Integrating Building Information Modelling and Firefly Algorithm to Optimize Tower Crane Layout

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Abstract -

Tower crane layout design and planning within construction site is a common construction technical issue and regarded as a complex combinatorial problem. To transport heavy materials, such as rebar, formwork, scaffolding, equipment and steel, tower cranes are needed and should be well located to reduce construction cost and improve safety management. Currently, practitioners in the industry are over-reliance on individual experience and subjective judgment during decision-making process. The purpose of this paper wants to develop a well-defined approach, which integrating Building Information Modelling (BIM) and firefly algorithm to come up with an optimal tower crane layout for construction projects. Firstly, BIM technology is utilized to automatically generate the quantity of materials which need to be transported. Then firefly algorithms are used to determine the locations of tower cranes, supply points and demand points according to transportation requirement, time and cost. Thirdly, the optimal tower crane layout scheme will be visualized by 4-Dimension (4D) BIM to verify its constructability and safety based on computer simulation and individual experience. Finally, a practical case is selected to evaluate the developed approach. In addition, some lessons learned and issues are highlighted that help direct future research and implementation. The optimization results of the example are very promising and it demonstrates the application value of the approach.

Keywords -

Tower crane; Firefly algorithm; Building Information Modelling (BIM); Site layout

1 Introduction

Tower crane layout design and planning within construction site is a common construction technical issue and regarded as a complex combinatorial problem. To transport heavy materials, such as rebar, formwork, scaffolding, equipment and steel, tower cranes are needed and should be well located to reduce construction cost and improve safety management. Affected by many uncertainties (variables) and variations, tower crane layout planning is a typical multi-objective problem. To facilitate the decision-making process for this problem, Tem et al proposed a non-structural fuzzy decision support system, which integrated both experts' judgment and computer decision modelling, to solve the appraisal of complicated construction problems. The system allowed assessments based on pairwise comparisons of alternatives using semantic operators that can provide a reliable assessment result even under the condition of insufficient precise information [1]. In order to reduce conflicts between groups of tower cranes, Irizarry and Karan Hence developed an integrated Geographic Information Systems- Building Information Modelling (GIS-BIM) model to effectively identify the feasible locations for defined tower cranes [2].Tam and Tong used artificial neural networks to model the non-linear tower crane operations, and developed genetic algorithms to determine the locations of the tower crane, supply points and demand points by optimizing the transportation time and costs [3]. Ju and Choo proposed a parameterized super element formulation for modelling the multiple-pulley cables in a crane system based on the friction-free assumption between the cable and pulleys. These cable passages had significant effect on both static tensions and dynamic properties of tower cranes and the proposed super element model provided more accurate and realistic results in dynamic analyses of the crane system [4]. Sacks et al developed an approach for unique association of isolated equipment operations with planned construction activities based on comparison of the values of various characteristics, calculated for each equipment operation, against preset filters of characteristic values for all expected basic construction activities [5]. Duong et al concerned with the control of an under-actuated three-dimensional tower crane system using a recurrent neural network (RNN), which is evolved by an evolutionary algorithm [6]. Ning et al used a continuous dynamic searching scheme to guide the max-min ant system so as to solve the dynamic tower crane layout problem under the two congruent objective functions of minimizing safety concerns and reducing construction cost [7]. In order to eliminate collisions between mobile crane and onsite facilities, virtual cranes were provided with motion-planning algorithms that enable them to find collision-free and time-efficient paths for each piece that needs to be erected [8].

Efficient material transportation plays an important role in reducing costs and time. Tam et al had developed traditional linear regression models and nonlinear neural network models for predicting hoisting times of a tower crane [9]. To transport heavy materials, tower cranes are needed and should be well located to reduce operating costs and improve overall efficiency. Huang et al had developed Quadratic assignment problem to simulate the material transportation procedure [10]. Leung et al had developed a quantitative model for predicting the hoisting times of tower cranes for public housing construction using artificial neural network and multiple regression analysis [11]. Input shaping is an effective method for reducing motion-induced vibration. Blackburn et al. had investigated the effect of nonlinear crane dynamics on the performance of input shaping. They presented nonlinear equations of motion and novel command-shaping algorithms for reducing vibration during the nonlinear slewing motions of tower cranes [12]. Aspiring to adopt a non-statistical quantitative approach to safety assessment due to the operation of tower cranes, Shapira and Simcha implemented a multi-attribute decision-making tool to elicit knowledge from experts and formalize it into a set of weighted safety factors [13].

Visual monitoring and alarming is an effective way to avoid accidents and to increase the efficiency of project management in the construction industry [14]. BIM is an emerging technology in construction industry and have been implemented in site layout visualization and optimization. Al-Hussein et al presented a practical methodology for integrating 3D visualization with special problem simulation for tower crane operation [14]. Lee et al proposed a robotic tower-crane system with a laser device, an encoder, and an accelerometer, and tested the feasibility of the system under indoor, outdoor, and swinging conditions [15]. Huang et al developed Construction Virtual Prototyping (CVP) system to assess the executability of a construction planning including site layout, temporary work design, as well as resource planning [16]. Hwang developed a collision-prevention approach, which comprised of real-time data collection platform, a visualization module, and a decision module, to real-time monitor equipment operations and assess the possibility of collision [17]. Yang et al demonstrated the use of a surveillance camera for assessing tower crane activities during the course of a workday. In particular, it seeks to demonstrate that the crane jib trajectory, together with known information regarding the site plans, provides sufficient information to infer the activity states of the crane [18]. Kang et al had developed a system for providing detailed planning and visualization in a virtual construction environment as well as for assisting crane operators in real-time during erection. [19]. Tower crane operators often operate a tower crane with blind spots. To solve this problem, video camera systems and anti-collision systems are often deployed. Lee et al introduced a newly developed tower crane navigation system that provides three-dimensional information about the building and surroundings and the position of the lifted object in real time using various sensors and a building information model [20]. However, due to the low transmission rate of a wireless network, sometimes it is not feasible to use a camera in a remote monitoring and alarming system for a tower crane [21]. Li and Liu developed a data-driven remote monitoring and alarming system for tower cranes, which integrated field data and 3D simulation. In addition, an experience-based and practical alarming system was embedded into the virtual monitoring system [21].

The purpose of this paper wants to develop a well-defined approach, which integrating Building Information Modelling (BIM) and firefly algorithm to come up with an optimal tower crane layout for construction projects. Firstly, BIM technology is utilized to automatically generate the quantity of materials which need to be transported. Then firefly algorithms are used to determine the locations of tower cranes, supply points and demand points according to transportation requirement, time and cost. Thirdly, the optimal tower crane layout scheme will be visualized by 4-Dimension (4D) BIM to verify its constructability and safety based on computer simulation and individual experience. Finally, a practical case is selected to evaluate the developed approach.

2 The Framework of Integrating BIM and Firefly Algorithm to Optimize Tower Crane Layout

This section describes a framework of integrating BIM and firefly algorithm to optimize tower crane layout (as shown in Figure 1) which includes four steps: creating BIM model, determining minimal number of tower cranes, determining optimal location of each tower crane, and BIM-based visualization and validation. Each is described in detail below.

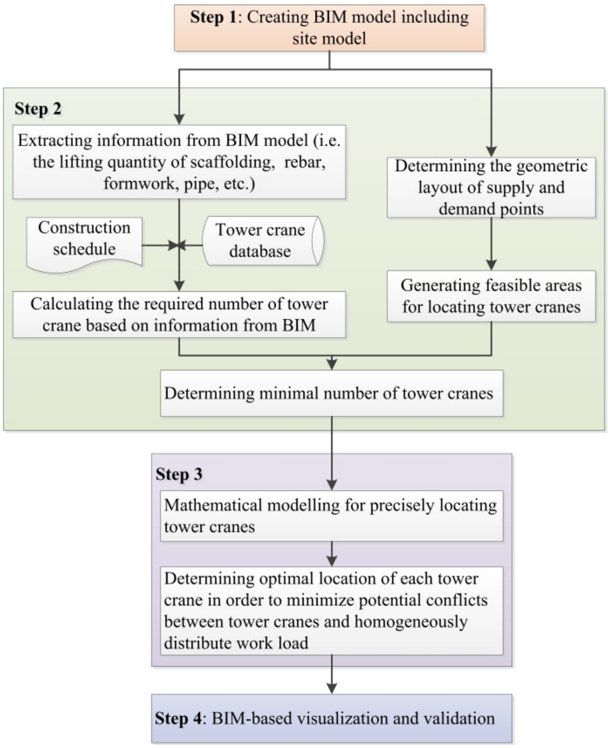

Figure 1. The framework of integrating BIM and firefly algorithm to optimize tower crane layout

2.1 Step 1: Creating BIM Model

BIM has been utilized in information sharing [23], construction management [24-26], facility management [27-29], visualization [30, 31]. In this step, BIM model is created based on design drawings and construction site survey map. In order to automated calculate lifting quantity, BIM model should contain scaffolding, rebar, formwork, steel structure and so on.

2.2 Step 2: Determining Minimal Number of Tower Crane

In this step, there are two main tasks need to be implemented. The first one is calculating the required number of tower cranes based on lifting material quantity, construction schedule and tower crane types. For example, the total lifting quantity of a building is 28000t, construction duration is 300 days, tower crane load is 1.5t per each lifting times, and each tower crane can lift 32 times per day, we can conclude the required number of tower cranes is 2 (the calculation method is 28000/[1.5*32*300]=1.94). The second one is assessing the require number of tower cranes based on feasible areas for locating tower cranes according to geometric layout of supply and demand points. When we get the results of the two tasks, the large value is the minimal number of tower cranes.

2.3 Determining Optimal Location of Each Tower Crane

In this step, there are three tasks need to be performed.

2.3.1 Problem description

For establishing a mathematical model for the location of cranes group, some assumptions are list below [22]:

(1) Geometric layout of all supply (S) and demand (D) points, together with the type and number of cranes, are predetermined.

(2) For each S-D pair, demand levels for transportation are known, e.g., total number of lifts, number of lifts for each batch, maximum load, unloading delays, and so on.

(3) The duration of construction is broadly similar over the working areas.

(4) The material transported between an S-D pair is handled by one crane only.

2.3.2 Mathematical model

The completed model consists of two sub-models: minimal conflicts between cranes, and a single-tower-crane optimization model for optimal location in terms of minimal hook transportation time.

To measure possibility of conflict, a parameter (NC), called the *conflict index* is introduced. The transportation of a crane corresponds to a triangle with apexes representing the supply point, demand point, and crane location. The number of intersections between two triangles reflects the severity of conflicts, i.e., the more intersections the more likely are conflicts.

Additionally, the intensity of material flows also affects possibility of conflicts. Hence, conflicts between cranes i and k can be represented as

$$NC_{ik} = \sum_{i=1}^{L}\sum_{j=1}^{J} n_{(ij,kl)}\left(Q_{ij} + Q_{kl}\right)$$

where $n_{ij,kl}$ define the number of intersections of the two triangles, respectively, consisting of crane i and task j, crane k and task l.

Q_{ij}, the number of lift of jth tasks in i-th task groups.

Q_{kl}, the number of lift of l-th tasks in k-th task groups.

Furthermore, the possibility of conflicts between two crane task pairs should be proportionate to $n_{ij,kl}\left(Q_{ij} + Q_{kl}\right)$. Therefore, for all cranes and all tasks, the conflict index (reflecting general possibility of conflicts) can now be calculated as

$\min f_1(x) = \min NC_{ik}$

$$= \min \sum_{i=1}^{I} \sum_{j=1}^{J} n_{(ij,kl)} (Q_{ij} + Q_{kl}) \qquad (1)$$

On the other hand, if (Dx_j, Dy_j, Dz_j) and (Sx_j, Sy_j, Sz_j) refer, respectively, to the location of S and D of a task, and (x_i, y_i) denotes location of foundation of a crane. The travel time of the *i*-th hook for task j T_i^j can be expressed as

$$T_i^j = T(D_{j'}\ , S_j) + N_j^k \left[L(S_j) + T(S_j, D_j) + U(D_j) + T(D_j, S_j)\right] - T(D_j, S_j)$$

where $i = 1, 2 \ldots I$; $j = 1, 2, \ldots, J$, and

$T(D_{j'}, Sj)$, hook travel time without loads from D of task j' (produced by last request) to S of present request j;

N_j^k , the repeated number of task j in batch k,

$T(S_j, D_j)$, hook travel time with loads from S_j to D_j;

$T(D_j, S_j)$, hook travel time without loads from D_j to S_j;

$L(S_j)$, hook delay time for loading at S_j;

$U(D_j)$, hook delay time for unloading at D_j.

Hence, the minimal average transportation time for all crane hooks is

$$min f_2(x) = min\, ATT(x, y) = \frac{1}{K} \min \sum_{i=1}^{I} \sum_{j=1}^{J} T_i^j \qquad (2)$$

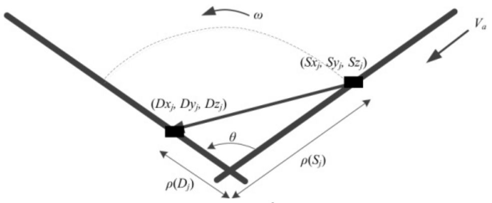

Figure 2 movement of hook during transportation

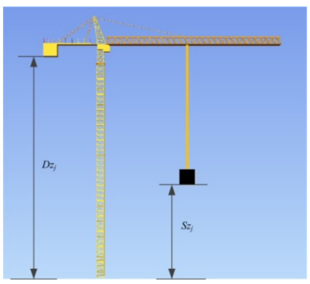

Figure 3 vertical transportation distance of hook

Additionally, for any hook (see Figure 2 and Figure 3), the transportation distance of a hook can be calculated by

$$\rho(D_j) = \sqrt{(Dx_j - x_i)^2 + (Dy_j - y_i)^2}$$

$$\rho(S_j) = \sqrt{(Sx_j - x_i)^2 + (Sy_j - y_i)^2}$$

$$l_j = \sqrt{(Dx_j - Sx_j)^2 + (Dy_j - Sy_j)^2}$$

Times for trolley radial and tangent movement:

$$T_a = \frac{|\rho(D_j) - \rho(S_j)|}{V_a};$$

$$T_\omega = \frac{1}{\omega} \cdot \arccos\left(\frac{l_j^2 - \rho(D_j)^2 - \rho(S_j)^2}{2 \cdot \rho(D_j)\rho(S_j)}\right);$$

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

Hook's vertical travel time $T_v = \frac{Dz_j - Sz_j}{V_v}$; hook's horizontal travel time $T_h = max(T_a, T_\omega) + \alpha \cdot min(T_a, T_\omega)$. So hook's transportation time

$$T = max(T_h, T_v) + \beta \cdot min(T_h, T_v)$$

where α and β are two parameters between 0 to 1; α represents the degree of coordination of hook movement in radial and tangential directions in the horizontal plane; and β reflects those in the vertical and horizontal planes. Especially, simultaneous movement occurs when $\alpha = 0$, and consecutive movement when $\alpha = 1$, depending on the skill of the operator and the spaciousness of the site. For β, simultaneous movement in two planes when $\beta = 0$ or consecutive movement when $\beta = 1$.

Though above analysis, a constrained multi-objective optimization model is established for the problem of cranes group location. In section 2.3.3, it will be transformed into an unconstrained optimization by using penalty function method in mathematics and then a intelligent optimization is applied to solve this model.

2.3.3 Firefly Algorithm for the Problem

Firefly algorithm is a novel nature-inspired algorithm inspired by social behaviour of fireflies. Fireflies are one of the most special, captivating and fascinating creature in the nature. By idealizing some of the flashing characteristics of fireflies, firefly-inspired algorithm was presented by Yang [32].

Firefly-inspired algorithms use the following three idealized rules:

(1) All fireflies are unisex which means that they are attracted to other fireflies regardless of their sex;

(2) The degree of the attractiveness of a firefly is proportion to its brightness, thus for any two flashing fireflies, the less brighter one will move towards the brighter one and the more brightness means the less distance between two fireflies. If there is no brighter one than a particular firefly, it will move randomly;

(3) The brightness of a firefly is determined by the value of the objective function. For a maximization problem, the brightness can be proportional to the value of the objective function.

In the firefly algorithm, there are four important issues:

Attractiveness: In the firefly algorithm, the main form of attractiveness function $\beta(r)$ can be any monotonically decreasing functions such as the following generalized form:

$$\beta(r) = \beta_0 e^{-\gamma r_{ij}^n}, \qquad n \ge 1 \qquad (3)$$

where r is the distance between two fireflies, β_0 is the attractiveness at r = 0 and γ is a fixed light absorption coefficient.

Distance: The distance between any two fireflies i and j at x_i and x_j is the Cartesian distance as follows:

$$r_{ij} = \|x_i - x_j\| = \sqrt{\sum_{k=1}^{d} (x_{i,k} - x_{j,k})^2} \quad (4)$$

where $x_{i,k}$ is the k-th component of the i-th firefly.

Movement: The movement of a firefly, i is attracted to another more attractive (brighter) firefly j, is determined by

$$\overline{x_i} = x_i + \beta(r) \times (x_i - x_j) + \alpha\left(r - \frac{1}{2}\right) \quad (5)$$

where the second term is due to the attraction while the third term is randomization with α being the randomization parameter and r is a random number generator uniformly distributed in [0, 1]. In this paper, an outline update mode is applied in original FA, that means the light intensity is updated and the new position of firefly is evaluated after all the firefly finish moving.

The steps of the FA can be summarized as the pseudo code shown below.

Generate initial population of fireflies $x_i, (i = 1,2,\ldots,n)$
Suppose that $f(x)$ is the objective function of $x_i = (x_{i1}, x_{i2}, \ldots, x_{in})$. Light intensity LI_i at x_i is determined by $f(x_i)$
Set light absorption coefficient γ , randomization parameter α and maximum generations.
While ($t < t_{max}$) %% t_{max} is maximum generation
  For $i = 1{:}\,n$ %% all n fireflies
  For $j = 1 : i$
    If ($LI_j > LI_i$)
      Move firefly i towards j in d-dimension by equation (5)
    End if
  End
 End
Attractiveness varies by equation (3)
Evaluate the new position of i-th firefly and update light intensity LI_i. %% outline update
Rank the fireflies and find the current best
End
Show result and visualization

2.4 BIM-based Visualization and Validation

The optimal layout scheme is calculated based on ideal construction environment, some factors which cannot be quantified are not considered in the mathematical model. In order to assure the constructability of the optimal tower crane layout scheme, BIM is used to conduct assessment based on construction expertise and experience of project participants. In addition, 3D visualized construction scheme of tower cranes will be generated so as to guide field workers install and dismantle tower cranes accurately.

3 Case Study

Case A is selected to validate the proposed method. This project includes 6 high-rise business buildings, 21 floors on the ground and 3 floors underground. The gross floor area is 420,000 m2 and occupied area is 40,000 m2.

3.1 Determining the Minimal Number of Tower Cranes

In this section, firstly the required number of tower cranes is calculated based on information from BIM model. The following information demonstrates the detailed calculate process.

(1) Calculating rebar lifting times

The rebar quantity of rebar in a standard level is about 100kg/m2x2000 m2=200 tons. Based on the tower crane load, which is 1.5 tons per lifting, the rebar lifting times in a standard level is: 200/1.5=135

(2) Calculating formwork lifting times

There are about 40 frame columns in standard level, tower crane can life one frame column’s formwork at a time because the formwork weight is in the range of tower crane load, so the lifting times of frame column’s formwork is 40.

The length of shear wall in standard level is 100 meter and the length of single formwork will be 3.3 meter on account of the higher story height. So the lifting times of the shear wall formwork in standard level is 100m/3.3m=30. Since there are more corner walls in this project, the lifting times is adjusted to 30*1.5=45.

The beam and slab area in standard level is about 2,100 ㎡. Based on the tower crane load, which is 90 ㎡ per lifting in consideration of the formwork stack height. Hence, the lifting times of beam and slab formwork in a standard level is: 2100/90=24.

The estimation amount of beam and slab formwork support system is 100 tons. The average lifting weight of tower crane is 1.5 tons at a time, so the lifting times of beam and slab formwork support system is: 100/1.5=67.

Synthesizes all types of formwork erection and dismantle, the total lifting times of formwork and support system in standard level is: (40+45+24+67)*2=352.

(3) Calculating other materials lifting times

Lifting times of scaffolding steel pipes: 15

Lifting times of door and window formwork: 15

Lifting times of embedded water and electricity pipes: 10

(4) Calculating the total lifting times

The total lifting times in a standard level is: 135+352+15+15+10=527

(5) Calculating the required number of tower cranes

Based on the construction experience and tower crane specification, each tower crane can lift 4 times per hour and 10 work hours per day. In addition, project duration is 9 days per a standard level. Hence, the required number of tower cranes is: ceiling [527/(4*9*10)] =2. Because there are 6 similar buildings in this project, at least 12 tower cranes are needed in this project.

Secondly, according to feasible areas for locating tower cranes according to geometric layout of supply and demand points, the require number of tower cranes is 12. When comparing the two results, the large value (i.e.12) is the minimal number of tower cranes.

3.2 Determining the Optimal Location of Each Tower Cranes

Figure 4 shows the optimal tower crane layout scheme, each location of tower crane is calculated based on the mathematical model developed in section 2.3.

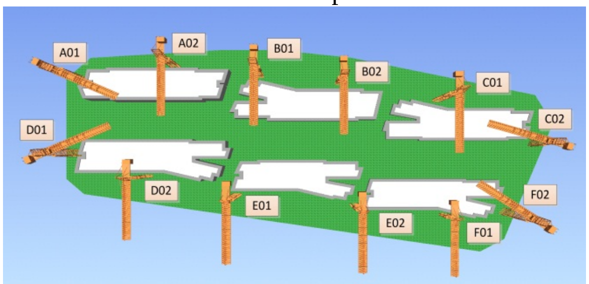

Figure 4. The optimal tower crane layout scheme

3.3 BIM-based Visualization and Validation

The optimal tower crane layout scheme is calculated based on a static and hypothetical scenario. In this project, the installation of each tower crane is divided into five times. BIM is used to calculate the installation height of each tower crane at a time in order to reduce collision. Tower cranes installation heights in stage one are shown in figure 5 and table 1. Tower cranes installation heights in stage two are shown in figure 6 and table 2. Tower cranes installation heights in stage three are shown in figure 7 and table 3. Tower cranes installation heights in stage four are shown in figure 8 and table 4. Tower cranes installation heights in stage five are shown in figure 9 and table 5.

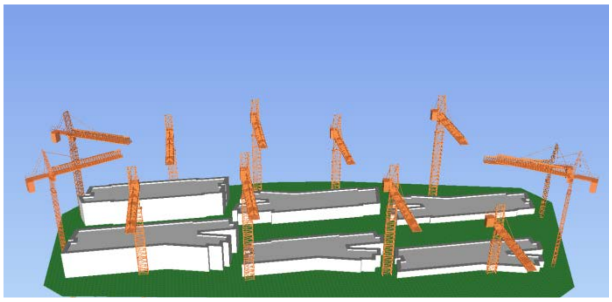

Figure 5. Tower cranes installation heights in stage one

Table 1. Accurate tower cranes installation heights in stage one

	A01	A02	B01	B02	C01	C02
Installation Height	58.8	50.4	58.8	50.4	58.8	39
	D01	D02	E01	E02	F01	F02
Installation Height	50.4	42	53.2	42	33.6	50.4

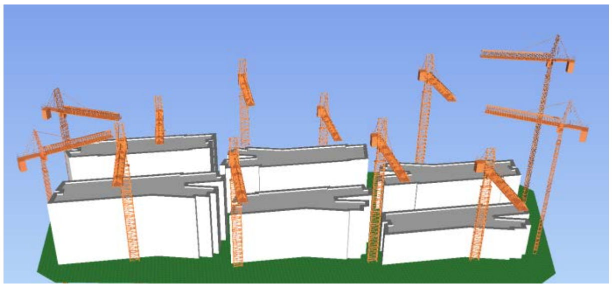

Figure 6. Tower cranes installation heights in stage two

Table 2. Accurate tower cranes installation heights in stage two

	A01	A02	B01	B02	C01	C02
Installation Height	70.2	58.8	85.2	58.8	85.2	95.8
	D01	D02	E01	E02	F01	F02
Installation Height	58.8	67.4	58.8	70.2	58.8	77.2

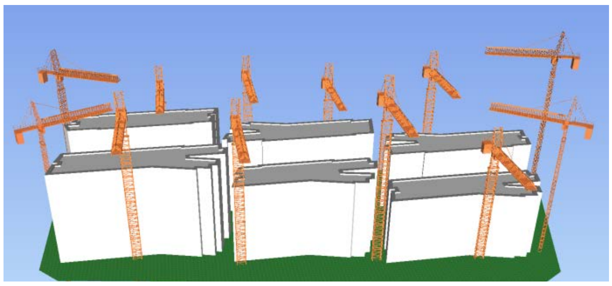

Figure 7. Tower cranes installation heights in stage three

Table 3. Accurate tower cranes installation heights in stage three

	A01	A02	B01	B02	C01	C02
Installation Height	95.4	77.2	85.2	74	85.2	95.8
	D01	D02	E01	E02	F01	F02
Installation Height	77.2	89.8	78.6	95.5	67.2	77.2

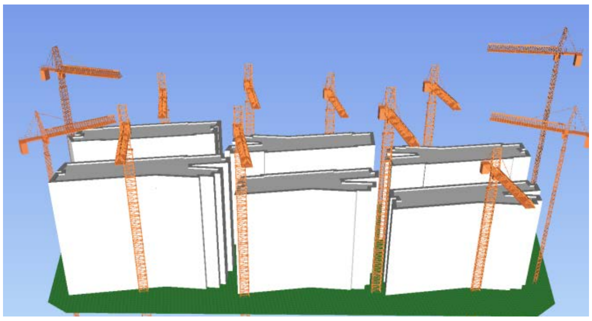

Figure 8. Tower cranes installation heights in stage four

Table 4. Accurate tower cranes installation heights in stage four

	A01	A02	B01	B02	C01	C02
Installation Height	117.8	99.6	107.6	96.4	107.6	131.8
	D01	D02	E01	E02	F01	F02
Installation Height	99.6	109.4	99.2	117.8	90.8	102.4

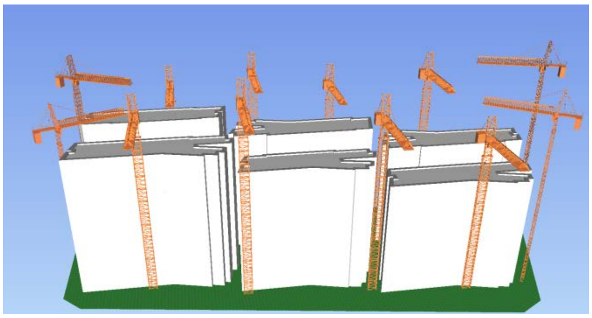

Figure 9. Tower cranes installation heights in stage five

Table 5. Accurate tower cranes installation heights in stage five

	A01	A02	B01	B02	C01	C02
Installation Height	123.4	108	118.8	107.6	118.8	131.8
	D01	D02	E01	E02	F01	F02
Installation Height	108	117.8	130	117.8	107.6	119.2

4 Conclusion

This paper has developed a well-defined approach, which integrates BIM and firefly algorithm to come up with an optimal tower crane layout for construction projects. The results show that: (1) less time is needed to create a tower crane layout scheme compare with traditional method, especially in multiple tower cranes layout; (2) the optimal tower crane layout scheme generated by the proposed method is better than the original scheme in less total material transportation cost and collisions; and (3) field workers can understand and perform the tower crane layout scheme easily and accurately due to its visualization and interaction.

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