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Optimization of crane setup location and servicing schedule for urgent material requests with non-homogeneous and non-fixed material supply

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ABSTRACT

Reducing hook movement distances could decrease crane operation times to deliver heavyweight materials in construction sites. Conventional scheduling methods include first-in-first-serve (FIFS), shortest-job-first (SJF), nearest-neighbor-first (NNF), and Traveling salesman problem (TSP). A new optimization model to optimize crane setup location, hook movement sequences and servicing schedules serving all supply and demand locations is proposed. Proposed model is able to model homogeneous and non-homogeneous material supply. Initial hook location can be given as input for optimization. Fixed material supply and demand location pairs are relaxed as model variables. Maximum crane lifting capacity is considered and multiple hook movement trips between material supply and demand locations are modeled if requested material weights exceed this maximum crane lifting capacity. Users may place "urgent" material demand requests and the proposed optimization model can optimize a servicing sequence to prioritize all urgent requests. The problem is formulated as a Binary-Mixed-Integer-Linear-Program (BMILP) which is solved by standard branch-and-bound techniques. Significant reduction in total operation time is achieved while comparing to other conventional scheduling strategies.

1. Introduction

Budget overrun is quite common in large-scale infrastructure construction projects. In 2014, McKinsey & Company, a global management consulting firm, revealed that large and complex projects generally take longer construction times to complete. Those construction projects that can be finished on schedule are exceptional cases [1]. In construction sites, cranes are installed to move heavy and bulky materials or structural components above ground surface [2]. Especially for high-rise building sites, cranes play important roles and their related activities are always planned along critical paths in a master construction program. Practical crane operations could be improved in two ways: optimizing crane layout patterns and planning physical crane motions [3]. Cranes are generally classified into mobile cranes and tower cranes. To promote automation in construction, many studies have been devoted to improve crane operations which are reviewed in the next literature review section.

In the present study, a new optimization method is proposed to optimize hook movements, their movement sequence and respective crane setup location to reach all material supply and demand locations for completing material demand requests. Without complex evaluations, work sequence might simply adopt first-in-first-serve (FIFS) approach in practice. However, it is possible to reduce total hook travel time and hook movement distance by optimizing the work sequence and crane setup location while serving all material demand requests. Users may also specify an initial hook location as model input to optimize hook movement sequences and paths. In the present formulation, 20 linear constraint sets are developed to outline the feasible solution space. Given pairs of material demand and supply locations would be relaxed as new model variables. Non-homogeneous and homogeneous material supplies are also modeled to simulate realistic construction site operations. Maximum lifting capacity of a crane is considered. Multiple hook movement trips (traveling repeatedly) between a pair of material supply and demand locations are modeled if a material demand request cannot be completed by a single hook movement trip due to exceeding the maximum (crane) lifting capacity. Urgent material demand requests could be placed by users and those urgent material request orders would be prioritized in the optimized work sequence. A complete hook movement route serving all material demand and supply locations and total operation times including hook movement, material loading and unloading times are optimized in the proposed formulation. The problem is formulated as a Binary-Mixed-Integer-Linear-Program (BMILP) and a standard branch-and-bound routine is applied to solve for optimal numerical solutions.

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2. Literature review

Tower cranes in construction sites are operated to move in a three-dimensional (3D: x-y-z) space. Intelligent devices were installed to assist daily operations. By recording movement paths through navigation systems, tower crane was enabled to operate in a semi-automatic mode for repetitive paths [4]. A laser-based 3D site measurement system (SMS) on RoboCrane enabled autonomous path planning and navigation [5]. With wireless video systems and radio frequency identifications (RFID), operational speed and work safety were improved [6]. With laser devices, encoders and accelerometers, a lifting-path tracking system for tower crane operations provided data records for refining movement paths [7].

In planning stages, efficiencies of employing tower cranes could be enhanced by (i) optimizing tower crane numbers, crane types and setup locations inside available site locations, (ii) simulating tower crane's operating paths to avoid overlapping and crash accidents, and (iii) optimizing work schedules and sequences to minimize hook movement distances and travel times of tower cranes. To set up multiple tower cranes in a construction site, overlapping area of tower crane groups should be minimized so as to avoid potential crashes [8]. Mathematical equations to estimate hook travel times were derived to measure practical efficiencies [8]. This classical model has been widely applied and optimized by different algorithms such as Genetic Algorithms [9], Mixed-Integer-Programming [10] and Particle Bee Algorithms [11]. Crane loading capacity and crane renting cost were added to enhance the optimization model [12].

To support different site activities and to cope with specific site conditions, selecting appropriate tower crane is also critical for successes of construction projects. Analytical Hierarchy Process (AHP) was applied to select tower crane as a multi-attribute decision making problem [13]. Some 27 intangible and qualitative "soft" factors were identified to influence the crane selection process [14]. Combining Genetic Algorithms and AHP in the selection process, tower crane specifications, project site conditions, project characteristics and costs of renting tower cranes were considered for selecting best tower cranes [15].

To promote smooth maneuvers and safe operations of tower cranes, hook movements of tower cranes were simulated. Through analyzing the hoisting mechanisms, tower cranes were modeled like a multi-degree-of-freedom robot and crane operation details were simulated and visualized [16,17,18]. To facilitate blind lifting and reduce accident risks, vision system [19], navigation system [20], quick collision detection algorithm [21] and path planning algorithm [22] were applied. A 3D visualization and simulation modules were integrated to model special crane operations [23]. To enhance visual effects of the simulation results, GIS and BIM platforms were combined to present the tower crane layout arrangement [24,25]. Operational safety of tower cranes was studied [26] and cumulative risks by combining individual risk factors for tower cranes were investigated [27,28,29].

For designing service schedules of cranes, hook movement times and their movement sequence should be considered. At container ports, work schedules of quay cranes for loading and unloading containers were to support the logistic chain in which start time and end time for every task needed to be optimized [30,31]. Minimizing total handling times or minimizing latest completion times for all jobs could be formulated using a NP-complete integer programming formulation [30,32]. Unidirectional schedules to avoid spatial crossing of cranes and other interference conditions should be implemented [33,34]. Optimization methods to solve this scheduling problem include Mixed-Integer-Linear-Programming [35–36], Genetic Algorithms [37–38] and problem specific solution heuristics [39,40]. For the Crane Service Sequencing Problems (CSSP), a Traveling Salesman Problem (TSP) approach has been applied to optimize the sequence of a crane erection schedule to reach all material demand and supply locations by minimizing travel times [3,41]. Challenges were to avoid subtour networks. Solution heuristics including nearest neighbor first (NNF) and shortest job first (SJF) methods were applied to solve this sequencing problem [42]. NNF and SJF will be applied to solve the present case study problem and their implementation details will be explained in the numerical example section. Nearest neighbor first algorithm was also applied to solve other large-scale path finding problems [43]. A parallel repetitive nearest neighbor algorithm was developed for solving a symmetric traveling salesman problem [44]. Instead of minimizing total hook movement times, another approach was to balance all waiting times for all received orders using game theory [45]. When deadline information is available or some specific tasks must follow certain sequential order patterns, Earliest Deadline First (EDF) scheduling method could be applied [46]. Sequencing and scheduling problem could also be optimized by metaheuristics adopting changeover time as objective function for minimization [47].

In the present study, both homogeneous and non-homogeneous material supplies at material supply locations depending on users' inputs are modeled. Another enhancement is to model the maximum lifting capacity of a crane as design considerations. When requested material quantity is exceeding a crane lifting capacity, multiple trip movements between pairs of material supply and demand locations should be modeled. More importantly, initial hook location of a crane is relaxed as a model input for optimizing the entire hook movement schedule. Special requests for urgent material needs at material demand locations are accepted as new model inputs and those urgent requests will be prioritized in the optimized work sequence. With these enhancements, more complex problems could be solved.

3. Notations

In the proposed formulation, following symbols and notations are used.

x	Position along x-axis;
y	Position along y-axis;
z	Position along z-axis;
i	Material supply location i;
I	Total number of material supply locations within a site area;
j	Material demand location j;
o	Material demand location o;
J	Total number of demand locations within a site area;
k	Available location k for setting up a crane;
K	Total number of available locations for setting up a crane;
u	Material type u;
U	Total number of material types;
r	Material demand request r;
s	Sequence s;
s'	Total number of prioritized work sequences;
R	Total number of material demand requests;
$\hat{R}$	A set containing all material demand requests $\hat{R} = \{1, 2, ..., R\}$
R'	A subset of $\hat{R}$ containing urgent material demand requests only $R' \subset \hat{R} = \{1, 2, ..., R\}$
S'	A set containing prioritized work sequence $\{1, 2, \ldots, s'\}$
Cr_k^x, Cr_k^y, Cr_k^z	Coordinates of a crane setup location k;
D_j^x, D_j^y, D_j^z	Coordinates of a material demand location j;
S_i^x, S_i^y, S_i^z	Coordinates of a material supply location i;
P_k^x, P_k^y, P_k^z	Coordinates of an initial hook location of a crane being set up at location k;
V_h^k	Hoisting velocity of a hook of a crane being set up at location k (m/min);
V_ω^k	Slewing velocity of a jib of a crane being set up at location k (rad/min);
V_a^k	Hook movement velocity along a jib of a crane being set up at location k (m/min);
h	Minimum hoisting height above material supply and demand

locations;

$l_{i,\, j}$ Distance between material supply location i and material demand location j;

$\rho(S_i, Cr_k)$ Distance between material supply location i and crane setup location k;

$\rho(D_j, Cr_k)$ Distance between material demand location j and crane setup location k;

$\rho(P_k, Cr_k)$ Distance between initial hook location P_k and crane setup location k;

${T_{r(i,j)}}^k$ Hook movement time along a jib of a crane being set up at location k from material supply location i to material demand location j;

${T_{\omega(i,j)}}^k$ Tangent hook movement time of a crane being set up at location k from material supply location i to material demand location j;

${T_{h(i,j)}}^k$ Horizontal hook movement time of a crane being set up at location k from material supply location i to material demand location j;

${T_{v(i,j)}}^k$ Vertical hook movement time of a crane being set up at location k from material supply location i to material demand location j;

${T_{i,\, j}}^k$ Hook movement time of a crane being set up at location k between material supply location i and material demand location j;

${PT_{r(i)}}^k$ Hook movement time along a jib of a crane being set up at location k from initial hook location to material supply location i;

${PT_{\omega(i)}}^k$ Tangent movement time of a hook of a crane being set up at location k from initial hook location to material supply location i;

${PT_{h(i)}}^k$ Horizontal hook movement time of a crane being set up at location k from initial hook location to material supply location i;

${PT_{v(i)}}^k$ Vertical hook movement time of a crane being set up at location k from initial hook location to material supply location i;

PT_i^k Hook movement time of a crane being set up at location k from initial hook location to material supply location i;

α Degree of coordination of hook movement in radial and tangential directions in horizontal plane ranging between '0.0' and '1.0' (where '0.0' stands for full simultaneous movement and '1.0' for full consecutive movement);

β Degree of coordination of hook movement in vertical and horizontal planes ranging between '0.0' and '1.0' (where '0.0' stands for full simultaneous movement and '1.0' for full consecutive moment);

γ_k Degree of control difficulty for hook movement when crane sets up at location k ranging between '1.0' and '10.0' (where '1.0' represents operation in normal condition and '10.0' in the most difficult situation);

μ_i^k Degree of obstacle blocking hook movement from an initial hook location to the material supply location i when crane sets up at location k ranging between '1.0' and '10.0' (where '1.0' represents normal operation without obstacle and '10.0' represents difficult operation with most numbers of obstacles);

${\mu'_{i,\, j}}^k$ Degree of obstacle blocking hook movement from a material supply location i to another material demand location j when crane sets up at location k ranging between '1.0' and '10.0' (where '1.0' represents normal operation without obstacle and '10.0' represents difficult operation with most numbers of obstacles);

$q_{r,\, j,\, u}$ Demand quantity of material type u in request r at a material demand location j;

$\eta_{i,\, u}$ A binary parameter '$\eta_{i,\, u} = 1$' meaning that material u is available at material supply location 'i' and '$\eta_{i,\, u} = 0$' if not;

λ_k A binary variable '$\lambda_k = 1$' indicating that a crane is set up at a location k but '$\lambda_k = 0$' means that the crane is not setting up at location k;

$\rho_{r,\, j,\, u}$ A binary parameter '$\rho_{r,\, j,\, u} = 1$' meaning that a material demand request r demanding material type u from a material demand location j exists but '$\rho_{r,\, j,\, u} = 0$' means that the request does not exist;

$x_{s,\, r}$ A binary decision variable '$x_{s,\, r} = 1$' means that a material demand request r is to be arranged in a work sequence number s but '$x_{s,\, r} = 0$ if not;

$y_{s,\, i,\, j,\, u,\, k}$ A binary decision variable '$y_{s,\, i,\, j,\, u,\, k} = 1$' means that a hook of a crane setting up at location k travels from material supply location i to material demand location j in a work sequence s carrying material type u or '$y_{s,\, i,\, j,\, u,\, k} = 0$, otherwise.

$z_{s,\, j,\, i,\, k}$ A binary decision variable '$z_{s,\, j,\, i,\, k} = 1$' means that a hook of a crane setting up at location k will travel from material demand location j to material supply location i in a work sequence s;

$\chi_{s,\, j,\, k}$ A binary decision variable '$\chi_{s,\, j,\, k} = 1$' means that a crane setting up at location k will travel to material demand location j in a work sequence s;

$\psi_{i,\, k}$ A binary decision variable '$\psi_{i,\, k} = 1$' means that a hook of a crane setting up at location k will travel to material supply location i in the first work sequence;

$\delta_{s,\, r,\, i,\, j,\, u,\, k}$ An auxiliary binary variable '$\delta_{s,\, r,\, i,\, j,\, u,\, k} = 1$' means that a hook of a crane setting up at location k will travel from material supply location i to material demand location j carrying material u given in a material demand request r and is arranged in a work sequence s and '$\delta_{s,\, r,\, i,\, j,\, u,\, k} = 0$', otherwise;

$\theta_{i,\, j,\, u}$ A set of given predetermined parameters for pairing material supply location i and material demand location j for material type u;

$f_{r,\, j,\, u}$ An integer variable specifying the total required number of trip(s) completing a material demand request r depending on the quantity demanded for material u at material demand location j;

π Maximum lifting capacity of a crane;

$T_{Loading}$ Time for loading material onto a hook at material supply location;

$T_{Unloading}$ Time for unloading material from a hook at material demand location;

ST Hook movement time from an arbitrary initial hook location of a crane to the first material supply location (preparing to complete the first work sequence) and the material loading time;

SDT Total operation time including hook movement times from all material supply locations to all material demand locations completing all material demand requests and the material unloading times at material demand locations;

DST Total operation time including hook movement times from all demand locations to all supply locations completing all material demand requests and the material loading time at material supply locations;

FT Total operation time for extra hook movement between material supply and demand locations including material loading and unloading times when material demand quantity exceeds the crane lifting capacity π;

ε Arbitrary large numerical figure.

4. Problem formulation

4.1. Hook movement time of a crane

Hook movements involve radial (along the jib), tangent (rotation of

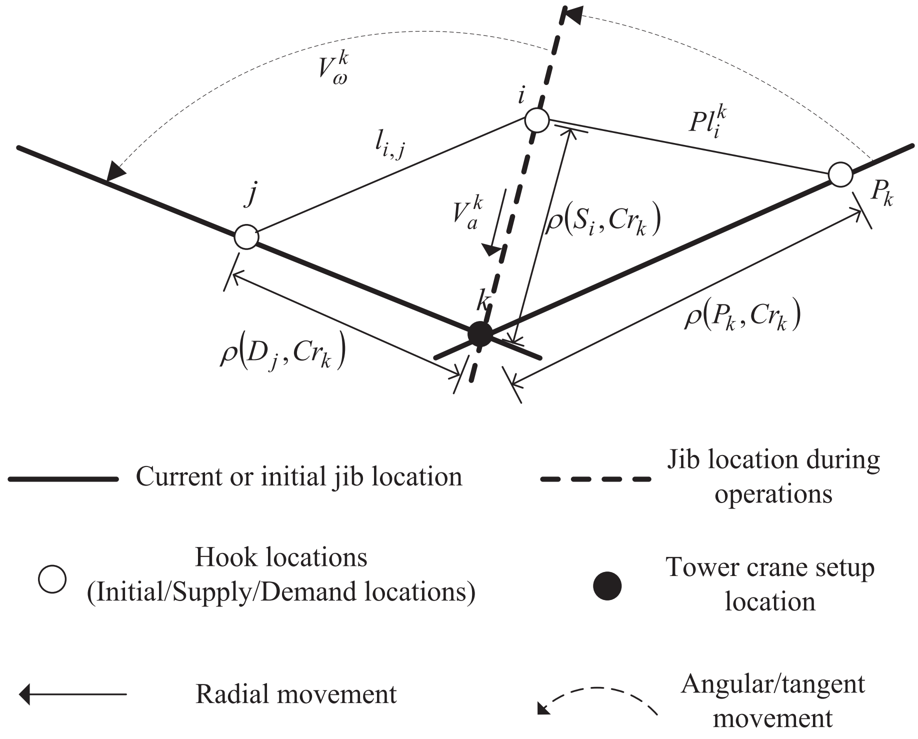

Fig. 1. General hook movement path of a crane.

crane), and vertical (up and down of hook) movement directions. Mathematical equations were set up to coordinate these individual movements to estimate hook movement times. Fig. 1 describes a general hook movement path of a crane among three locations marked with "" including an initial hook location P_k, a material supply location i and a material demand location j. Eqs. (1)–(5) calculate linear movement distances among material demand, material supply, initial hook and crane setup locations.

$$Pl_i^k = \sqrt{(S_i^x - P_k^x)^2 + (S_i^y - P_k^y)^2} \quad (1)$$

$$l_{i,j} = \sqrt{(S_i^x - D_j^x)^2 + (S_i^y - D_j^y)^2} \quad (2)$$

$$\rho(P_k, Cr_k) = \sqrt{(P_k^x - Cr_k^x)^2 + (P_k^y - Cr_k^y)^2} \quad (3)$$

$$\rho(S_i, Cr_k) = \sqrt{(S_i^x - Cr_k^x)^2 + (S_i^y - Cr_k^y)^2} \quad (4)$$

$$\rho(D_j, Cr_k) = \sqrt{(D_j^x - Cr_k^x)^2 + (D_j^y - Cr_k^y)^2} \quad (5)$$

Based on distances $\rho(S_i, Cr_k)$ and $\rho(P_k, Cr_k)$, hook movement time in radial direction from initial hook location P_k to material supply location i, $PT_{r(i)}{}^k$, can be calculated by Eq. (6) where $V_a{}^k$ is the radial velocity. Eq. (7) is derived based on cosine law. Movement time in tangent direction, $PT_{\omega(i)}{}^k$, can be calculated based on velocity $V_\omega{}^k$ for rotating a crane. Similarly, movement times from material supply location i to material demand location j in the two movement directions, $T_{r(i,j)}{}^k$ and $T_{\omega(i,j)}{}^k$, can be calculated similarly by Eqs. (8) and (9), respectively.

$$PT_{r(i)}^k = \frac{|\rho(P_k, Cr_k) - \rho(S_i, Cr_k)|}{V_a^k} \quad (6)$$

$$PT_{\omega(i)}^k = \frac{1}{V_\omega^k} \cdot \arccos\left[(-1) \cdot \frac{(Pl_i{}^k)^2 - \rho(S_i, Cr_k)^2 - \rho(P_k, Cr_k)^2}{2 \cdot \rho(S_i, Cr_k) \cdot \rho(P_k, Cr_k)}\right], [0 \leq \arccos(\theta) \leq \pi] \quad (7)$$

$$T_{r(i,j)}^k = \frac{|\rho(S_i, Cr_k) - \rho(D_j, Cr_k)|}{V_a^k} \quad (8)$$

$$T_{\omega(i,j)}^k = \frac{1}{V_\omega^k} \cdot \arccos\left[(-1) \cdot \frac{(l_{i,j})^2 - \rho(S_i, Cr_k)^2 - \rho(D_j, Cr_k)^2}{2 \cdot \rho(S_i, Cr_k) \cdot \rho(D_j, Cr_k)}\right], [0 \leq \arccos(\theta) \leq \pi] \quad (9)$$

To effectively coordinate hook movements in radial and tangent directions, a continuous parameter α is set numerically between 0.0 and 1.0 in Eqs. (10) and (11) to model the control skill level of a crane operator in which a larger α represents a non-skillful operator who tends to separate the radial and tangent movements without control coordination.

$$PT_{h(i)}^k = \max(PT_{r(i)}^k, PT_{\omega(i)}^k) + \alpha \cdot \min(PT_{r(i)}^k, PT_{\omega(i)}^k) \quad (10)$$

$$T_{h(i,j)}^k = \max(T_{r(i,j)}^k, T_{\omega(i,j)}^k) + \alpha \cdot \min(T_{r(i,j)}^k, T_{\omega(i,j)}^k) \quad (11)$$

Movement time in the vertical direction can be obtained by dividing the height difference between material supply location i and material demand location j by a vertical velocity $V_h{}^k$. A parameter h can be added in Eqs. (12) and (13) to model a minimum hoisting height for practical operations. Fig. 2 illustrates hook movement paths in vertical direction from an initial hook location (left-most hook) to a material supply location (middle hook) and then from that material supply location to another material demand location (right-most hook). Vertical hook movement distance h is required so that potential collisions to supporting structural members (platforms to support materials) can be prevented [20,32,33].

$$PT_{v(i)}^k = \frac{|(P_k^z - S_i^z) + 2 \cdot h|}{V_h^k} \quad (12)$$

$$T_{v(i,j)}^k = \frac{|(S_i^z - D_j^z) + 2 \cdot h|}{V_h^k} \quad (13)$$

Movement times from an initial hook location to a material supply location, $PT_i{}^k$, and from the material supply location to another material demand location, $T_{i,j}{}^k$, by a crane can be calculated by Eqs. (14) and (15), respectively. A continuous numerical parameter β between 0.0 and 1.0 could be assigned to specify the coordination level a crane movement in vertical and horizontal directions. A larger β reflects a

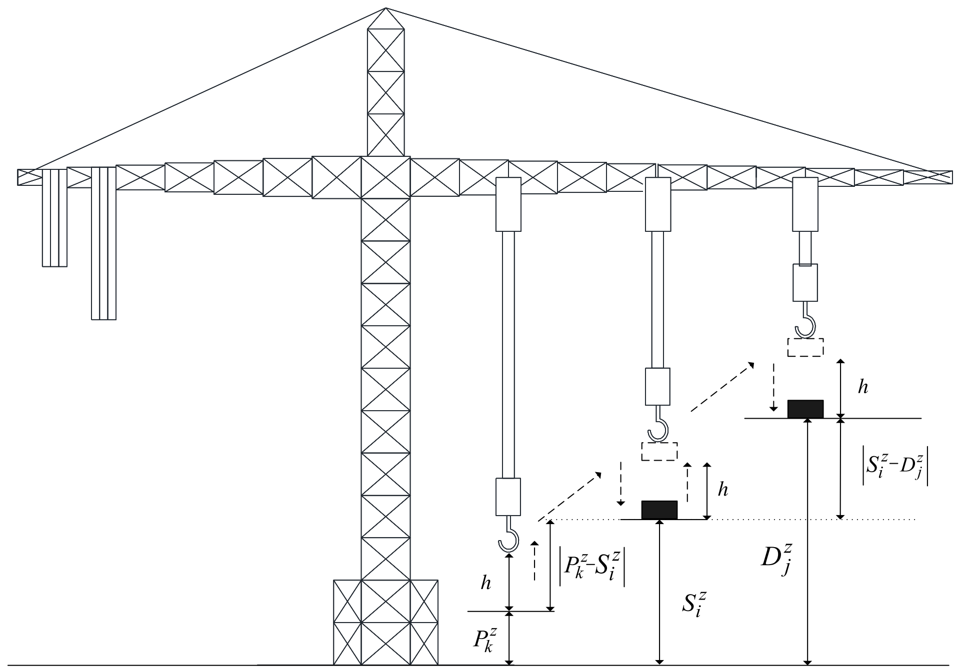

Fig. 2. Vertical hook movement routes of a tower crane

lower skill level of an operator to control a crane and coordination would be reduced while moving along the vertical and horizontal directions. Another user input parameter γ_k is set to model the level of difficulty in operating a crane due to different site conditions when a crane is set up at a location k [12]. Longer operation time is expected at a difficult crane setup location k. To simulate the existences of obstacles blocking the direct crane movements along the Euclidean distances, longer movement paths and longer hook movement times should be required. Two more coefficients, μ_i^k and $\mu'^{k}_{i,j}$, are introduced to denote the degree of obstacles between 1.0 (without obstacles) and 10.0 (with most numbers of obstacles delaying the hook movements), respectively, from initial hook location to material supply location i and from material supply location i to material demand location j while crane sets up at location k.

$$PT_i^k = \mu_i^k\{\gamma_k[\max(PT_{h(i)}^k, PT_{v(i)}^k) + \beta\cdot\min(PT_{h(i)}^k, PT_{v(i)}^k)]\} \tag{14}$$

$$T_{i,j}^k = \mu'^{k}_{i,j}\{\gamma_k[\max(T_{h(i,j)}^k, T_{v(i,j)}^k) + \beta\cdot\min(T_{h(i,j)}^k, T_{v(i,j)}^k)]\} \tag{15}$$

Based on Eqs. (1)–(15), hook movement times of a crane being set up at a location k can be evaluated.

4.2. Ordering received material demand requests in work sequence

Binary variable $x_{s,r}$ is defined to represent the schedule of a material demand request r ($\forall r \in \{1,2,\ldots,R\}$) in a work sequence s ($\forall s \in \{1,2,\ldots,R\}$). $x_{s,r}$ = '1' means that material demand request r is scheduled in a work sequence s; otherwise, $x_{s,r}$ = '0'. To ensure each material demand request appears exactly once in a work sequence, two linear constraint sets Eqs. (16) and (17) are required. In Eq. (16), for each material request $r \in \{1,2,\ldots,R\}$ where R is the total number of material demand requests, it should appear exactly once in the optimized work sequence without omission or duplication. Similarly, in Eq. (17), for each sequence $s \in \{1,2,\ldots,R\}$, exactly one material demand request is assigned.

$$\sum_{s=1}^{R} x_{s,r} = 1, \quad \forall\ r \in \{1,2,\ldots,R\} \tag{16}$$

$$\sum_{r=1}^{R} x_{s,r} = 1, \quad \forall\ s \in \{1,2,\ldots,R\} \tag{17}$$

4.3. Prioritizing urgent material demand requests

In practice, material demand requests at material demand locations may have different urgency levels to be served. In the present formulation, users can input 'urgent' material demand requests. These requests should be prioritized in the optimized work sequence. In the present formulation, we define a subset $R' \subset \widehat{R}$ to be the urgent request (s) where $\widehat{R} = \{1,2,\ldots,R\}$. Likely, these urgent request(s) should be prioritized in the work sequence starting from s = 1, 2, …, s' where $s' = |R'|$. Mathematically, we have Eqs. (18) and (19) to ensure that all urgent material demand requests can be prioritized in the optimized work sequence. Orders of those urgent requests in the work sequence are still model variables to be determined in the optimization process.

$$\sum_{s=1}^{s'} x_{s,r} = 1, \quad \forall\ r \in R' \tag{18}$$

$$\sum_{r\in R'} x_{s,r} = 1, \quad \forall\ s \in \{1,2,\ldots,s'\} \tag{19}$$

4.4. Hook movements from material supply to demand locations

To complete a single material demand request by a crane model involves two steps: (1) hook moves to a material supply location and then (2) hook moves from that material supply location to the requested material demand location. These two steps (1) and (2) are illustrated graphically (in a plan view) in Fig. 3. After unloading materials at demand locations, hook movement will repeat these 2 steps until all material demand requests are completed. In the proposed formulation, lifting capacity of a crane is also considered as an operational constraint. If the requested material quantity exceeds the maximum lifting capacity of a crane, then multiple movement trips between the material supply and demand locations are required to be modeled.

A binary variable $y_{s,\ i,\ j,\ u,\ k}$ and three other binary parameters $\eta_{i,\ u}$, λ_k and $\rho_{r,\ j,\ u}$ are defined and used in this section. When $y_{s,\ i,\ j,\ u,\ k}$ equals '1', there exists a material demand request at material demand location

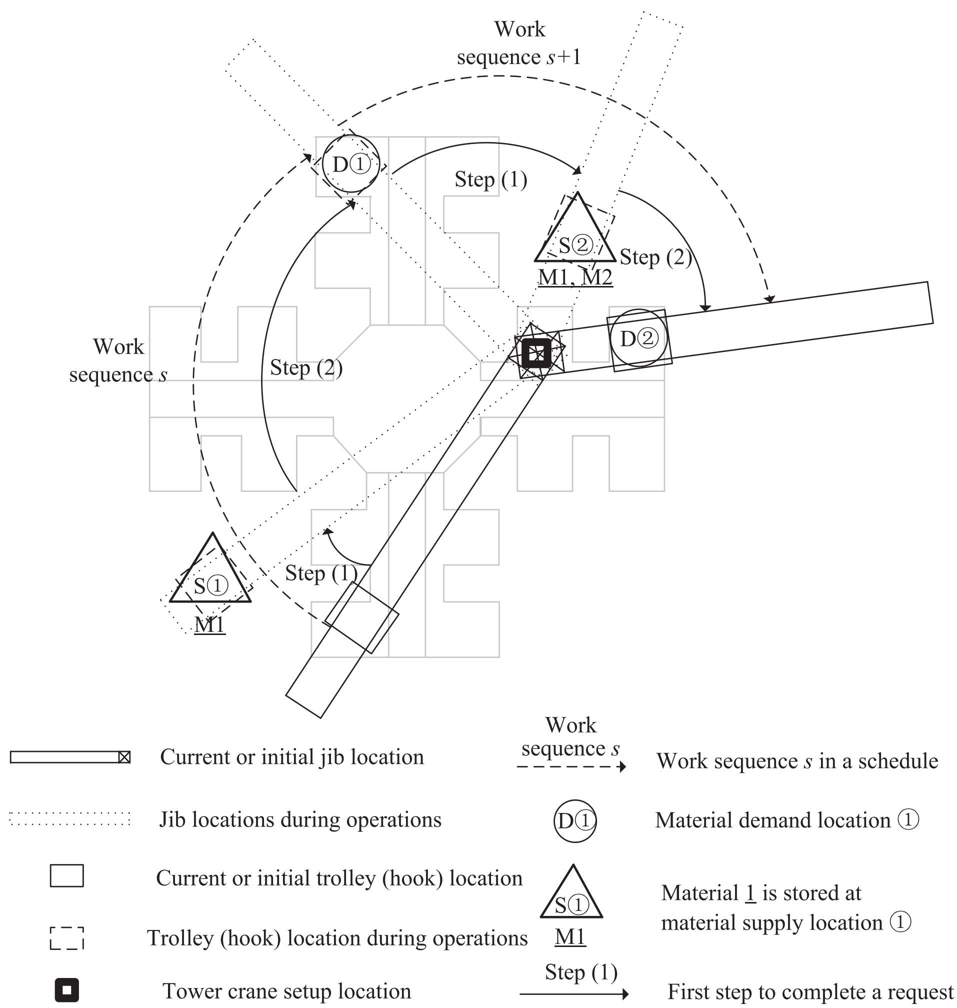

Fig. 3. Jib and hook movements to complete two consecutive material demand requests.

j for material type u from material supply location i being arranged in work sequence s serving by a crane setting up at location k. In the optimization process, only one material supply location should be selected for severing a material demand request. For these, two linear constraint sets in Eqs. (20) and (21) are introduced. A parameter $\lambda_k = 1$ if a crane sets up at location k. Another parameter $\rho_{r,\,j,\,u} = 1$ if material type u is requested at material demand location j in material demand request r. If the binary variable $x_{s,\,r} = 1$ such that a material demand request r is scheduled in a work sequence s, all these conditions will then force $\sum_{i=1}^{I} y_{s,i,j,u,k} \geq 1$ implying that at least one material supply location supplying material type u must be selected to serve the material demand request at location j in Eq. (20).

$$3 - \rho_{r,j,u} - x_{s,r} - \lambda_k \geq 1 - \sum_{i=1}^{I} y_{s,i,j,u,k}$$

$$\forall\, r \in \{1, 2, .., R\};\ \forall\, s \in \{1, 2, .., R\};\ \forall\, j \in \{1, 2, ..., J\};\ \forall\, u \in \{1, 2, ..., U\};\ \forall\, k \in \{1, 2, ..., K\} \quad (20)$$

To avoid a material demand request being served by multiple material supply locations, constraint set Eq. (21) is also introduced.

$$\sum_{i=1}^{I} \sum_{u=1}^{U} y_{s,i,j,u,k} \leq 1, \quad \forall\, s \in \{1, 2, .., R\};\ \forall\, j \in \{1, 2, ..., J\};\ \forall\, k \in \{1, 2, ..., K\} \quad (21)$$

A binary variable $\eta_{i,\,u} = 1$ if material type u is available at material supply location i or $\eta_{i,\,u} = 0$ if unavailable. Subsequently, hook cannot collect material type u at material supply location i. Thus, $y_{s,\,i,\,j,\,u,\,k}$ should be '0' that is restricted by constraint set Eq. (22). Similarly, if a crane is not set up at location k, respective hook movements should also be prohibited by constraint set in Eq. (23).

$$\eta_{i,u} \geq y_{s,i,j,u,k}, \quad \forall\, s \in \{1, 2, .., R\};\ \forall\, i \in \{1, 2, ..., I\}\ \forall\, j \in \{1, 2, ..., J\};\ \forall\, u \in \{1, 2, ..., U\};\ \forall\, k \in \{1, 2, ..., K\} \quad (22)$$

$$\lambda_k \geq y_{s,i,j,u,k}, \quad \forall\, s \in \{1, 2, .., R\};\ \forall\, i \in \{1, 2, ..., I\}\ \forall\, j \in \{1, 2, ..., J\};\ \forall\, u \in \{1, 2, ..., U\};\ \forall\, k \in \{1, 2, ..., K\} \quad (23)$$

4.5. Hook movement from (last) material demand location to next material supply location according to material demand requests

Detailed hook movements from last material demand location to next material supply location connecting two consecutive material demand requests are modeled in the present study. While designing the optimal work schedules, such hook movement times are critical and should be optimized. Step (1) movement given in Fig. 3 is from material demand location D① to material supply location S② in a work sequence $s + 1$. Step (1) hook movements from last material demand location to next material supply location involve two different material demand requests that are scheduled in consecutive work sequences s and $s + 1$. Mathematically, when a binary variable $x_{s,\,r}$ and the two binary parameters $\rho_{r,\,j,\,u}$ and λ_k are all '1' in constraint set Eq. (24), then another binary $\chi_{s,\,j,\,k}$ must also be '1' indicating that a hook of a crane setting up at a location k will travel to a material demand location j in a work sequence s.

$$3 - x_{s,r} - \rho_{r,j,u} - \lambda_k \geq 1 - \chi_{s,j,k}, \quad \forall s \in \{1,2,..,R\}; \forall r \in \{1,2,..,R\}; \forall j \in \{1,2,...,J\}; \forall u \in \{1,2,...,U\}; \forall k \in \{1,2,...,K\} \tag{24}$$

For binary variable $z_{s,j,i,k} = 1$, a hook of a crane setting up at a location k travels from last material demand location j (previous material demand request is completed in the work sequence s) to next material supply location i to collect the demanded material for the next request being scheduled in the work sequence $s + 1$. From Fig. 3, $\chi_{s,j,k} = 1$ indicates that a hook of a crane setting up at a location k travels to a material demand location $j(=1)$ in a work sequence s before another Step (1) movement commences in a work sequence $s + 1$. Denoting by $y_{s+1,i,o,u,k} = 1$, Step (2) movement in a work sequence $s + 1$ starts at next material supply location $i(=2)$ where o is the material demand location, u is the material type demanded and k is the crane setup location. When both variables $\chi_{s,j,k} = 1$ and $y_{s+1,i,o,u,k} = 1$, $z_{s+1,j,i,k}$ is then forced to be "1" by constraint set in Eq. (25). Hook movement is then modeled connecting the last material demand and next material supply locations across two work sequences s and $s + 1$ smoothly.

$$2 - \chi_{s,j,k} - y_{s+1,i,o,u,k} \geq 1 - z_{s+1,j,i,k}, \quad \forall s \in \{1,2,..,R-1\}; \forall j \in \{1,2,...,J\}; \forall o \in \{1,2,...,J\}; \forall i \in \{1,2,...,I\}; \forall u \in \{1,2,...,U\}; \forall k \in \{1,2,...,K\} \tag{25}$$

To ensure that every single material demand request is not served by more than one material supply location, Eq. (26) is required to restrict all Step (1) movements in all work sequences.

$$\sum_{i=1}^{I} z_{s,j,i,k} \leq 1, \quad \forall s \in \{1,2,..,R\}; \forall j \in \{1,2,...,J\}; \forall i \in \{1,2,...,I\}; \forall k \in \{1,2,...,K\} \tag{26}$$

4.6. Multiple movement trips between pairs of material supply and demand locations due to exceeding lifting capacity of a crane in a material demand request

When actual material demand quantities in the demand requests exceed the lifting capacity of a crane, a single trip of the hook movement cannot complete the whole material demand request and multiple trips from the material supply location to the material demand location should be arranged. To model the existence of such multiple movement trips, an auxiliary binary variable $\delta_{s,r,i,j,u,k}$ is defined which is governed by five linear constraint sets in Eqs. (27)–(31). When a binary variable $x_{s,r}$ and two parameters $\rho_{r,j,u}$ and λ_k all equal to '1', then constraint set Eq. (27) ensures $\sum_{i=1}^{I} \delta_{s,r,i,j,u,k} \geq 1$. At least one material supply location i is selected to supply material type u to the demand location j for the material demand request r being served by a crane setting up at location k and scheduled in the work sequence s.

$$3 - x_{s,r} - \rho_{r,j,u} - \lambda_k \geq 1 - \sum_{i=1}^{I} \delta_{s,r,i,j,u,k}, \quad \forall s \in \{1,2,..,R\}; \forall r \in \{1,2,..,R\}; \forall j \in \{1,2,...,J\}; \forall u \in \{1,2,...,U\}; \forall k \in \{1,2,...,K\} \tag{27}$$

Constraint set in Eq. (28) is further introduced to ensure that no more than one material supply location of material type u is being selected for crane operations to complete a material demand request.

$$\sum_{i=1}^{I} \sum_{u=1}^{U} \delta_{s,r,i,j,u,k} \leq 1, \quad \forall s \in \{1,2,..,R\}; \forall r \in \{1,2,..,R\}; \forall j \in \{1,2,...,J\}; \forall k \in \{1,2,...,K\} \tag{28}$$

In constraint sets Eqs. (29)–(31), if any one of the following binary parameters $\rho_{r,j,u}$, $\eta_{i,u}$ or λ_k equal '0', then multiple hook movement trip becomes unnecessary and $\delta_{s,r,i,j,u,k} = 0$ is required.

$$\rho_{r,j,u} \geq \delta_{s,r,i,j,u,k}, \quad \forall s \in \{1,2,..,R\}; \forall r \in \{1,2,..,R\}; \forall i \in \{1,2,...,I\}; \forall j \in \{1,2,...,J\}; \forall u \in \{1,2,...,U\}; \forall k \in \{1,2,...,K\} \tag{29}$$

$$\eta_{i,u} \geq \delta_{s,r,i,j,u,k}, \quad \forall s \in \{1,2,..,R\}; \forall r \in \{1,2,..,R\}; \forall i \in \{1,2,...,I\}; \forall j \in \{1,2,...,J\}; \forall u \in \{1,2,...,U\}; \forall k \in \{1,2,...,K\} \tag{30}$$

$$\lambda_k \geq \delta_{s,r,i,j,u,k}, \quad \forall s \in \{1,2,..,R\}; \forall r \in \{1,2,..,R\}; \forall i \in \{1,2,...,I\}; \forall j \in \{1,2,...,J\}; \forall u \in \{1,2,...,U\}; \forall k \in \{1,2,...,K\} \tag{31}$$

4.7. Number of multiple hook movement trips required for a pair of material supply and demand locations

In Eq. (32), a constant parameter π specifies the lifting capacity of a crane and $q_{r,j,u}$ is the quantity demanded for material type u at material demand location j. Mathematically, a symbol $\lceil\rceil$ is to round up a numerical value calculated by a given mathematical function (inside) to its nearest integer. For example, if π is "30" units and $q_{r,j,u}$ is "50" units then $\frac{q_{r,j,u}}{\pi}$ is "1.667" and $\left\lceil \frac{q_{r,j,u}}{\pi} \right\rceil$ converts "1.667" to an integral number '2'. Material demand request r demanding material type u at material demand location j needs to travel exactly 2 times from the material supply location to the material demand location.

$$f_{r,j,u} = \left\lceil \frac{q_{r,j,u}}{\pi} \right\rceil, \quad \forall r \in \{1,2,..,R\}; \forall j \in \{1,2,...,J\}; \forall u \in \{1,2,...,U\} \tag{32}$$

In constraint set (33), if $f_{r,j,u}$ is '0' whenever material demand request does not exist, then $\delta_{s,r,i,j,u,k}$ must be forced to be '0' which means that multiple hook movement trip is not required (where ε is an arbitrary large integer).

$$\varepsilon \cdot \delta_{s,r,i,j,u,k} \geq f_{r,j,u} \geq \delta_{s,r,i,j,u,k}, \quad \forall s \in \{1,2,..,R\}; \forall r \in \{1,2,..,R\}; \forall i \in \{1,2,...,I\}; \forall j \in \{1,2,...,J\}; \forall u \in \{1,2,...,U\}; \forall k \in \{1,2,...,K\} \tag{33}$$

4.8. Initialization of the hook movement for the first material demand request

By optimizing the first material supply location in a work sequence, the hook movement time from an arbitrary initial hook location to the first material supply location can be determined. A specific binary variable $\psi_{i,k}$ is introduced to represent whether the hook of a crane setting up at location k will travel to material supply location i in the "first" work sequence as initialization. Constraint set Eq. (34) is required that is only effective for the first hook movement of the optimized work sequence $s = 1$. If $z_{s=1,j,i,u,k}$ equals "1", then the binary variable $\psi_{i,k}$ is "1" implying that the hook will travel to the first material supply location i to initiate the entire crane operation process.

$$1 - z_{s=1,j,i,k} \geq 1 - \psi_{i,k}, \quad \forall j \in \{1,2,...,J\}; \forall i \in \{1,2,...,I\}; \forall k \in \{1,2,...,K\} \tag{34}$$

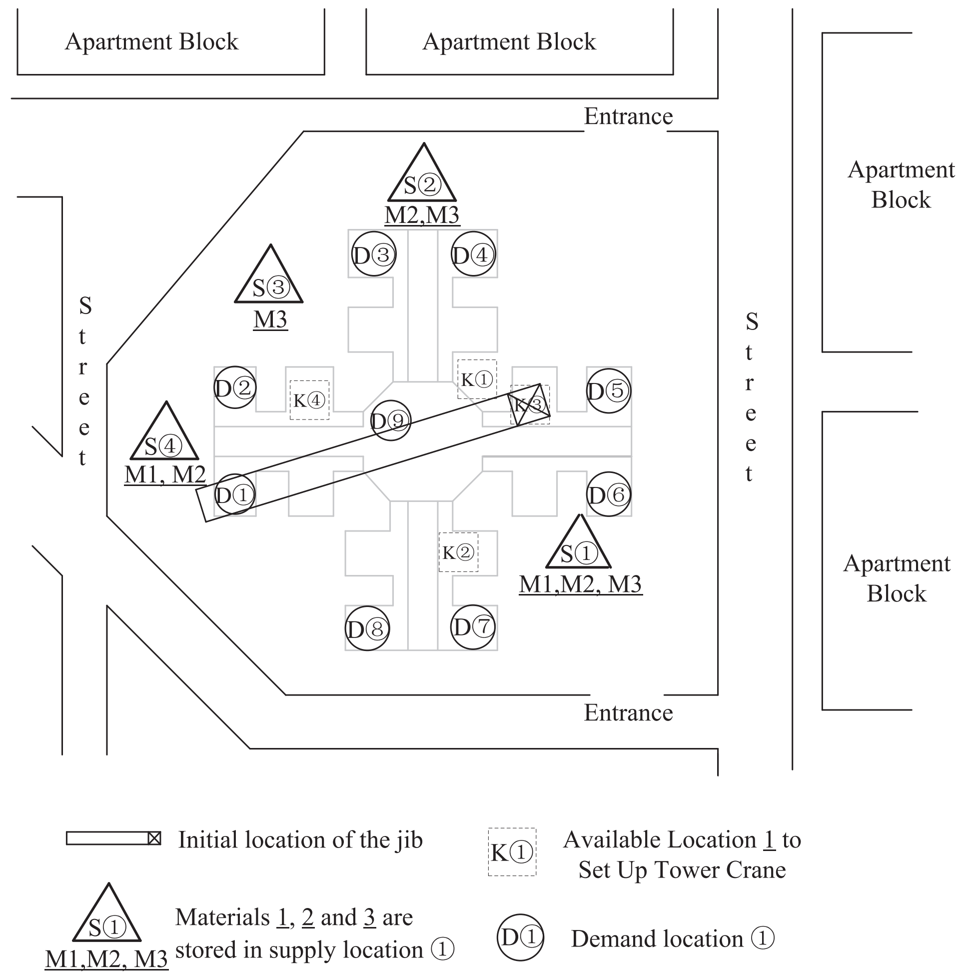

Fig. 4. Settings of a building construction site.

4.9. Predetermined pairs of material supply and demand locations (optional)

To predetermine a specific supply location to serve a demand location, a set of given binary parameters $\theta_{i,j,u}$ is introduced in constraint set (35). When $\theta_{i,j,u}$ equals '1', it represents that material demand location j for material type u can only be served by material supply location i. If $\theta_{i,j,u}$ equals '0', then $y_{s,i,j,u,k}$ must be '0' which means that material u from supply location i must not be transported to demand location j in sequence s by a crane setting up at location k.

$$\theta_{i,j,u} \geq y_{s,i,j,u,k}, \quad \forall\, s \in \{1,2,..,R\};\ \forall\, i \in \{1,2,...,I\};\ \forall\, j \in \{1,2,...,J\};\ \forall\, u \in \{1,2,...,U\};\ \forall\, k \in \{1,2,...,K\} \tag{35}$$

4.10. Objective function for optimization

Objective function in Eq. (40) is derived to minimize total hook movement and operation times of a crane to complete all material demand requests. Hook movement and operation times are composed by four components (i)–(iv) as follows. (i) Hook movement time from an arbitrary initial hook location to the first material supply location according to the material demand requests which is denoted by ST. With inputs of the initial hook location by users and the first material supply location from $\psi_{i,k}$, hook movement time between these two locations, PT_i^k, can be calculated by Eq. (14). Hook movement and crane operation time ST can be evaluated by Eq. (36). (ii) Sub-total of hook movement times only from material supply locations to material demand locations for all material demand requests in the optimized work sequence plus their respective crane operation times, SDT, can be evaluated by Eq. (37). (iii) Hook movement times only from material demand locations to material supply locations for all material demand requests together with their crane operation times denoted by DST in the optimized work sequence is calculated by Eq. (38). (iv) Additional hook movement times and crane operation times, FT, if quantity of material demanded exceeds the lifting capacity of a crane, are given by Eq. (39). Total required number of repetitive movements is $f_{r,j,u}$ that should be greater than or equal to "2" numerically so as to trigger the additional hook movement times in the objective function evaluation for optimization. Total hook movement and crane operation times to transport all materials comprising (i)-(iv) will be set as an objective function in Eq. (40).

$$ST = \sum_{k=1}^{K}\sum_{i=1}^{I}\sum_{j=1}^{J}(PT_i^k + T_{Loading})\cdot\psi_{i,k} \tag{36}$$

$$SDT = \sum_{k=1}^{K}\sum_{u=1}^{U}\sum_{j=1}^{J}\sum_{i=1}^{I}\sum_{s=1}^{S}(T_{i,j}^k + T_{Unloading})\cdot y_{s,i,j,u,k} \tag{37}$$

$$DST = \sum_{k=1}^{K}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{s=2}^{S}(T_{i,j}^k + T_{Loading})\cdot z_{s,j,i,k} \tag{38}$$

$$FT = \sum_{k=1}^{K}\sum_{s=1}^{R}\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{u=1}^{U}(T_{i,j}^k + T_{Loading} + T_{Unloading})\cdot\delta_{s,r,i,j,u,k}\cdot(f_{r,j,u} - 1) \tag{39}$$

$$Minimize\ (ST + SDT + DST + FT) \quad (40)$$

The problem can be formulated as a Binary-Mixed-Integer-Linear-Program (BMILP) by minimizing the total cost objective function in Eq. (40) subject to linear constraint sets Eqs. (1)–(39). Optimized crane setup location and crane movement sequence can be found to schedule all received material demand requests. The BMILP problem is a standard problem that can be effectively solved by the branch-and-bound technique and the Gurobi™ solver 7.0 in Python platform could be applied to solve for global optimum solutions [48].

5. Numerical examples

In this section, a set of numerical examples using identical site conditions, material demand patterns and problem settings is given to illustrate the new model features and performances. Scheduling all received material demand requests is optimized. Both non-homogeneous and homogeneous material storages at material supply locations will be considered. Fig. 4 presents the hypothetical problem settings. Three material types M1, M2, and M3 where $u = 1, 2, 3$ and $U = 3$ are supplied which are available from four material supply locations S① to S④ where $i = 1, 2, 3, 4$ and $I = 4$. Details of the material supply locations given in 3D coordinates and available types of materials at each supply location are given in Table 1. Four feasible tower crane setup locations are modeled $k = 1, 2, 3, 4$ and $K = 4$. Their location coordinates together with the initial hook location coordinates are given in Table 2. Nine material demand locations from D① to D⑨ where $j = 1, 2, 3, \ldots, 9$ and $J = 9$ are modeled in the numerical examples. Coordinates of the material demand locations are given in Table 3.

A heavy-load 4000 HC 100 Liebherr tower crane is selected and modeled in the numerical example. From its technical specifications, hoisting velocity $V_h = 136$ m/min, radial velocity $V_a = 60$ m/min and slewing velocity $V_w = 0.5$ rad/min are inputs to model crane movements. Parameters specifying crane operator's skill levels to control hook movements, α and β, are set to be 1.0 and 0.25, respectively. Site specific parameter for a crane setting up at a location k, γ_k, is set as 1.0 for normal operating conditions without incurring additional delay. It is further assumed that the Euclidean hook movement paths between all material supply and demand locations are free from obstacle blockages and no additional time delay is induced taking $\mu_i^k = 1.0$ and $\mu_{i,j}^{\prime k} = 1.0$. Material loading time, $T_{Loading}$ and unloading time, $T_{Unloading}$ for respectively loading materials onto a hook and unloading materials from a hook are assumed to be constant at 1.0 time unit (minute). Ten material demand requests are given to serve 9 material demand locations. Details are given in Table 4. Column 1 lists the ten material demand requests. The associated demand locations and material types are tabulated in Columns 2 and 3, respectively. Two sets of material demand quantities without and with triggering the crane overloading are given in the next two columns. Column 6 gives the lifting capacity of the modeled crane. Columns 7 and 8 then specify the required numbers of movement trips for the crane to complete each material demand request. Without overloading, hook is able to move in a single trip to complete the material transportation for each material demand request in Column 7. When crane is overloading for some material demand requests, Column 8 gives the respective numbers of trips that are required for the hook movements to complete the material demand requests.

7 study cases are modeled to illustrate different solution characteristics for comparisons and discussions. Detailed information about the 7 study cases are given as follows. In the literature review section, different service strategies such as first-in-first-out/ first-in-first-serve (FIFO/FIFS), shortest job first (SJF) and nearest neighbor (i.e. nearest neighbor's request next) first (NNF) methods were reviewed. Based on the identical problem settings as given above in the numerical examples, these servicing strategies can be operated to solve the Crane Service Sequencing Problem (CSSP). Also, the modified Traveling Salesman Problem (TSP) has been formulated and applied to solve the CSSP [41]. To implement FIFS in Case 1, SJF in Case 2, NNF in Case 3, and modified TSP in Case 4 for solving the present numerical examples, these 4 cases require pre-determined pairs of material supply and demand locations. Table 5 then provides additional details for pairing material supply and demand locations for the ten material demand requests. With respect to each material demand request, demand

Table 1
Details of material supply locations.

Material supply location, i	Location coordinates (3D)			Types of material supply, u
	S_i^x	S_i^y	S_i^z	
1	73	37	2	1,2,3
2	55	73	1.5	2,3
3	35	67	0	3
4	22	46	0	1,2

Table 2
Details of crane setup locations and initial hook location.

Crane setup location, k	Cr_k^x	Cr_k^y	Cr_k^z
1	65	57	30
2	60	33	30
3	70	52	30
4	42	52	30
Initial hook location	P_k^x	P_k^y	P_k^z
	34	41	15

Table 3
Details of material demand locations.

Material demand location, j	Location coordinates (3D)		
	D_j^x	D_j^y	D_j^z
1	34	41	15
2	34	51	15
3	51	65	15
4	60	65	15
5	76	51	15
6	76	41	15
7	60	26	15
8	51	25	15
9	43	44	15

Table 4
Details of material demand requests.

Material request, r	Demand location, j[a]	Material type, u	Quantity of material demand (weight unit), $q_{r,j,u}$		Lifting capacity of crane (weight unit), π	Required number of trips between material supply and demand locations, $f_{r,j,u}$	
			Cases 1–5	Cases 6, 7		Cases 1–5	Cases 6, 7
1	D②	3	20	75	30	1	3
2	D④	2	30	40		1	2
3	D⑨	3	10	30		1	1
4	D③	2	25	15		1	1
5	D⑥	3	25	50		1	2
6	D③	2	10	25		1	1
7	D⑤	3	30	80		1	3
8	D⑦	2	25	55		1	2
9	D①	2	10	20		1	1
10	D⑧	1	25	50		1	2

[a] For D②, subscript $j = 2$ for identifying the demand location.

Table 5
Ten material demand requests with paired material supply locations.

Material request, r	Demand location, j	Material type, u	Supply location i	Material request, r	Demand location, j	Material type, u	Supply location i
1	D②	3	S③	6	D③	2	S②
2	D④	2	S②	7	D⑤	3	S①
3	D⑨	3	S③	8	D⑦	2	S①
4	D③	2	S②	9	D①	1	S④
5	D⑥	3	S①	10	D⑧	1	S①

Table 6
Details of hook movement paths by First-in-first-serve (FIFS) method in Case 1.

Resultant sequence, s	Material request, r	Material type, u	Demand quantity, $q_{r,j,u}$	Hook movement of crane		Hook movement time, $T_{i,j}^{k}$	Cumulative operation time[a]
				Location i	Location j		
1	1	3	20	D①	S③	1.54	2.54
				S③	D②	1.00	4.54
2	2	2	30	D②	S②	2.12	7.66
				S②	D④	0.30	8.96
3	3	3	10	D④	S③	1.24	11.2
				S③	D⑨	1.56	13.76
4	4	2	25	D⑨	S②	2.61	17.37
				S②	D③	0.83	19.2
5	5	3	25	D③	S①	4.89	25.09
				S①	D⑥	0.73	26.82
6	6	2	10	D⑥	S②	6.22	34.04
				S②	D③	0.83	35.87
7	7	3	30	D③	S①	4.89	41.76
				S①	D⑤	2.57	45.33
8	8	2	25	D⑤	S①	2.57	48.90
				S①	D⑦	1.29	51.19
9	9	1	10	D⑦	S④	2.38	54.57
				S④	D①	0.52	56.09
10	10	1	25	D①	S①	3.15	60.24
				S①	D⑧	1.81	63.05

Total operation time: 63.05 time units (mins).

[a] Cumulative operation time includes hook movement time between material demand and supply locations and the constant loading or unloading time of 1.0 time unit (min).

Table 7
Details of hook movement paths by Shortest-job-first (SJF) method in Case 2.

Optimized sequence, s	Material request, r	Material type, u	Demand quantity, $q_{r,j,u}$	Hook movement of crane		Hook movement time, $T_{i,j}^{k}$	Cumulative operation time*
				Location i	Location j		
				D①	S②	2.66	3.66
1	2	2	30	S②	D④	0.30	4.96
				D④	S④	2.34	8.30
2	9	1	10	S④	D①	0.52	9.82
				D①	S①	3.15	13.97
3	5	3	25	S①	D⑥	0.73	15.7
				D⑥	S②	6.22	22.92
4	6	2	10	S②	D③	0.83	24.75
				D③	S②	0.83	26.58
5	4	2	25	S②	D③	0.83	28.41
				D③	S③	0.58	29.99
6	1	3	20	S③	D②	1.00	31.99
				D②	S①	3.68	36.67
7	8	2	25	S①	D⑦	1.30	38.97
				D⑦	S③	3.39	43.36
8	3	3	10	S③	D⑨	1.55	45.91
				D⑨	S①	3.13	50.04
9	10	1	25	S①	D⑧	1.81	52.85
				D⑧	S①	1.81	55.66
10	7	3	30	S①	D⑤	2.57	59.23

Total operation time: 59.23 time units (mins).

*Cumulative operation time includes hook movement time between material demand and supply locations and the constant loading or unloading time of 1.0 time unit (min).

Remark: Shaded figures are sorted hook movement times in ascending order in the sequence for implementing the SJF.

Table 8
Physical separations among 9 material demand locations (in meters).

	D①	D②	D③	D④	D⑤	D⑥	D⑦	D⑧	D⑨
D①	–	10.00	29.41	35.38	43.17	42.00	30.01	23.34	9.48
D②	10.00	–	22.02	29.53	42.00	43.17	36.07	31.06	11.41
D③	29.41	22.02	–	9.00	28.65	34.66	40.02	40.00	22.47
D④	35.38	29.53	9.00	–	21.26	28.84	39.00	41.00	27.02
D⑤	43.17	42.00	28.65	21.26	–	10.00	29.68	36.07	33.73
D⑥	42.00	43.17	34.66	28.84	10.00	–	21.93	29.68	33.14
D⑦	30.01	36.07	40.02	39.00	29.68	21.93	–	9.06	24.76
D⑧	23.34	31.06	40.00	41.00	36.07	29.68	9.06	–	20.62
D⑨	9.48	11.41	22.47	27.02	33.73	33.14	24.76	20.62	–

Remark: Shaded figures highlight the next nearest material demand locations.

Table 9
Details of hook movement paths by nearest neighbor first (NNF) method in Case 3.

Optimized sequence, s	Material request, r	Material type, u	Demand quantity, $q_{r,j,u}$	Hook movement of crane		Hook movement time, $T_{i,j}^{k}$	Cumulative operation time[a]
				Location i	Location j		
				D①	S④	0.52	1.52
1	9	1	10	S④	D①	0.52	3.04
				D①	S③	1.54	5.58
2	3	3	10	S③	D⑨	1.56	8.14
				D⑨	S③	1.56	10.70
3	1	3	20	S③	D②	1.00	12.70
				D②	S②	2.12	15.82
4	6	2	10	S②	D③	0.83	17.65
				D③	S②	0.83	19.48
5	4	2	25	S②	D③	0.83	21.31
				D③	S②	0.83	23.14
6	2	2	30	S②	D④	0.30	24.44
				D④	S①	5.49	30.93
7	7	3	30	S①	D⑤	2.57	34.50
				D⑤	S①	2.57	38.07
8	5	3	25	S①	D⑥	0.73	39.80
				D⑥	S①	0.73	41.53
9	8	2	25	S①	D⑦	1.29	43.82
				D⑦	S①	1.29	46.11
10	10	1	25	S①	D⑧	1.81	48.92

Total operation time: 48.92 time units (mins).
[a] Cumulative operation time includes hook movement time between material demand and supply locations and the constant loading or unloading time of 1.0 time unit (min).

location, material type demanded and corresponding supply location are all provided in Table 5. It should be noted that the nearest material supply location has been paired to various material demand locations for fair assessments.

In Cases 5–7, our proposed optimization method is applied to solve the problem with identical settings mentioned above except that the predetermined pairs of material supply and demand locations given in Table 5 are relaxed as model variables. Case 5 is regarded as the basic model to minimize Eq. (40) subject to linear constraint sets in Eqs. (1)–(17), (20)–(31), (34), and (36)–(39). If optional constraint set in Eq. (35) is included in Case 5, then restrictions of pairing the material supply and demand locations given in Table 5 will be effective and the optimization results from our proposed method would return to the results obtained by the modified TSP method as in Case 4. To trigger the proposed model to consider crane overloading effects, Case 6 is conducted to optimize again the objective function in Eq. (40) subject to linear constraint sets in Eqs. (1)–(17), (20)–(34), and (36)–(39). Eqs. (32) and (33) are added in Case 6 while comparing to the constraint sets being used in Case 5 to determine the hook movement frequencies. Eq. (39) would then calculate the extra hook operation times due to multiple trips between pairs of material supply and demand locations. Lastly, constraint sets in Eqs. (18) and (19) are added to the formulation for optimization in Case 7 that is to minimize Eq. (40) subject to linear constraint sets in Eqs. (1)–(34) and (36)–(39). Key difference between Case 6 and Case 7 is that Case 7 further enables a new model function to accept "urgent" material demand requests from users' inputs while optimizing the work sequence. Those "urgent" material demand requests will then be prioritized to the top of the schedule being served. It is found that very different model results are obtained for comparisons and relevant discussions are given as follows.

In Case 1, work sequence is the simplest one based on a first-in-first-serve (FIFS) basis. No optimization is required. Without changing the order of the ten given material demand requests in Table 5, the sequence s just follows the material (demand) request r (i.e. $s = r$). And this schedule sequence is regarded as the results of adopting the FIFS strategy. Since the associated material supply locations and material types to be supplied are all given in Table 5, individual hook movement time for each request between the given pair of material supply and demand locations can directly be calculated using Eqs. (1)–(15). Adding the constant material loading and unloading times to the hook movement times, the total operation time is calculated to be 63.05 time units (mins) for completing all material demand requests. Details are tabulated in Table 6 listing all material demand requests and their respective hook movement times between the fixed pairs of material supply and demand locations. Column 1 lists the order of sequence from 1 to 10. Column 2 gives the respective material demand request. Column 3 collects the material type being requested in the associated material request. Column 4 gives the material demand quantity.

Table 10
Details of hook movement paths by modified TSP model with fixed pairs of material supply and demand locations in Case 4.

Optimized sequence, s	Material request, r	Material type, u	Demand quantity, $q_{r,j,u}$	Hook movement of crane		Hook movement time, $T_{i,j}^{k}$	Cumulative operation time[a]
				Location i	Location j		
				D①	S④	0.52	1.52
1	9	1	10	S④	D①	0.52	3.04
				D①	S③	1.54	5.58
2	1	3	20	S③	D②	1.00	7.58
				D②	S②	2.12	10.70
3	4	2	25	S②	D③	0.83	12.53
				D③	S②	0.83	14.36
4	2	2	30	S②	D④	0.30	15.66
				D④	S②	0.30	16.96
5	6	2	10	S②	D③	0.84	18.80
				D③	S③	0.59	20.39
6	3	3	10	S③	D⑨	1.56	22.95
				D⑨	S①	3.13	27.08
7	8	2	25	S①	D⑦	1.30	29.38
				D⑦	S①	1.30	31.68
8	5	3	25	S①	D⑥	0.73	33.41
				D⑥	S①	0.73	35.14
9	10	1	25	S①	D⑧	1.81	37.95
				D⑧	S①	1.81	40.76
10	7	3	30	S①	D⑤	2.57	44.33

Total operation time: 44.33 time units (mins).
[a] Cumulative operation time includes hook movement time between material demand and supply locations and the constant loading or unloading time of 1.0 time unit (min).

Table 11
Details of hook movement paths by the proposed optimization method in Case 5.

Optimized sequence, s	Material request, r	Material type, u	Demand quantity, $q_{r,j,u}$	Hook movement of tower crane		Hook movement time, $T_{i,j}^{k}$	Cumulative operation time[a]
				Location i	Location j		
1	6	2	10	D①	S④	0.52	1.52
				S④	D③	1.69	4.21
2	2	1	30	D③	S②	0.83	6.04
				S②	D④	0.30	7.34
3	4	1	25	D④	S②	0.30	8.64
				S②	D③	0.83	10.47
4	1	3	20	D③	S③	0.59	12.06
				S③	D②	1.00	14.06
5	3	3	10	D②	S③	1.00	16.06
				S③	D⑨	1.56	18.62
6	9	2	10	D⑨	S④	0.55	20.17
				S④	D①	0.52	21.69
7	10	1	25	D①	S④	0.52	23.21
				S④	D⑧	1.86	26.07
8	8	2	25	D⑧	S①	1.81	28.88
				S①	D⑦	1.30	31.18
9	5	3	25	D⑦	S①	1.30	33.48
				S①	D⑥	0.73	35.21
10	7	3	30	D⑥	S①	0.73	36.94
				S①	D⑤	2.57	40.51

Total operation time: 40.51 time units (mins) @ $k = 3$ (optimal crane set up location).
[a] Cumulative operation time includes hook movement time between material demand and supply locations and the constant loading or unloading time of 1.0 time unit (min).

Columns 5 and 6 provide the hook movement details from one location to another. Column 7 then shows the respective hook movement time for each hook movement. Column 8 gives the cumulative operation time including hook movement, loading and unloading times. And the last row of the Table 6 presents the total operation time which should be matching the last entry of Column 8. Tables 6, 8–11, and 13–14 are presented in similar formats. Optimization results for Cases 2–7 could be retrieved similarly.

In Case 2, shortest job first (SJF) strategy is applied. Working logic is to examine the ten material demand requests including the material supply and demand locations and the material types being requested. With respect to each request, the nearest material supply location supplying the requested material for the material demand location is given in Table 5. 3D coordinates of all material supply and demand locations are given in Tables 1 and 3, respectively. Euclidean distances between all pairs of material supply and demand locations can be calculated using the Pythagoras's theorem. From Eqs. (1)–(15), respective hook movement times could be obtained. By sorting these hook movement times in ascending orders (i.e. the shaded hook movement times in Table 7) for all the material supply and demand pairs, hook movement sequence is then scheduled. Table 7 summarizes the computation results using the SJF strategy. Total operation time is 59.23 time units (mins).

In Case 3, nearest neighbor first (NNF) method (regarded as the nearest neighbor's request next) is implemented. Work sequence is optimized by searching the next nearest material demand locations from the existing one. In the present numerical example, hook movement starts from an initial hook location and then moves to the next

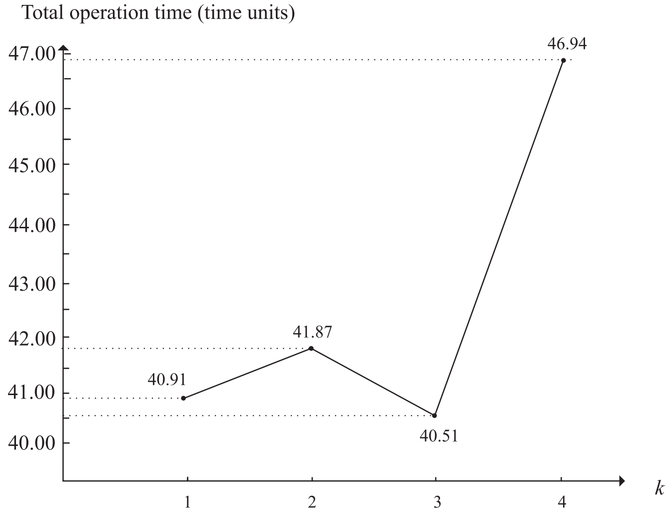

Fig. 5. Total operation time (objective function value in Eq. (40)) against crane setup location *k*.

nearest material demand location. Upon completing one material demand request, the next nearest material demand location will be identified and then served until all material demand requests are completed. In the present numerical examples, initial hook location is set at demand location D① and thus material request $r = 9$ for demand location D① is firstly selected by default in the resultant work sequence. Based on physical separations among the 9 modeled material demand locations which are calculated based on the given coordinates in Table 3, the next nearest material demand location is identified to be D⑨, where is 9.48 m away from material demand location D①, in material request $r = 3$. Thus, optimized sequence $s = 2$ will be scheduled for material request $r = 3$. Based on the coordinates given in Table 3 for all material demand locations, all their Euclidean distance separations can be directly calculated using the Pythagoras's theorem and results are tabulated in Table 8. According to the shaded figures in Table 8 highlighting the next nearest material demand locations, other remaining material requests can then be scheduled similarly to form the following sequence D① → D⑨ → D② → D③ → D④ → D⑤ → D⑥ → D⑦ → D⑧. Details of hook movement paths can be found in Table 9. Total

Table 12
Total operation times using different scheduling methods in Cases 1–5.

Scheduling method	FIFS (Case 1)	SJF (Case 2)	NNF (Case 3)	Modified TSP (Case 4)	Proposed optimization method[a] (Case 5)
Total operation time (time units)	63.05	59.23	48.92	44.33	40.51
Difference from Case 5[a]	−22.54	−18.72	−8.41	−3.82	–

[a] (i) Total operation time in Case 5 minus Total operation time in Case 1, 2, 3, or 4. (ii) Negative results mean that the proposed optimization method in Case 5 outperforms all other scheduling methods in Cases 1–4 with lesser total operation time.

hook movement time is found to be 48.92 time units (mins).

In Case 4, the numerical example problem is formulated as a modified TSP model [41]. Since there are totally ten material demand requests with fixed pairs of material supply and demand locations, the modified TSP problem likes to solve a problem of ten nodes. To ensure all the ten nodes being reached once, there are 10! (=3.628,800) solution combinations. Through exhaustive search, the minimum numerical solution of the total operation time is found to be 44.33 time units (mins) for completing the ten material demand requests. Details of the hook movements are given in Table 10.

In Case 5, the proposed optimization method is applied to solve the crane scheduling problem with identical problem settings as used in Cases 1–4. However, the fixed pairs of material supply and demand locations given in Table 5 will be relaxed as model variables. Depending on the availability of material supply, material supply locations to serve the ten given material demand requests for various material demand locations would become model variables. Referring to Table 2 and Fig. 4, four available crane setup locations are modeled. The proposed optimization method is capable to optimize the crane setup location. With all these model relaxation, total operation time is optimized to be 40.51 time units (mins) which has around 9% improvement while comparing to that by the modified TSP model in Case 4. The optimized crane setup location is found to be $k = 3$. Details of the hook movements optimized by the proposed optimization method can be found in Table 11. Fig. 5 plots the objective function value with respect to the

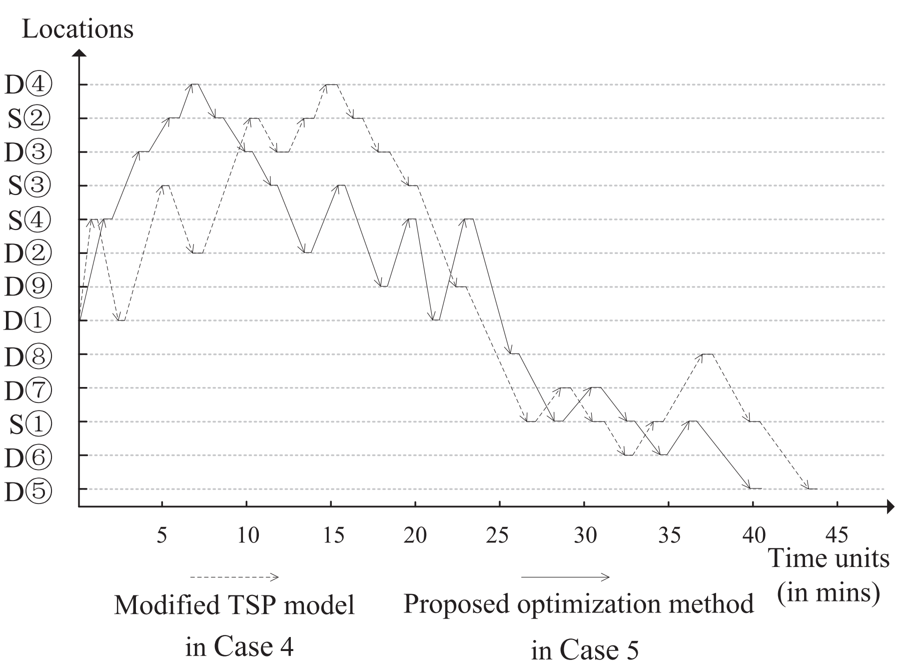

Fig. 6. Hook movement paths by the modified TSP model in Case 4 and the proposed optimization method in Case 5.

Table 13
Details of hook movements in Case 6 with multiple hook movement trips due to overloading effects.

Optimized sequence, *s*	Material request, *r*	Material type, *u*	Demand quantity, $q_{r,\ j,\ u}$	Hook movement of crane		Hook movement time, $T_{i,\ j}^{k}$	Additional multiple trip operation time[a]	Cumulative operation time[b]
				Location *i*	Location *j*			
				D①	S④	0.52	–	1.52
1	6	2	25	S④	D③	1.69	–	4.21
				D③	S②	0.83	–	6.04
2	2	2	40	S②	D④	0.30	2.60	9.94
				D④	S②	0.30	–	11.24
3	4	2	15	S②	D③	0.83	–	13.07
				D③	S③	0.59	–	14.66
4	1	3	75	S③	D②	1.00	8.03	24.69
				D②	S③	1.00	–	26.69
5	3	3	30	S③	D⑨	1.56	–	29.25
				D⑨	S④	0.55	–	30.80
6	9	2	20	S④	D①	0.52	–	32.32
				D①	S④	0.52	–	33.84
7	10	1	50	S④	D⑧	1.86	5.73	42.43
				D⑧	S①	1.81	–	45.24
8	8	2	55	S①	D⑦	1.30	4.60	52.14
				D⑦	S①	1.30	–	54.44
9	5	3	50	S①	D⑥	0.73	3.47	59.64
				D⑥	S①	0.73	–	61.37
10	7	3	80	S①	D⑤	2.57	14.29	79.23

Total operation time: 79.23 time units (mins) @ $k = 3$ (optimal crane set up location).
[a] Additional multiple trip operation time is calculated by Eqs. (37) and (38) due to overloading effects.
[b] Cumulative operation time includes hook movement time between material demand and supply locations and the constant loading or unloading time of 1.0 time unit (min).

Table 14
Details of hook movements in Case 7 with multiple hook movement trips and prioritized urgent material demand requests.

Optimized sequence, *s*	Material request, *r*	Material type, *u*	Demand quantity, $q_{r,\ j,\ u}$	Hook movement of crane		Hook movement time, $T_{i,\ j}^{k}$	Additional multiple trip operation time[a]	Cumulative operation time[b]
				Location *i*	Location *j*			
				D①	S④	0.52	–	1.52
1	9	2	20	S④	D①	0.52	–	3.04
				D①	S④	0.52	–	4.56
2	10	1	50	S④	D⑧	1.86	5.73	13.15
				D⑧	S①	1.81	–	15.96
3	5	3	50	S①	D⑥	0.73	3.47	21.16
				D⑥	S①	0.73	–	22.89
4	7	3	80	S①	D⑤	2.57	14.29	40.75
				D⑤	S①	2.57	–	44.32
5	8	2	55	S①	D⑦	1.30	4.60	51.22
				D⑦	S④	2.38	–	54.6
6	6	2	25	S④	D③	1.69	–	57.29
				D③	S②	0.83	–	59.12
7	2	2	40	S②	D④	0.30	2.60	63.02
				D④	S②	0.30	–	64.32
8	4	2	15	S②	D③	0.83	–	66.15
				D③	S③	0.59	–	67.74
9	1	3	75	S③	D②	1.00	8.03	77.77
				D②	S③	1.00	–	79.77
10	3	3	30	S③	D⑨	1.56	–	82.33

Total operation time: 82.33 time units (mins) @ $k = 3$ (optimal crane set up location).
[a] Additional multiple trip operation time is calculated by Eqs. (37) and (38) due to overloading effects.
[b] Cumulative operation time includes hook movement time between material demand and supply locations and the constant loading or unloading time of 1.0 time unit (min).

available crane setup location *k*. In the present study, the proposed optimization method is formulated as a Binary-Mixed-Integer-Linear-Programming problem (BMILP). For the computational problem size in Case 5, there are 9017 binary variables and 31,637 linear constraints. It takes about 20 min to solve the problem using a Gurobi 7.0 solver with a i7-4820K CPU @3.70 GHz which is considered computationally manageable. It is expected that computing time will be increased if more material demand requests are to be scheduled.

Fig. 6 plots the hook movement details with direct comparisons between the modified TSP model in Case 4 and the proposed optimization method in Case 5. From the same initial hook location, a series of arrows is drawn to simulate individual hook movements. Heads of arrows are pointing to next hook locations. And tails of arrows are the prior hook locations. It is observed that very different patterns of arrows are found in Cases 4 and 5 implying that the hook movement patterns are quite different. Shorter arrow lines are generally observed in the proposed optimization results (solid lines in Fig. 6) connecting the nearest pairs of material supply and demand locations and also the consecutive pairs of material demand and supply locations (well preparing to serve the next material demand request). In Fig. 6, solid lines of arrows are terminated earlier indicating that the total operation time required to complete the ten material demand requests in Case 5 is less than that in Case 4. As a whole, the proposed optimization method (in Case 5) outperforms the FIFS (in Case 1), SJF (in Case 2), NNF (in Case

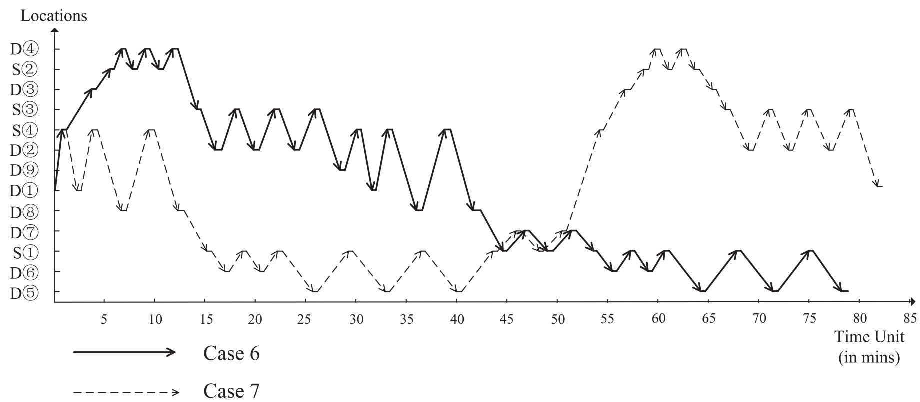

Fig. 7. Optimized hook movement paths with multiple hook movement trips in Case 6 and urgent material demand requests in Case 7.

3), and the modified TSP model (in Case 4).

Total operation times including the hook movement times and material loading and unloading times obtained by the scheduling methods from Cases 1–5 for respectively FIFS, SJF, NNF, the modified TSP model, and the proposed optimization method are given and compared in Table 12. Taking the total operation time of the proposed optimization method in Case 5 as a reference, results from Cases 1–4 show that the identical ten material demand requests are completed using longer total operation times. Their differences are given in Table 12. Negative numerical differences of the total operation times reveal that Case 5 outperforms all other cases to optimize a more effective schedule for the hook movements.

With these promising findings, the proposed optimization method is extended to deal with more complex problem settings. Case 6 is to model a problem scenario when material demand quantities exceed the lifting capacity of a crane. Then, multiple movement trips of the hook traveling to and from the same pair of material supply and demand locations are required to complete a single material demand request. Case 7 is further extended to accept some urgent material demand requests from user inputs so that those urgent material demand requests can be prioritized on top of the optimized work sequence.

In Case 6, settings of the original material demand requests of are slightly revised so as to trigger the new model features. In Table 4, quantities of material demand in some requests for Cases 6 and 7 are increased and become exceeding the crane lifting capacity. Required numbers of hook movements are thus increased and more than one hook movement trip is needed to complete some of the material demand requests. Based on the revised quantities of material requests given in Table 4, details of the optimized hook movements and work schedule for Case 6 are presented in Table 13. A new column is given to specify the "Additional multiple trip operation time" that is required due to the overloading effects to trigger additional hook movements between material supply and demand location pairs. For material demand quantity being greater than the crane lifting capacity which is $\pi = 30$ units in the numerical examples, additional hook movement trips and longer operation times are triggered. For instance, for material demand request $r = 2$, material demand quantity is 40 units which are larger than the crane lifting capacity of 30 units. A single hook movement trip from material supply location S② to material demand location D④ is insufficient. Additional return trip back from material demand location D④ to material supply location S② to load the requested material (i.e. 0.30 + 1.0 time units) by Eq. (38) and another trip to deliver the outstanding amount of the requested material from material supply location S② to material demand location D④ to unload the material (i.e. 0.30 + 1.0 time units) by Eq. (37) are both required. Thus, an additional operation time of 2.60 (= 0.30 + 1.0 + 0.30 + 1.0) time units is added to complete material demand request $r = 2$. Five more such multiple trip operation times are calculated for those material demand quantities being greater than the crane lifting capacity. Total operation time in Case 6 is found to be 79.23 time units (mins) as presented in Table 13.

In Case 7, material demand locations D①, D⑧ and D⑥ are considered to place urgent material demand requests. Urgent material demand requests $r' = 5$, 9, and 10 are required to be prioritized in the optimized work sequence. Through adding constraint sets in Eqs. (18) and (19) to the BMILP formulation, the proposed optimization method can successfully prioritize these 3 material demand requests to the optimized work sequence. Table 14 presents the optimization results. Still, minimizing the total operation time is the objective function for optimization. It is found that the work sequence is quite different while comparing to the optimization result in Case 6. Fig. 7 plots the two optimized hook movement paths for completing the ten identical material demand requests. To fulfill the urgent material demand requests, the total operation time is slightly increased from 79.23 to 82.33 time units (mins).

6. Conclusions

The proposed study aims to enhance the work efficiency of practical crane operations through minimizing the total hook movement time and total operation time by scheduling the crane movement sequence. Binary variables and linear governing constraint sets are designed to model the crane operations and detailed hook movements. The optimization problem is formulated as a Binary-Mixed-Integer-Linear-Programming (BMILP) and solved by a Gurobi solver. Significant reduction in total operation time is observed by the proposed optimization method while comparing to conventional scheduling strategies. New model features are developed including (i) crane setup location could be optimized, (ii) non-homogeneous and homogeneous material supply are modeled, (iii) initial hook location is defined as model input from users, (iv) conventionally fixed pairs of material supply and demand locations could be relaxed as model variables, (v) maximum lifting capacity of crane is introduced and multiple hook movement trips between material supply and demand locations are modeled, (vi) users may input urgent material demand requests so that their servicing orders are prioritized in the optimized schedule. With these, the proposed optimization model could optimize the crane scheduling and hook movement patterns to serve all received material demand requests. The present formulation is able to be extended to deal with multiple crane operations as further works. Additional constraints are required to ensure safe crane operations and avoid spatial conflicts.

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