TSP-BASED MODEL FOR ON-SITE MATERIAL HANDLING OPERATIONS WITH TOWER CRANES

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ABSTRACT

Today, with the necessity of timely, on-budget and high quality completion of projects, proper use of construction equipment is essential to ensure project success. Construction equipment places a large monetary burden on the project and if not utilized efficiently, it can result in economic losses. Cranes are one of the most important and expensive operational devices on construction sites. They play a central role, and often activities that rely on crane services fall on the project's critical path. Currently, material-handling scheduling is done by the crane operator or by an on-duty superintendent using his/hers personal judgment, making the process manual and time-consuming. Thus, developing an optimal schedule, which considers different dynamic constraints in construction job site, may not be possible based on the current practice. This leads to longer operation times and a negative impact on project cost. This paper presents the latest results of an ongoing study, which aims to design and implement a near-real time crane operation decision support system to be utilized directly by the crane operator or as an aid for the superintendent in scheduling optimal operation services. This system has several advantages such as maximizing the efficiency of crane operations, guaranteeing the best operation possible to reduce the crane's travel time, reducing crews and equipment idle time, and minimizing the dependence on subjective human judgments.

KEYWORDS

Optimization, Scheduling, Tower crane, Automation, Decision support system

INTRODUCTION

Building a high quality product with less time under a limited budget is the goal of construction projects. Construction industrialization and using prefabricated and modularized material offer substantial opportunities to achieve this goal. In construction industrialization, the building elements are manufactured off-site and are transported, installed or assembled on site afterward (Pan et al., 2012). Therefore, onsite production process is being replaced mainly by installation of the elements and material which is transported to the site. Consequently, material handling devices are becoming more and more dominant in building construction sites (Shapira et al., 2007). Among all material handling devices, cranes, including tower and mobile, are the most popular ones. The onsite transportation process highly depends on crane services and thus, planning the usage of the crane service is crucial to finish the project tasks with respect to time limitations. This process is subject to several uncertainties and thus requires careful planning and control to reduce the risk (Peurifoy et al., 2010).

Previously, increasing crane operation productivity has been investigated mostly via two approaches: first, through facility layout planning in the design phase by appropriately locating tower cranes and supply locations to reduce crane's total travel time (Huang et al., 2011; Tam et al., 2001; Tam & Tong, 2003; Zhang et al., 1996; Zhang, et al., 1999) Second, reducing crane travel time has also been investigated by using add-on technologies such as vision systems (Everett & Slocum, 1993; Lee et al., 2012 ; Shapira et al., 2008) and collision detection systems (Sivakumar et al., 2003; Kang & Miranda, 2006; Lei et al., 2012) to facilitate crane navigation especially when the operator's line of sight is obstructed.

Traditionally, in a construction job site, the tower crane operator is in contact via radio communication system with the working deck and is in touch with the signal men on the ground. The signal men facilitate the crane movement when the operator has a limited line of sight through a set of hand signals. Requests received from different crews in the jobsite are sent to the tower crane cabin using radio communication system and will be processed by the operator who normally plans services based on the FIFO (first-in-first-out) rule. In more advanced cases, crane's operation schedule is finalized by an in-charge superintendent who receives material delivery requests from different working parties ahead of time (sometimes a day in advance). In case of new/urgent requests during operations, changes in the schedule are implemented in coordination with the superintendent. Failure in timely submission of requests can cause significant delays and reduce the efficiency of the developed schedule.

This paper presents a site-level material supply planning and scheduling decision support system (DSS) for tower cranes. The DSS is based on an asymmetric Traveling Salesman Problem formulation. This DSS can assist the on-duty superintendent in charge of planning the crane service allocation or can be used directly by the crane operator to reduce the operation time. The output of the optimization model is the chronological sequence of the locations, the crane must visit to optimize the travel time through minimizing the travel distance.

PROBLEM DESCRIPTION

To illustrate the problem graphically, consider a construction site layout with a central tower crane in charge of material handling process (

Figure **1**-left side). The site layout could be presented as a bipartite graph, consisting of two disjoint sets (

Figure **1**-right side): material locations (supply nodes) and crew locations (demand nodes). Requested material is sent to the crews using the available tower crane. Each location is not intrinsically a supply or demand node and can play each role based on the received requests. The bipartite graph is a dynamic graph built after requests received and will be updated every time one request is been fulfilled or a new request is submitted. Travel time is associated with each link connecting a crew (C) node with a material (M) node. Solid arcs in

Figure **1** show outstanding crane requests and the dotted arcs show the outgoing routes from crew locations in the returning path.

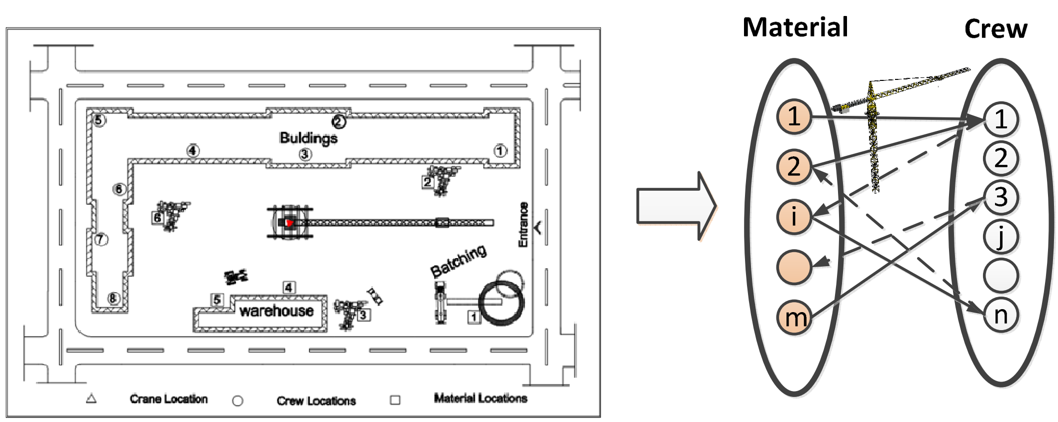

Figure 1 - Construction site layout and its representative bipartite graph

The problem is to determine the sequence of locations the tower crane must visit in order to fulfill the service requests received, such that the total travel time is minimized. Depending on the number of crews (assume w) requesting crane service, there are w alternative options for the crane operator to choose the crew that receives service first. After fulfilling the first crew's demand, there are w-1 outstanding demands to choose from, if in the meanwhile no other request has entered. This process will continue until all requests have been fulfilled which results in w! possible ways to fulfill all crews' requests. Since w! grows significantly with w, exhaustive or brute-force search, which means enumerating all possible candidates for the solution and checking whether each candidate satisfies the problem statement, is not feasible. Furthermore, fulfilling a random request or the first received request and then going to the next nearest point to fulfill the next request, etc. (nearest neighbor algorithm), does not necessarily result in the shortest path and the minimum completion time (Gutin & Punnen, 2004). Thus, the challenge is to design a robust method to determine the optimal sequence of tasks that yields the minimum completion time.

We refer to this problem as "Crane Service Sequence Problem (CSSP)." CSSP is similar to a well-known combinatorial optimization problem, namely the Traveling Salesman Problem (TSP). TSP is one the most notorious problems in Operation Research because it is easy to explain and so tempting to try and solve (Wolsey, 1998). The problem is to find the sequence in which the travelling salesman visits n cities and returns to his starting point with the minimum travel time such that each city is visited only once. Unlike its easy description, TSP is an NP-complete problem that has become a representative of difficult combinatorial optimization problems. In TSP, starting at city 1, the salesman has $n-1$ choices for second city and $n-2$ for the next choice, and so on. Thus, there are $(n-1)!$ feasible tours in case of asymmetry (where the distance from city i to j is not equal to the distance from city j to i), and if the distances from city i to j are equal in both directions (symmetry), the number of possible tours will be $(n-1)!/2$. The conclusion to be drawn is that using complete enumeration can only solve such a problem for small values of n.

CSSP can be formulated as a TSP by defining each request (starting from a material node and ending to a crew node) as a city, and connecting arcs as travel time of switching between requests. CSSP can be then reduced to an asymmetric TSP. However, unlike TSP, in CSSP crane can visit one location several times. CSSP becomes a search of the shortest tour (total travel time) starting from the crane idle position, visiting a given set of requests exactly once (a Hamiltonian tour) and returning to its initial position. In CSSP, crew and material locations might be visited more than once while request nodes can be only visited once. In case of requesting the same service multiple times [for instance when several (say 10) trips are required for the crane to deliver a given volume of material from a supply node to a demand node] each request will be represented as one node (10 nodes in this example) to meet the constraint of visiting request nodes only once.

PROBLEM FORMULATION

CSSP is based on "request time matrix" $(P: p_{kl})$ which reflects the travel time required when switching between requests. The CSSP can be represented by a directed graph G = (V, A), where $V = \{1, \ldots, n\}$ is a set of n vertices (representing requests); and $A = \{(k,l): k, l \epsilon V\}$ is a set of directed arcs. A is associated with a non-symmetric cost matrix (p_{kl}).The CSSP mathematical formulation is as follows:

$$Minimize \quad z = \sum_k \sum_l p_{kl} y_{kl} \tag{1}$$

$$Subject\ to:$$

$$\sum_{l:l\neq k} y_{kl} = 1 \qquad \forall\, k,l \in V, (k,l) \in A \tag{2}$$

$$\sum_{k:k\neq l} y_{kl} = 1 \qquad \forall\, k,l \in V, (k,l) \in A \tag{3}$$

$$\sum_{k\in S} \sum_{l\in \bar{S}} y_{kl} \geq 1 \qquad S \in V,\ 2 \leq |s| \leq n-2,\ (k,l) \in A \tag{4}$$

$$y_{kl} \in \{0,1\} \qquad \forall\, k,l \in V, k \neq l \tag{5}$$

In this algorithm, y_{kl} is the decision variable describes which arcs is in the optimal tour and can take 0 or 1. In other words, $y_{kl} = 1$ if the crane hook goes directly from request node k to request node l, and $y_{kl} = 0$ otherwise (constraint (5)). Constraints (2) and (3) ensure that every vertex is only visited once as it is stated in the TSP definition. However, considering only constraints (2) and (3) does not assure a single continuous path and therefore, to preserve the sequence integrity, an additional stipulation is needed. Constraint (4) is called subtour elimination constraint, and prohibits solutions with the incidence of two or more disjoint vertices in the graph. The symbol S in constraint (4) is a subset of the vertices in the graph and $\bar{S} = V \setminus S$ is the complement of S. The physical interpretation of connectivity constraint (4) is that in every CSSP solution, there must be at least one arc pointing from S to its complement $(\bar{S})$. In other words, S cannot be disconnected (Laporte, 1992).

Crane hook's total transportation time is the sum of two time components : 1) the fixed travel time associated with outgoing arcs from material nodes representing outstanding requests (solid arcs in

Figure **1**) that must be fulfilled; and 2) the time associated with ingoing arcs to material nodes (dotted arc in

Figure **1**) representing the returning route that can be optionally chosen among different available options. Given that the former time component is fixed, cost saving can be accomplished through optimizing the latter time component, which is the focus of this research.

The CSSP formulation is based on the request time matrix ($P\colon p_{kl}$), which is developed based on the location travel time matrix ($C\colon c_{ij}$) combined with the received requests. C_{ij} is a square, symmetric matrix reflecting time in the incomplete graph connecting the material, crew, and initial crane locations. The maximum possible edges in CSSP with n crews, m material locations and Cr cranes is denoted by $k_{n,m.Cr}$ and is equal to: $m \times n + Cr\ (m + n)$. Travel time matrix's elements are calculated using basic site layout geometry and crane specification with polar coordination based on Zhang et al.'s (1996) seminal tower crane's mathematical travel time prediction model. This model was used thereafter in other works with minimal changes (Huang et al., 2011; Tam et al., 2001; Tam et al., 2003; Zhang et al., 1999). In this model, $(r_{Si}, \theta_{Si}, z_{Si})$ are coordinates of the *i*th supply location, and $(r_{Dj}, \theta_{Dj}, z_{Dj})$ are the coordinates of the *j*th demand location. r and θ are the radial distance and counterclockwise angle from and arbitrarily origin (crane's base location) and axis (x-axis). Trolley's travel time between nodes i and j is the composed of its radial ($T_r^{(i,j)}$), angular ($T_a^{(i,j)}$), and vertical ($T_v^{(i,j)}$) travel times between two nodes:

$$T_r^{(i,j)} = \frac{\left| r_{S_i} - r_{D_j} \right|}{V_r} \tag{6}$$

$$T_a^{(i,j)} = \frac{\left| \theta_{S_i} - \theta_{D_j} \right|}{V_a} \tag{7}$$

Vertical component of the travel time is calculated similarly; however a factor is added, referred to "minimum hoisting height", to account for the additional height traversed to move the material depending on loaded material type, site topography, obstruction and safety factors.

$$T_v^{(i,j)} = \frac{\{\left| S_i^z - D_j^z \right| + 2 \times \mathrm{MinHoistingHeight}\}}{V_v} \tag{8}$$

Radial $V_r(\mathrm{m/min})$, angular $V_a(\mathrm{rpm})$, and vertical $V_v(\mathrm{m/min})$ velocities can be obtained from the in-service crane manufacturing specifications.

As the crane's hook moves in different directions simultaneously, total travel time cannot be simply estimated as the sum of its three components. Three parameters are used to account for simultaneous crane motions and site conditions. $\propto$ and β are used degree of simultaneity indicators for movements in horizontal and vertical planes, respectively. Both parameters are between zero and one, while zero reflects fully simultaneous movements and one reflects fully consecutive movements. γ is used to account for work site conditions and obstruction existence in site.

$$T_h^{(i,j)} = \max\left\{T_r^{(i,j)}, T_a^{(i,j)}\right\} + \propto \cdot \min\left\{T_r^{(i,j)}, T_a^{(i,j)}\right\} \tag{9}$$

$$T_{(i,j)} = \gamma \cdot (\max\left\{T_h^{(i,j)}, T_v^{(i,j)}\right\} + \beta \cdot \min\left\{T_h^{(i,j)}, T_v^{(i,j)}\right\}) \tag{10}$$

Where: $0 \leq \propto \leq 1$, $0 \leq \beta \leq 1$, $1 \leq \gamma \leq \infty$.

Using equation 6 to 10, travel time between all points is calculated and the "location travel time matrix" is constructed. Using the location travel time matrix, request time matrix is built and used to get the optimized sequence based on the CSSP algorithm.

EVALUATION AND RESULTS

To show how the suggested DSS can help with increasing the efficiency of crane operation scheduling, the formulated optimization model is applied to a sample construction site layout in

Figure 2 with 6 material supply locations, 8 demand (crew) locations, and one central tower crane. For simplicity, the coordinates of the initial tower crane hook location are set to (0,0,0) and the coordinates of material and crew locations are provided in Table 1 based on that.

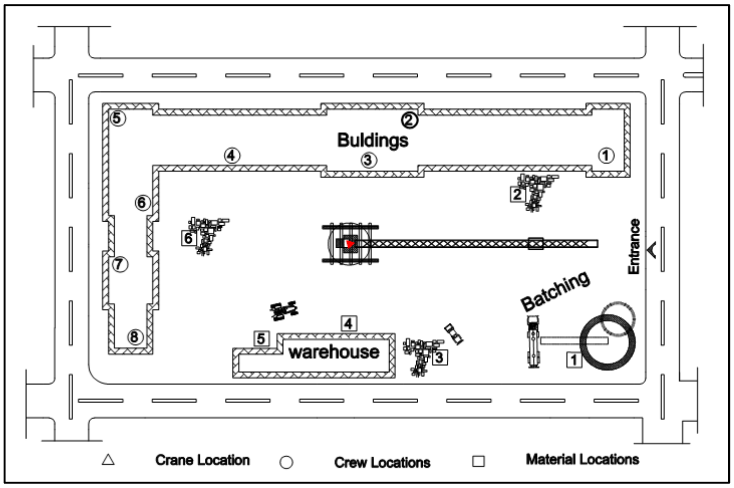

Figure 2: Sample construction site layout

Table 1 - Coordinates of supply and demand locations

Material (supply) node	Location (x,y,z)	Crew (demand) node	Location (x,y,z)
1	(76,-39,0)	1	(86,29,10)
2	(57,16,0)	2	(20,41,5)
3	(30,-39,0)	3	(6,29,3)
4	(0,-27,0)	4	(-40,30,12)
5	(-30,-32,0)	5	(-79,42,4)
6	(-55,1,0)	6	(-70,13,5)
		7	(-77,-7,0)
		8	(-72,-32,0)

Heavy-load 4000 HC 100 LIEBHERR tower crane's velocities ($V_v = 25\ m/min$, $V_a = 0.6\ revolution/min$, and $V_r = 60\ m/min$) are used here in order to determine the "location travel time matrix" using the prediction model described in the "problem formulation" section. α and β are assumed to be 0.25 and 1, respectively based on previous studies (Huang et al., 2011; Tam et al., 2001; Zhang et al., 1999). γ is set to one assuming normal site conditions (Huang et al., 2011). Job site requests are generated randomly using a uniform distribution. Request travel time matrix is then developed using the location travel time matrix combined with the generated requests. For each set of requests, the model is run for 100 times. Then, the mean and standard deviation of operation time for FIFO is compared to the optimal travel time based on the proposed CSSP method. In FIFO, requests are fulfilled based on "First-In-First-Out" concept. In this algorithm, no intelligence is involved and the crane operator processes the requests based on the received order of requests. The CSSP method optimizes the requests sequence to minimize the total travel time. To solve the proposed CSSP, MATLAB is coupled with CONCORDE, and the symmetric TSP exact solver is used.

Table 2 compares the results obtained based on the suggested algorithm with FIFO scheduling. The intelligence added to the requests' processing to select the optimal order of fulfillment results in, on average, 27% savings in operation time .The time saving increases with higher number of requests. To evaluate the significance of the optimized results compared to the FIFO approach, the t-test has been performed and the significance level (p-value) is calculated. The significance-level column in the table shows that the results are significantly different and the null hypothesis ($\mu_{FIFO} = \mu_{Optimal}$) has been rejected for all numbers of requests, underlying the reliability of the method in producing optimal results.

Table 2 - CSSP travel time compared with the traditional schedling algorithm

Requests' numbers	**Order of fulfillment**		**Time saving percentage**	**Significance level (p-value)**
	FIFO (min.)	**Optimal (min.)**		
10	27.9 ± 2.19	23 ± 1.6	17%	$< 10^{-15}$
20	53.6 ± 2.9	42 ± 2.3	22%	$< 10^{-15}$
30	79.5 ± 3.9	60.5 ± 3	24%	$< 10^{-15}$
40	103.7 ± 3.9	77.9 ± 3.2	25%	$< 10^{-15}$
50	128.2 ± 5.2	95.5 ± 4.2	25%	$< 10^{-15}$
100	250.9 ± 7.9	181.2 ± 5.3	28%	$< 10^{-15}$
200	495.6 ± 8.8	351.4 ± 6.3	29%	$< 10^{-15}$
300	730.5 ± 13.8	512.5 ± 10.2	30%	$< 10^{-15}$
400	984.9 ± 16.7	686.8 ± 13.5	30%	$< 10^{-15}$
500	1218.2 ± 16.7	845.7 ± 14.3	31%	$< 10^{-15}$
1000	2392.7 ± 31.4	1632.1 ± 11.6	32%	$< 10^{-15}$

CONCLUSION

In traditional crane scheduling, the operator or in-charge superintendent plans the crane services manually based on his/her personal judgment, which is subjective, time-consuming, inefficient and does not guarantee optimal operations. This study developed an optimization model which can minimize the crane operation time and cost. This TSP-based optimization model can suggest the best location sequence to the operator. Given the importance of cranes as the backbone of construction operations, optimal scheduling of crane operations not only has direct cost savings, but also results in indirect cost saving by minimizing the idle time of equipment and crew on the job site as well as the downstream delays in the job process. The time saving in this method is associated with travel time. Thus, in situations where travel times are considerable, the resulting time saving in crane cycle is significant. This is often the case in high rise building construction. The proposed method, however, has some simplifying assumptions which can be addressed in future studies. Acceleration and deceleration are not considered in the travel time prediction model. In addition, the proposed CSSP model works with deterministic times, overlooking the stochastic nature of travel times.

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