays an important role in layout planning. Furthermore, when the crane lays right above the fix supply point, the total delivering time reaches the highest.

Among those situations, the line chart of situation II is the smoothest line and reaches the minimal time which indicates the importance of considering the layout planning in early stage. Meanwhile, it is a bad choice to lay attached tower crane just above the supply point that always leads to a costly result.

According to the proposed model, the mainly direct factors of the total travel time are the trolley sliding movement and jib rotation movement that influenced by the angle $\theta$ of $\rho_D^K$ and the difference of $\rho_S^K$ and $\rho_D^K$, respectively. And the optimization layout planning is to achieve a balance between the two factors.

Contrast with situation II and III, situation I is waster money which $\theta$ isn't able to less than 90 degrees while the difference of $\rho_S^K$ and $\rho_D^K$ is the same with others. Therefore, when solving the layout planning problem, the angle is a more important than the difference.



(a)



(b)

Figure 10 Results of situation III(i)



(a)



(b)

Figure 11 Results of situation III(ii)



(a)



(b)

Figure 12 Results of situation III(iii)

# 6 Conclusion

This paper analyses the relationship among attached tower crane, demand point and material supply point, then simulates the movement of hook travel. Based on mentioned above, an optimization model is generated in order to select the type of attached tower crane and find the optimal location of the crane and material supply point based on finding the minimal cost. Furthermore, to evaluate and visualise the outputs, simulating the layout

planning to ensure the optimal scheme is feasible and guide the site manager fully understand it. Finally, this algorithm leads to a more cost-efficient result than the traditional method that determined based on experience.

Compared with current study, the object of this study is attached tower crane, and this paper is more pertinent because it concerns the crane features as constraints when determine the layout planning. In addition, this paper discusses the main influence factors when positioning attached tower crane and supply point. Based on the practical case, many experiment has been done and reveals a few rules. The experiments are divided into three typical situations according to realistic site construction and aim to analyses the influence essential factors in layout planning. The results show that the angle between $\rho_S^K$ and $\rho_D^K$ is more important than the difference of $\rho_S^K$ and $\rho_D^K$.

# 7 Acknowledgements

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