Optimization of Luffing-Tower Crane Location in Tall Building Construction

Dongmin Lee[1], Hyunsu Lim[2], Hunhee Cho[3] and Kyung-In Kang[4]

Abstract: The luffing-tower crane (T/C) is a key facility used in the vertical and horizontal transportation of materials in a tall building construction. Locating the crane in an optimal position is an essential task in the initial stages of construction planning. This paper proposes a new optimization model to locate the luffing T/C in the optimal position to minimize the transportation time. An optimization algorithm, the Harmony Search (HS) algorithm, was used and the results show that HS has high performance characteristics to solve the optimization problem in a short period of time. In a case study, the proposed model offered a better position for T/C than the previous heuristic approach.

Keywords: Tower crane, Optimization, Harmony Search algorithm

I. INTRODUCTION

Material handling is considered a significant task of construction projects, and tower cranes (T/C) are the most important facilities used for this, especially in a tall building construction site [1]. As the operation efficiency of T/Cs largely depends on their locations, this should be comprehensively taken into account in the project planning stages [2]. To ensure a good T/C location, a suitable T/C needs to be assigned to an appropriate position that can optimize operations. Also, optimizing the locations of a group of T/Cs is crucial in a tall building project, since many T/Cs are used and located in close proximity. Much information is required to select the optimal location of T/C, such as machine performance specifications, material lifting planning, space constraints conditions, etc. Unfortunately, much of this information is qualitative and requires subjective judgments, which cannot be appropriately utilized by the users who determine the locations of T/Cs with their heuristic approaches. Therefore, a more objective approach for crane location is required.

Due to the importance of the appropriate assigning of locations for T/Cs, many models have been developed based on lifting time and cost [3]. A mathematical model was first developed by Rodriguez-Ramos and Francis [4] to find the optimum location of a tower crane on a construction site. The model focused on the radial and angular movement of construction materials. The objective of the model was the minimization of the total transportation cost incurred by the operation of the crane. Zhang et al. [5] proposed a major important model based on a mathematical formula for a group of T/Cs and the main function was then later used by Tam and Hoang et al. [6-8]. Tam developed a simulation model for predicting tower crane operations, and a Genetic algorithm was used to optimize the T/C layout. The previous researches are classified as two part, one is suggesting a new optimization algorithm to solve the locating problem, and another is ensuring the validity of the optimization model. On the other hands, the previous researches are commonly more focused on a general case such as low-rise building not a high-rise building.

Although many models and various methodologies have been developed to optimize T/C locations, previous studies have common limitations. Existing models focus on the T-type crane or mobile crane, even though the luffing type crane is most widely used in a tall building construction. Abdelmegid et al.[9] include the importance of crane types, but their operation models and mathematical formulas assume typical patterns used in the T-type crane.

Therefore, this paper suggests a new model for determining luffing T/C location in a tall building construction. The objective of the model is to find the optimal location of the luffing T/C that can minimize material transportation time. The model application is limited to the RC structure of the tall building construction case, and luffing type tower cranes are primarily considered when locating cranes. A new approaches, the Harmony Search algorithm (HS) is used to optimize the T/C selection problem, and its high performance criteria enhances the ability to find better solutions in a short period of time.

II. TOWER CRANE SELECTION MODEL

In tall building projects, locating tower cranes is an important task in the initial stages of construction planning since it has a major role in project cost and duration related to project productivity. For example, according to the location of T/C, the transportation distance for materials will completely different since the working patterns of T/C is changed by the location of T/C, and this critically affects the time and cost of the entire construction. It is also important that suitable types of T/Cs are located at the appropriate locations since transportation load varies according to the

[1,2] Ph.D candidate, School of Civil, Environmental and Architectural Engineering, Korea University, Seoul, Korea, ldm1230@korea.ac.kr
[3] Professor, School of Civil, Environmental and Architectural Engineering, Korea University, Seoul, Korea, hhcho@Korea.ac.kr(*Corresponding Author)
[4] Professor, School of Civil, Environmental and Architectural Engineering, Korea University, Seoul, Korea, kikang@Korea.ac.kr

location. As the lifting load of a location increases, the power required of the T/C installed also increases. The current T/C selection process used in practice is shown in Fig. 1 based on the literature review for an RC structure.

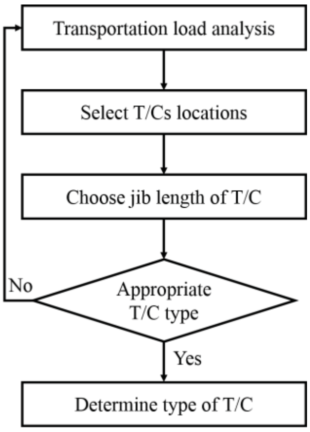

Fig. 1. T/C selection process in practice

When locating a T/C in an RC construction, the material lifting load, such as maximum material weight and the quantity of materials, is first analyzed. The materials are mainly packing units of steel.

Secondly, the possible location of T/C is determined considering interference with the concrete pumping machine, building core, other T/Cs, and various site conditions. Two options are possible when locating T/Cs: internal (inside) or external (outside) of the building. When T/Cs are located inside the building, they are generally attached to the core or walls. If T/Cs are installed outside of the building, the locations are determined according to the distances to the entrance gate or stock yard. Since each option has pros and cons, each option should be carefully considered.

After the locations are determined, the jib length of the T/C should be selected considering the working radius of the T/C (related to the maximum torque and lifting efficiency). Even if the lifting capacity of the T/C is greater than the maximum load of a material, the supply and demand point of materials must be within the working radius.

Selecting the T/C machine type is also a significant task; generally, T-type or luffing-type machines are used. The T-type is more efficient, less expensive, and easier to control than the luffing type, but the luffing type is more widely used in tall building construction since it has more flexible mobility and causes less interruption to other objects when operating. The selected alternatives are finally determined by experts through economic and safety analysis.

In this optimization model, material handling time should be calculated in accordance with the lifting materials, mainly steel bars in RC building construction. On the other hand, historical data of the average lifting time and the installation and dismantling time of such materials are analyzed and the appropriate number of T/Cs is selected. The project cycle time is also important, because the proper number of T/Cs is dependent on the objective of the cycle time (3-day cycle or 4-day cycle). An example of this analysis is shown in table 1.

Table 1. Required number of T/C calculation examples (HYUNDAI Development Company)

Section	**Section #OO / 3-day cycle**		
	D+1	**D+2**	**D+3**
Steel bar units	532 min	300 min	560 min
Prefab Steel	240 min	185 min	-
Link Beams	-	250 min	150 min
MEP	52 min	60 min	70 min
The others	80 min	80 min	80 min
Total lead time	15.1 h	14.6 h	14.3 h
Working efficiency	85 %	85 %	85 %
Operational time	17.7 h	17.2 h	16.9 h
Required T/C (20 ton class)	**1.8**	**1.8**	**1.7**

The 1.8(D+1), 1.8(D+2), and 1.7(D+3) values imply that at least 2 tower cranes are needed in this section to avoid any lifting delay. The results are roughly calculated based on a specific assumption; 20 ton class luffing crane (hoisting capa.: 50m/min, luffing: 2.5min, 1.0min). Once the number of T/Cs required is determined, the location of each T/C should then be decided.

III. Harmony Search (HS) for T/C Selection

Recently developed by Geem et al. [10], HS mimics the music improvisation process where music players improvise the pitches of their instruments to obtain better harmony. Detailed descriptions of HS can be found in Geem et al. [10]. This paper suggests a new model for T/C location using the HS algorithm. The proposed process is illustrated in Fig. 2

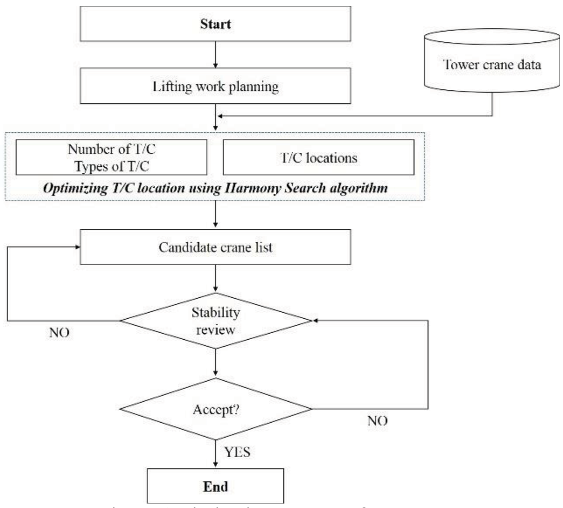

Fig. 2. Optimization process of

The detailed optimization process is explained below.

1. Define the variables and parameters.

$XD_j, YD_j, ZD_j = coordiate\ of\ a\ demand\ point(m)$

$XS_i, YS_i, ZS_i = coordinate\ of\ a\ supply\ point(m)$

$P(D_{ij})$
$= distance\ from\ supply\ point(i)\ to\ demand\ point(j)(m)$

$P(D_j) = distance\ from\ crane\ point\ to\ demand\ point(m)$

$P(S_i) = distance\ from\ crane\ point\ to\ supply\ point(m)$

$XS'_i = XS_i cos\theta - XS_i sin\theta + XCr_n * XS_i - XCr_n cos\theta *$
$XS_i + YCr_n sin\theta * XS_i$(rotation θ °)(m)

$YS'_i = YS_i sin\theta + YS_i cos\theta + YCr_n * YS_i - XCr_n sin\theta * YS_i -$
$YCr_n cos\theta * YS_i$(rotation θ °)(m)

$XCr_n, YCr_n, ZCr_n = coordiate\ of\ a\ tower\ crane(m)$

$V_L = luffing\ velocity(m/min)$

$V_H = hoisting\ velocity\ of\ hook(m/min)$

V_ω = *slewing velocity of crane jib(r.p.m)*

Z_L = *luffing movement height(m)*

$T_\omega = time\ for\ slewing\ movement\ of\ hook(min)$

$T_L = time\ for\ luffing\ movement\ of\ hook(min)$

$T_H = time\ for\ hoisting\ of\ hook(min)$

$T_b = material\ binding\ \ \&\ unting\ time$

$\Theta_{ij} = angle\ between$ $P(S_j)$ and $P(D_j)$

$HMCR = hamony\ memory\ considering\ rate$

$HM = harmony\ memory$

$PAR = pitch\ adjusting\ rate$

Decision variable = Location of T/Cs, $(\boldsymbol{XCr_n}, \boldsymbol{YCr_n}, \boldsymbol{ZCr_n})$

2. Define feasible demand and supply points for materials

.

$$\begin{matrix} XD_1, XD_1, ZD_1 & XS_1, YS_1, ZS_1 \\ XD_2, XD_2, ZD_2 & XS_2, YS_2, ZS_2 \\ \vdots & \vdots \end{matrix}$$

3. Define the available positions for the T/C location

$$\begin{matrix} XCr_1, YCr_1, ZCr_1 \\ XCr_2, YCr_2, ZCr_2 \\ \vdots \\ XCr_n, YCr_n, ZCr_n \end{matrix}$$

4. Generate a harmony vector for the decision variables

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \cdots & x_{N-1}^1 & x_N^1 & f(x^1) \\ x_1^2 & x_2^2 & \cdots & x_{N-1}^2 & x_N^2 & f(x^2) \\ \vdots & \cdots & \cdots & \cdots & \cdots & \vdots \\ x_1^{HMS} & x_2^{HMS} & \cdots & x_{N-1}^{HMS} & x_2^1 & f(x^1) \end{bmatrix}$$

Where,
N: number of decision variables
HMS: harmony memory size

4. Constraints check

The maximum weight of materials must be less than the maximum capacity of T/C to avoid safety problem. Especially, the tip load (max. capa. at max. length) is a significant load constraint factor when locating T/C.

$$\forall Weight\ of\ steel\ member < \forall tip\ load\ of\ T/C$$

5. Define fitness function

The aim of the proposed model is the minimization of the material transportation time by locating T/Cs in appropriate positions. The fitness function (objective function) is shown below.

$$\boldsymbol{Objective\ Function = minimize\ \sum T_T}$$

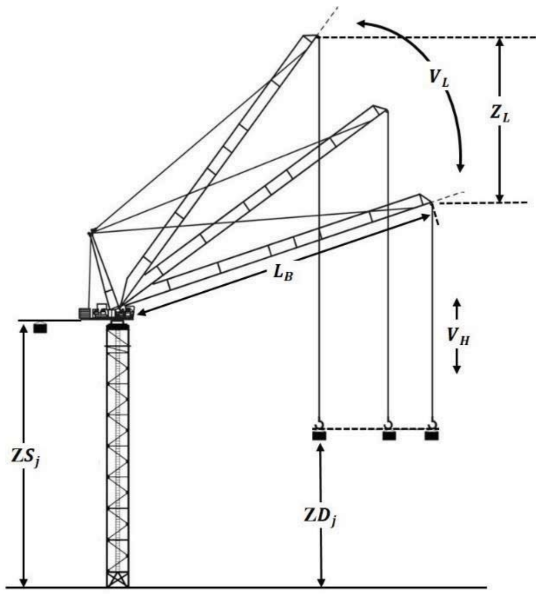

Fig. 3. Movement of crane hook

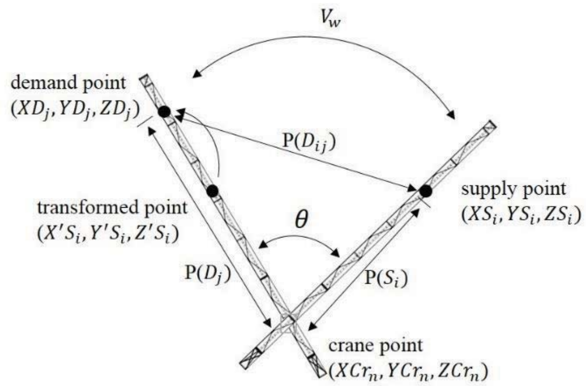

Fig. 4. Movement of crane hook

$$P(D_j) = \sqrt{(XD_j - XCr_n)^2 + (YD_j - YCr_n)^2}$$

$$P(S_j) = \sqrt{(XS_i - XCr_n)^2 + (YS_i - YCr_n)^2}$$

$$P(D_{ij}) = \sqrt{(XD_j - XS_i)^2 + (YD_j - YS_i)^2}$$

$$T_{\omega} = \frac{1}{V_w} \cdot \arccos\left(\frac{\mathrm{P}(D_{ij})^2 - P(D_j)^2 - P(S_i)^2}{2 \cdot P(D_j) \cdot P(S_j)}\right)$$

$$T_L = \frac{\left(\sqrt{L_B^2 - \{(XCr_n - XS'_i)^2 + (YCr_n - YS'_i)^2} - \sqrt{L_B^2 - \{(XCr_n - XD_j)^2 + (YCr_n - YD_j)^2\}}\right)}{V_L}$$

$$T_H = \frac{|ZS_i - ZD_j|}{V_H}, \quad \Theta = \arccos\left(\frac{\mathrm{P}(D_{ij})^2 - \mathrm{P}(D_j)^2 - \mathrm{P}(S_i)^2}{2\mathrm{P}(D_j)\mathrm{P}(S_i)}\right)$$

$$where,\ T_T = 2 \times (T_{\omega} + T_L + T_H) + T_b$$

6. Harmony Memory Considering Rate(HMCR) and Pitch Adjustment Rate(PAR) rules are applied to the functions.

7. Repeat the process until the termination condition

If newly generated harmony vector $\boldsymbol{x}^{new}$ is better than the worst harmony $\boldsymbol{x}^{new}$ in HM (the evaluation is based on fitness function), then exclude $\boldsymbol{x}^{worst}$ from the HM. As a result, HM will be updated with better solutions as the iteration continues.

IV. CASE STUDY

A. Case description

The proposed optimization model was applied to an actual project to verify its applicability and demonstrate the benefits. Three high-rise residential buildings, T1, T2, and T3 (at least 46-storys), are located near each other and all of the applied T/C were luffing type cranes. The designed layout planning for the site and the available area for T/C are illustrated in Fig. 5.

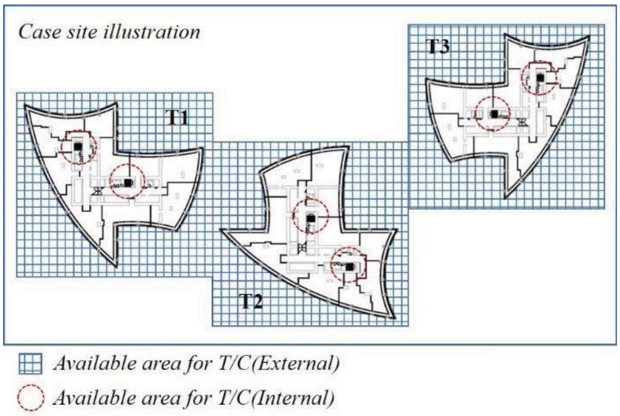

Fig. 5. Available area for T/C location

On the other hand, the lifting load for the case site can be calculated quantitatively from the lifting work planning. Since this case site plan uses a various cycle time according to the progress of project (5day-3day-4day), the proposed model adopts a criterion with a 3 day cycle. Also, when calculating the lifting load, the lifting of rebar and steel members is only considered because these are the main materials of T/C handling. The lifting load differs according to the day and section zones, even in a 3-day cycle. Therefore, global optimization is required when locating T/C, considering the lifting load each day. See Table 2.

Table 2. Quantities of steel reinforcement

		Zone	D+1	D+2	D+3
3-Day Cycle	CORE	A	30		4
		B		3	25
	Perimeter zone	A	9		16
		B	13	7	
		C		19	11
Total			52	29	56

Also, after a T/C location has been selected, the required T/C capacity at a certain length can be obtained. Even though the maximum lifting capacity of a T/C is greater than the maximum weight of materials, these specific load constraints (tip load, 50m, 40m, 30m) must be satisfied (constraints check). A detailed database for the case site is drawn in Table 2.

Table 3. Required T/C capacity at certain points

Section		T1	T2	T3
Internal Capa. (ton)	Tip load	5.0	5.0	5.0
	60m	9.0	15.0	8.2
	50m	15.0	16.0	9.5
External Capa. (ton)	Tip load	5.0	5.0	5.0
	50m	8.5	8.5	7.5
	30m	12.0	10.5	11.0

In this study, the developed optimization model was only applied to the T1 area as a preliminary research. Also, an infinite number of feasible points in the T1 area is possible for T/C, but only 15 available selected positions were taken into account in the optimization process.

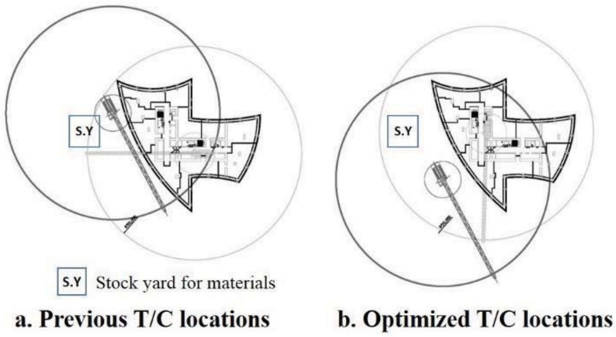

Fig. 6. Comparison between heuristic and optimized models

Table 4. Comparative analysis

	Previous locations	Optimized locations
Installation type	1 external, 1internal	1 external, 1internal
Slewing time(T_{ω})	79.7 min	85.5 min
Luffing time(T_L)	181.8 min	120.4 min
Hoisting time(T_H)	545 min	544 min
Total transportation time ($T_{\omega} + T_L + T_H$)	**806.5 min**	**749.9 min**

The two location solutions from the heuristic approach and the proposed model are illustrated in Fig.6. The installation type was the same as the 1 external and 1 internal, but their locations somewhat differ. The slewing time of the optimized model is longer than that of the previous model. It seems that the optimized model suggests more slewing motion than the previous model. The luffing time was reduced according to the proposed model by about 34% (181.8 min for heuristic solution and 120.4 min for optimized model). The hoisting time was almost the same since the vertical movement is not related to the T/C location. The differences between the slewing time and luffing time are significant. Since the average time of luffing spent is longer than the slewing time, the luffing factor should be more reflected when locating the T/C. Luffing time is related to the distances between the position of cranes and the material supply point and material demand point. Therefore, the luffing time could be minimized by arranging a T/C such that the difference is minimized.

V. CONCLUSION

Tower cranes are typically used on many building construction sites to lift various materials vertically and horizontally. The increase of transportation distance and complex work procedure in tall building construction make it difficult to select the optimal T/C location. Therefore, the proposed model could assist decision-making when determining the T/C location using an objective approach.

In fact, developing an optimization model for T/C locations has been variously conducted around the world. The most critical difference between this study and the previous studies is in the type of T/C. Previous researches placed greater focus on the T-type or mobile type cranes when considering the location of T/C. Some studies are open to the possibilities of a luffing type crane, but there calculation models and mathematical formula assume a typical pattern used in the T-type crane. The newly suggested model for determining the luffing crane operation time can be used in many studies, including luffing crane movement.

Further improvement of the suggested model can be carried out to expand its applicability. Also, as the number of T/Cs used increases, their location optimization could be even more critical and previous heuristic approaches cannot evaluate their efficiencies. On the other hand, other optimization algorithms or research methodologies can be applied to the proposed model in order to assess the most suitable technique for the problem.

ACKNOWLEDGEMENTS

This research was supported by a grant(14CHUD-B059157-06) from High-tech Urban Development Program funded by Ministry of Land, Infrastructure and Transport of Korean government.

REFERENCES

[1] S. Alkass, M. Alhussein, and O. Moselhi, "Computerized crane selection for construction projects," *Journal of Construction Engineering and Management. Association of Researchers in Construction Management,* vol. 2, pp. 427-36, 1997.

[2] A. Sawhney and A. Mund, "IntelliCranes: an integrated crane type and model selection system," *Construction Management and Economics,* vol. 19, pp. 227-237, 2001/03/01 2001.

[3] J. Irizarry and E. P. Karan, "Optimizing location of tower cranes on construction sites through GIS and BIM integration," *Journal of Information Technology in Construction (itcon),* vol. 17, pp. 351-366, 2012.

[4] W. Rodriguez-Ramos and R. Francis, "Single Crane Location Optimization," *Journal of Construction Engineering and Management,* vol. 109, pp. 387-397, 1983.

[5] P. Zhang, F. C. Harris, P. Olomolaiye, and G. D. Holt, "Location optimization for a group of tower cranes," *Journal of construction engineering and management,* vol. 125, pp. 115-122, 1999.

[6] C. T. Tam, Thomas K.L; Chan Wilson K.W, "Genetic Algorithm for Optimizing Supply Locations around Tower Crane," *Journal of Construction Engineering and Management,* vol. 127, pp. 315-321, 2001.

[7] C. Tam and T. K. Tong, "GA-ANN model for optimizing the locations of tower crane and supply points for high-rise public housing construction," *Construction Management and Economics,* vol. 21, pp. 257-266, 2003.

[8] C. Huang, C. K. Wong, and C. M. Tam, "Optimization of tower crane and material supply locations in a high-rise building site by mixed-integer linear programming," *Automation in Construction,* vol. 20, pp. 571-580, 2011.

[9] M. A. Abdelmegid, K. M. Shawki, and H. Abdel-Khalek, "GA optimization model for solving tower crane location problem in construction sites," *Alexandria Engineering Journal,* 2015.

[10] Z. W. Geem, J. H. Kim, and G. Loganathan, "A new heuristic optimization algorithm: harmony search," *Simulation,* vol. 76, pp. 60-68, 2001.