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Optimum Tower Crane Selection and Supporting Design Management

Regular Paper

Hyo Won Sohn[1], Won Kee Hong[1], Donghoon Lee[1], Chae-Yeon Lim[1], Xiangyu Wang[2] and Sunkuk Kim[1,*]

1 Department of Architectural Engineering, Kyung Hee University, Korea
2 School of Built Environment, Curtin University, Australia
* Corresponding author E-mail: kimskuk@khu.ac.kr

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Abstract To optimize tower crane selection and supporting design, lifting requirements (as well as stability) should be examined, followed by a review of economic feasibility. However, construction engineers establish plans based on data provided by equipment suppliers since there are no tools with which to thoroughly examine a support design's suitability for various crane types, and such plans lack the necessary supporting data. In such cases it is impossible to optimize a tower crane selection to satisfy lifting requirements in terms of cost, and to perform lateral support and foundation design. Thus, this study is intended to develop an optimum tower crane selection and supporting design management method based on stability. All cases that are capable of generating an optimization of approximately 3,000 ~ 15,000 times are calculated to identify the candidate cranes with minimized cost, which are examined. The optimization method developed in the study is expected to support engineers in determining the optimum lifting equipment management.

Keywords Tower Crane Management, Support Design, Crane Selection, Optimization, Lifting Plan

1. Introduction

A Tower Crane (TC) plan is divided into a tower crane selection phase, and a lateral support and foundation design phase. The respective phases need to satisfy lifting, stability and economic requirements. After a prior examination of stability it is reasonable to determine the economic feasibility by analysing the input cost of the candidate cases. However, engineers do not analyse economic feasibility after establishing lifting plans that are suitable for the construction conditions once they have implemented the construction projects; instead, support design and economic analysis are executed based on data provided by equipment suppliers. This results in only certain parts of various plans being examined that may be drawn based on lateral support designs or the foundation designs of a single tower crane, which makes it difficult to minimize cost.

There are two obstacles that prevent engineers from establishing plans for all the available tower cranes. First, it is extremely difficult and time-consuming to consider different types of supporting systems that can be applied to tower cranes. Second, there is a lack of systematic techniques and data for a method that considers both the stability and economic feasibility of the given candidate. Studies of optimum tower crane selection in accordance with project conditions [1-4] were conducted previously, but an examination of stability was excluded. In addition, Lee et al. [5] proposed a method for analysing the economic feasibility of lateral support and Kim et al. [6] suggested a cost calculation method that can be applied to foundations.

However, these studies do not consider stability and economic feasibility throughout the overall crane management phase, including tower crane selection and support design. In addition, several studies analysing tower crane stability were carried out [14-17], but they did not include economic analyses.

Therefore, this study moves beyond the limitations of previous studies to develop an optimum tower crane selection and supporting design management method. The proposed method is implemented focusing on the process of reviewing tower crane stability and techniques of economic analysis. Furthermore, as demonstrated in Figure 1, the first reviews are of the prior TC selection, followed by the second reviews of foundation design and lateral support, deducing systematic results.

In general, climbing TCs are more common in many countries. However, in high-density, high-rise and multiple building construction projects, stationary TCs are more common because they can cover multiple buildings with a single TC and have good structural stability, easy lateral support, and economic feasibility. In addition, the lateral and gravity load supports of stationary and climbing TCs are quite different from each other, and support systems for different TCs need many different details. Since it is difficult to include all the details in a single paper, only stationary TCs are presented in this paper.

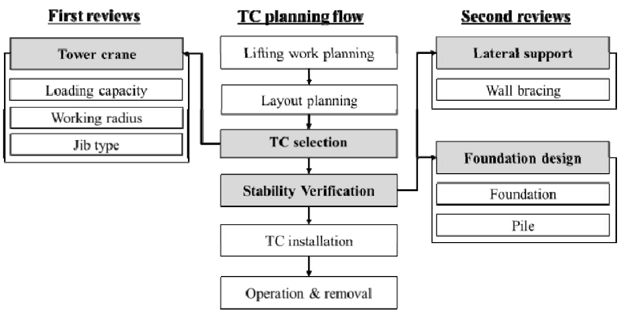

Figure 1. Study Scope

To achieve the objective of this study, we first examine the trends in the study of construction project lifting plans and crane selection, and then propose a process by which to identify the optimum TC and supporting design in consideration of economic feasibility. Secondly, we build a detailed process per phase for economic analysis in connection with the proposed process. Lastly, we develop an economic optimization method that ensures stability based on the established process. The developed processes are helpful in selecting the optimum tower crane(s) by analysing the interconnection of each tower crane's performance (capability), lateral support structure, foundation design, and the individual components required. Furthermore, the economic optimization method is adopted as a technique for optimizing lifting plans.

2. Literature Review

Studies of tower crane selection and stability have been conducted using a wide range of methods. Furusaka and Gray selected optimum tower cranes by using an object function that minimizes rental, installation, and removal costs, proposing a model that combines various crane types. However, their method is difficult to apply to buildings 20 floors or higher that are advantageous in terms of construction period and cost when the same crane is used constantly [1]. Gray and Little [4] proposed a process for selecting mobile cranes and tower cranes that are suitable for the given design at the initial design phase. However, there was no method for examining the stability of the selected crane, and no other method for utilizing the crane information available in the market. Ho et al. [2, 3] suggested an optimum tower crane selection system that can select the most suitable cranes under various site conditions, and examine their stability easily and quickly, as illustrated in Figure 2. However, their study limits the crane installation height to free-standing height, and the review process considers only foundation design and not economic feasibility. Moreover, the TC selection (Figure 2-A) does not clearly propose consideration items and order. Thus, this study supplements the process of Ho et al. which proposes a tower crane selection and supporting design management process (Figure 8).

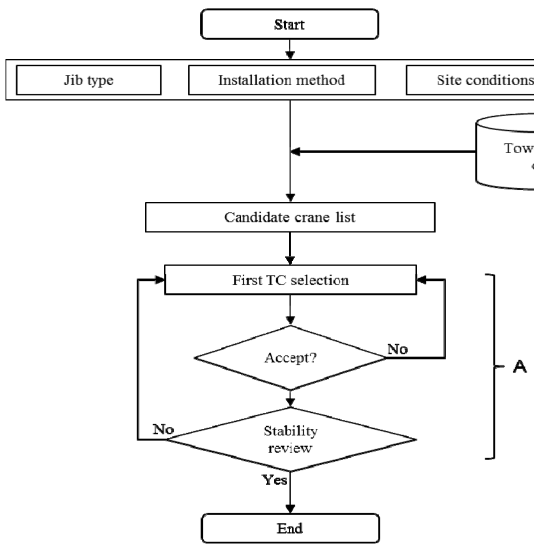

Figure 2. Opti-TC System Process [2]

Gray et al. [14] proposed a systematic approach to the selection of an appropriate crane for a construction site considering stability. Similarly, previous studies related to TC plans have taken stability into account [11-13, 15-17], yet the results were ineffective since there was no economic optimization for the lateral support and foundation. There have been other studies related to lifting plans [7 - 10], but they did not address the concept of Optimum Tower Crane Selection.

Lee et al. [5] developed a lateral support design algorithm for tower cranes. The algorithm can calculate the cost of combining components that fulfil the structural stability of the tower crane lateral support and addresses wall bracing design, bracket design, and stability and cost review. However, these reviews lack a specific method for optimizing structure and component selection, making them ineffective. In addition, Kim et al. [6] suggested a cost calculation method for foundations, but there was no review of stability and economic feasibility throughout the overall phases of tower crane selection. Ali et al. [19] conducted a study on collision avoidance when addressing the combined lifting of mobile cranes, and Perez et al. [18] developed an algorithm for planning collision-free paths among polyhedral obstacles. There are multiple studies on the stability of mobile cranes [20-24], yet they differ from this study since the supporting method differs from that of tower cranes. As for studies related to cranes, studies on the cause of accidents such as overturn and collision [25], and studies related to information technology [26-28] were conducted. Furthermore, studies related to productivity in relation to project conditions include a study into optimizing multiple lifts by Lin and Haas [29] and a computational method for coordinating multiple construction cranes developed by Kang et al. [30]. There was also a study on crane safety monitoring systems [26, 31, 32]. These studies focused on securing stability and safety with no consideration of the optimization process or economic analysis. Most constructions of high-rise buildings are carried out with a tower crane that is installed and operated at a free-standing height. Thus, this study proposes an economically optimized method based on stability, considering a lateral support method when the crane is installed at or above its free-standing height.

3. Economic Analysis of Tower Crane Selection

3.1 Economic Analysis Flow

As lifting plans and crane selection have multiple, dynamic interrelations, influencing factors including not only construction period and cost, but also working radius, work-efficiency, interference with neighbouring buildings and other projects, the number and location of cranes, on-site installation, climbing, maintenance, and removal should be comprehensively taken into account [11]. Since this paper involves fairly complicated dynamic algorithms and stochastic solutions, it is limited to selecting an optimum stationary TC or TCs from among TCs available in the market which satisfy the conditions, maximum lifting load and working radius, provided by the results of the lifting work planning being conducted in cooperation with work groups and satisfying schedule requirements.

The optimum tower crane selection phase can be conceptually illustrated as shown in Figure 3. When the lifting capacity of the tower crane is determined in accordance with the site conditions, available candidate cranes are selected for lateral support and foundation designs. When economic feasibility is compared based on the identified data, an optimum tower crane plan can be selected. After the stability review, the selected candidate tower cranes and components are identified, and subjected to an economic review to determine the optimum tower crane plan.

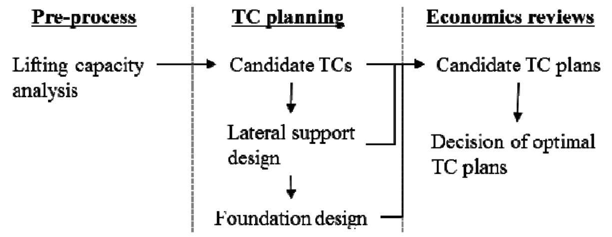

Figure 3. Flow of Economic Review of TC

After the stability review, information on tower cranes and lateral support, and foundation designs are combined to create a TC plan, which is defined as a case for this study. As demonstrated in Figure 4, the generation model used to examine a given case includes a series of processes for extracting the relevant data for the candidates per phase, reviewing stability, and calculating the required cost. In other words, a case includes detailed information and the cost of the support design, the stability of which is secured. When the same method is repeated with a changed structure, multiple cases can be generated. The most economical case among those generated is the optimum tower crane plan. To devise an optimum plan, the generation model is repeated around 3,000 times when the lifting load is 20 tons or more and about 15,000 times when the load is 5 tons or less, and the generated cases are saved in order of the required cost.

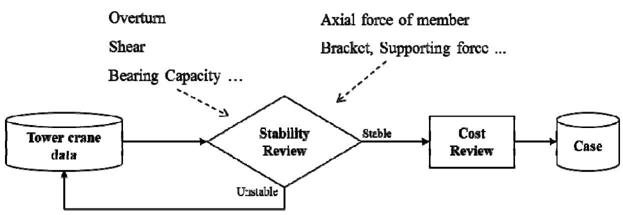

Figure 4. Case generation (Generation model)

3.2 Flow by Economic Analysis Phase

For tower crane selection, the first step is to review drawings, analyse lifting loads, and examine site conditions to establish a basic lifting plan. Based on the established lifting plan, the location, capacity, and the number of tower cranes are determined. Engineers then select tower cranes that are suitable for the given site conditions, as shown in Figure 5. These variables are reviewed in accordance with the cause-effect sequence. After the tower cranes are selected, an appropriate jib length should be selected, and the TC type may be altered depending on the jib type. Moreover, TC and jib types affect stability, which should all be taken into consideration. After stability reviews of the selected TC and jib types have been conducted as illustrated in Figure 5, their economic feasibility is analysed.

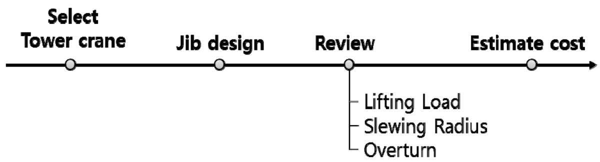

Figure 5. TC selection flow

Lateral support design is performed mainly in five steps, as shown in Figure 6. In the first step, a tower crane is selected and a wall brace structure is designed. When the structure is determined, suitable supporting beams and brackets are selected to carry out a stability review of the axial force of members and support points. If no abnormality is detected during the stability review, the design is completed. Multiple design solutions that are capable of ensuring tower crane stability may be generated, and economic analyses are conducted for those solutions.

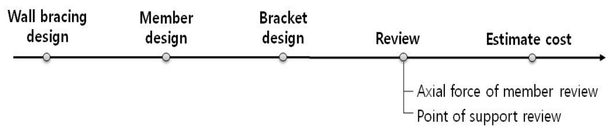

Figure 6. Lateral support design flow

As illustrated in Figure 7, there are two types of tower crane foundation – a single foundation or a foundation with piles. These two types have different design and stability review features. In the case of a single foundation, its overturn, shear, bearing capacity, and pile resistance force should be examined, whereas a foundation with piles requires a stability review of the pile resistance force and pile pull-out. If it is impossible to ensure bearing capacity only with a single foundation or difficult to ensure economic feasibility due to excessive size, then the 'B' pile plan step is conducted at point A, as shown in Figure 7. The stability review method applied to tower crane selection and lateral support design is also adopted for the stability review of the foundation. Economic analyses of the candidates are then conducted.

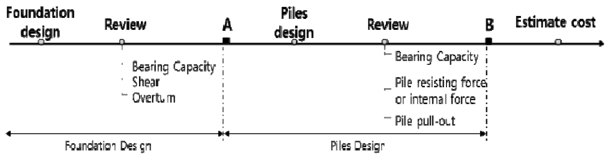

Figure 7. Foundation design flow

As demonstrated in Figure 8, the process of making the tower crane plan is composed of steps 1~3. In step 1, TC candidates are chosen based on jib types, installation methods, and operation conditions during the first step of tower crane selection [2]. Here it is important to check whether the tower cranes can be rented and information regarding the selected TC candidates is utilized for the designs at steps 2 and 3. Step 2 of lateral support design and foundation design is conducted with detailed reviews, so the study proposes a process for each phase. For a simplified process, economic analysis is carried out for each phase of the tower crane selection, lateral support design, and foundation design. The features to be reviewed for the economic analyses (such as equipment types and members) are individually extracted in accordance with the selection process to generate a case.

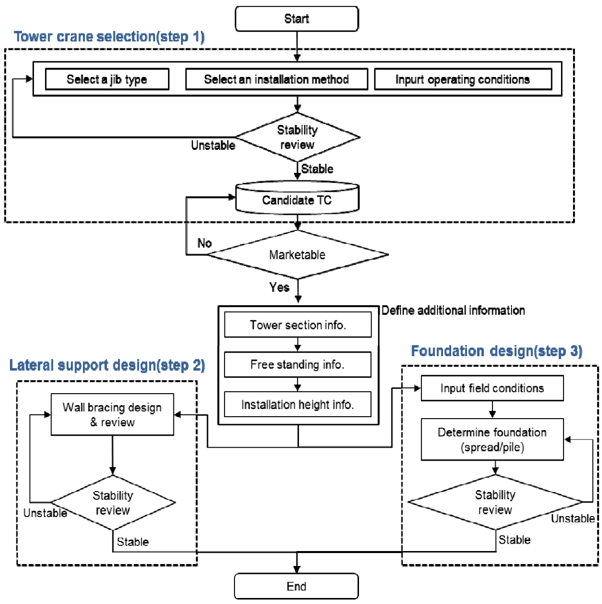

Figure 8. TC selection and supporting design process

4. Tower Crane Selection

As previously specified, TC types are selected based on plane requirements such as the site lifting load and working radius, as well as elevation requirements such as the lifting height. The lifting capacity determined by the slewing radius of a TC may vary by TC type, so plane analysis should be conducted based on the on-site lifting plan as described in the detailed process of tower crane selection (step 1) shown in Figure 9. Here the aim is to minimize the tower crane rental cost (CTC) as shown in formula 1, and the working radius (WR) and lifting capacity (LC) should meet or exceed the requirements. The highest lifting height is then examined to analyse the appropriateness of the given TC type. The information on the selected TC and jib candidates is saved for the calculation of the rental cost, which is the basis for the processes of step 2 and step 3.

$$\textit{Minimize} \{ C_{TC} \} \quad (1)$$

Subject to: $WR_{(t)} \geq$ ***required working radius***

$LC_{(t)} \geq$ ***required lifting load***

where, $WR_{(t)}$ ***= working radius of selected tower crane***

$LC_{(t)}$ ***= lifting capacity of selected tower crane***

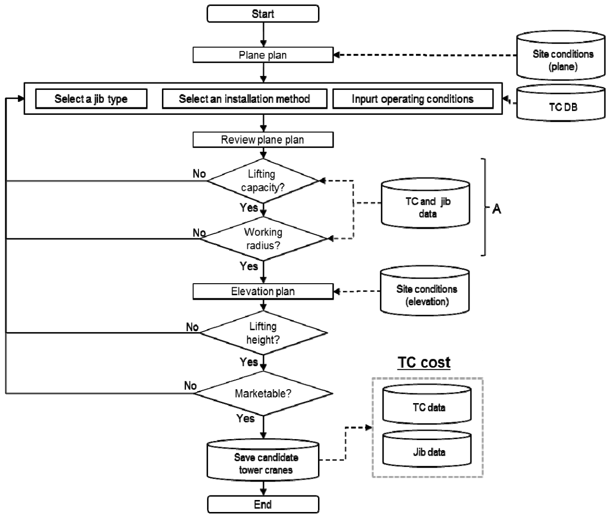

Figure 9. Economic Review upon TC Selection Process (step 1)

When analysing the plane for TC selection, the lifting capacity, adjusted for the working radius, should meet the required lifting load. The working radius defined here differs from the slewing radius (which indicates the available working scope based on the lifting capacity), and it should be reviewed based on the maximum lifting load. That is, TC types and jib lengths should both be considered, implying that a single TC type may have various jibs that meet the required lifting load. In addition, lateral support and foundation designs may be altered depending on the jib length, even changing the lifting capacity. Figure 10 is a graph expressing the working radius, suitable for the lifting load of a 20 ton TC, and the dotted line represents a working radius of 35 m for a 10 ton lifting work load when the slewing radius is 72 m (jib length).

Radius (m)	19.8	36	40	44	48	51.7	56	60	63.3	68	72	75
Load (ton)	20	10.3	9.11	8.13	7.31	6.65	6	5.48	5.09	4.61	4.25	4

Table 1. Radius - Lifting capacity relationship (20 ton, 72 m jib)

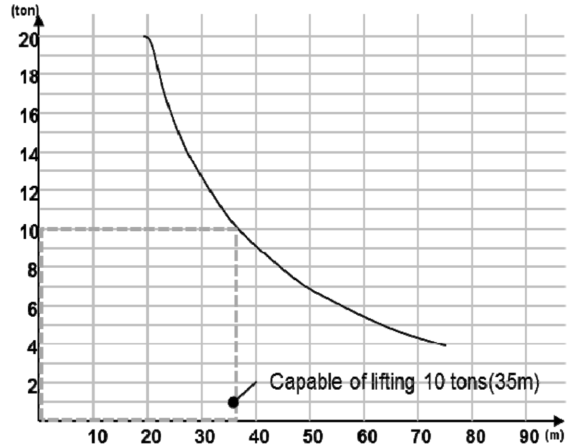

Figure 10. Radius - Lifting capacity relationship (20 ton, 72 m jib)

Figure 11 shows the relationship of the working radius to lifting capacity when a 50 m jib is applied to the same TC shown in Figure 10. The working radius for a 10 ton lifting work is 50 m when a 50 m jib is applied, which is broader than the expensive 72 m jib. As shown in this case, the TC type and jib should be selected based on the radius-lifting capacity relationship by analysing the lifting work to be performed on site, and this is closely related to economic feasibility. Therefore, when reviewing the lifting capacity and working radius at point A in Figure 9, the information for both the TC and jib should be applied.

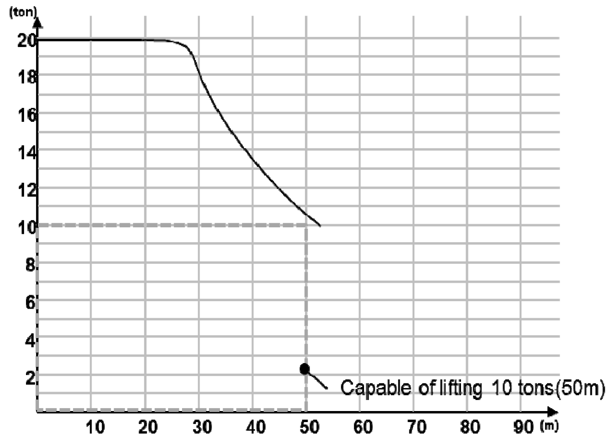

Figure 11. Radius - Lifting capacity relationship (20 ton, 50 m jib)

5. Lateral Support Design

The lateral support process of the tower crane (step 2 of Figure 8) requires a consecutive review of stability as demonstrated in Figure 12. There are two types of lateral support methods: a wall bracing method and a rope guying method. However, the scope of the study is limited to the wall bracing method. The wall bracing method involves firmly fixing the tower crane mast to the building wall or slab depending on the site conditions and location of the tower crane installation. After selecting a tower crane and taking into account the site conditions, project characteristics, and work conditions, both stability and economic feasibility are reviewed for lateral support design, and the tower crane is then firmly braced and fixed. The wall bracing of the tower crane is largely composed of a master frame, a spacing support, and a bracket.

Radius (m)	20	36	40	44	48	51.7
Load (ton)	20	15.04	13.39	12.04	10.9	10

Table 2. Radius - Lifting capacity relationship (20 ton, 50 m jib)

The stability review of the lateral support is performed consecutively and a flow chart of this process is shown in Figure 12. Above all, the information concerning the tower crane selected during the stability review is used to input the lifting load and lateral force, which are the basis for the lateral support design. The wall bracing method is implemented in accordance with the site conditions based on the wall bracing design data and the information of the selected tower crane. Furthermore, after establishing the installation height and intervals of the wall bracing, the components and brackets for the support are set. A wide range of component and bracket specifications should be applied to confirm stability. When applicable components are chosen, compressive stress, reaction and the compressive stress of the bracing part are reviewed. If it lacks stability, such components and brackets should be replaced to ensure stability. The reviews are intended to minimize the cost (CWB) as shown in formula 2, and the compressive stress (σc) should meet the constraints of formula 2. These stability reviews and the selection of components and brackets are consecutively implemented to generate various lateral support plans.

$$\textit{Minimize}\ \{\, C_{WB} \,\} \qquad (2)$$

$$\textit{Subject to:}\ \ \sigma_c \le f_c \ \text{(Compressive stress)}$$

where σ_c: Compressive stress acting on lateral support section
f_c: Allowable compressive stress of lateral support components

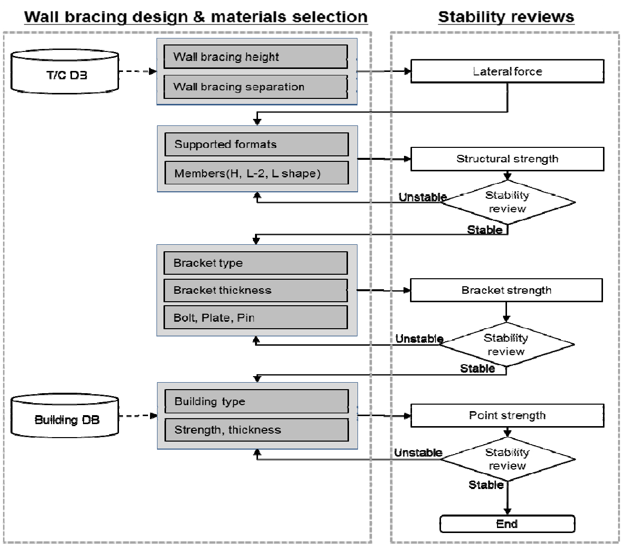

Figure 12. Features of the Review for the Lateral Support Design

The lateral support design process is composed of two steps – the supporting beam selection and bracket selection – as illustrated in Figure 13. Firstly, the information concerning the tower crane selection (TC type, section size, and jib length) determined in the previous stage is used while taking into account the lateral support method of the tower crane. The next step is to establish the installation height and spacing; first, the supporting beam installation height is inserted, and then the supporting beam separation is set. The designed lateral force (which is the lateral force applied to the spacing supporting beam at the height where the wall bracing is installed) should be reviewed, and the spacing supporting beam to be installed on a plane and the supporting point coordinates should be set. In addition, the bracing member type should be determined. Initially, structural shape steels such as H-shape steel, L-2 shape steel, or L-shape steel should be determined, and then the final member type that can secure structural stability should be selected. Finally, the bracing cost is calculated based on the information regarding the installation method, component length and component types.

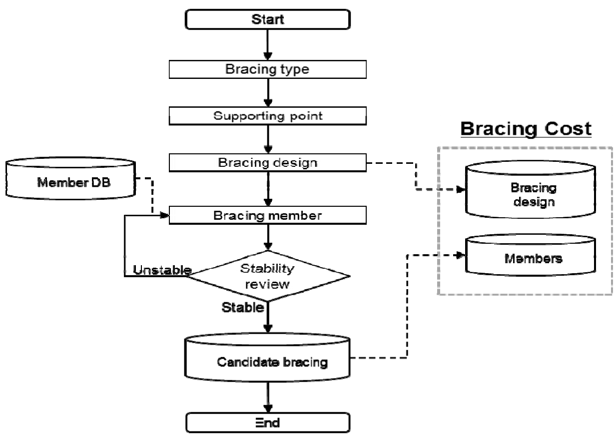

Figure 13. Economic Review Process for Bracing (step 2-1)

As shown in formula 3, the price (P_s) is substituted for the quantity of shape steel (Q_s), and the price (P_j) is reflected in the joint quantity (Q_j) to be added to the labour cost (C_l) to calculate the wall bracing cost (C_W).

$$C_w = (Q_s \times P_s) + (Q_j \times P_j) + C_l \qquad (3)$$

The components used in the economic review of the wall bracing are used, by specification, to determine the appropriate components based on the allowable stress. H-shape steel, L-shape steel, and L2-shape steel are used for the wall bracing supports, and round steel, which is rarely used, is excluded. Tables 3-5 present extracted data for the respective steel shapes and representative components are organized by specification.

No.	H	B	t1	t2	r	area	weight
1	100	50	4	6	7	9.94	7.8
2	125	60	4.5	6.5	8	13.39	10.5
3	148	75	5	7	8	17.85	14
				⋮			
n	900	300	16	28	28	309.8	243

Table 3. H-Shape Steel Specifications

No.	A	B	t	r1	r2	area*2	area	Weight*2	weight
1	40	40	3	4.5	2	4.672	2.336	3.66	1.83
2	45	45	4	6.5	3	7.784	3.892	5.48	2.74
3	50	50	6	6.5	4.5	11.288	5.644	8.86	4.43
						⋮			
n	250	250	35	24	18	325.2	162.6	256	128

Table 4. L2-Shape Steel Specifications

No.	A	B	t	r1	r2	area	weight
1	40	40	5	4.5	3	3.755	2.95
2	45	45	4	6.5	3	3.892	2.74
3	50	50	4	6.5	3	3.892	3.06
				⋮			
n	250	250	35	24	18	162.6	128

Table 5. L-Shape Steel Specifications

Figure 14 shows a bracket design process for the lateral support design, and stability reviews of the plates, bolts, pins, and supporting structures are performed to review the compressive and tension forces in order to secure the axial force of the components. Furthermore, the maximum reaction imposed at each supporting point is reviewed to ensure stability. Furthermore, the cost is calculated based on the information regarding the structure reinforcing method, brackets, bolts and pins, as with the method applied to the bracing selection process.

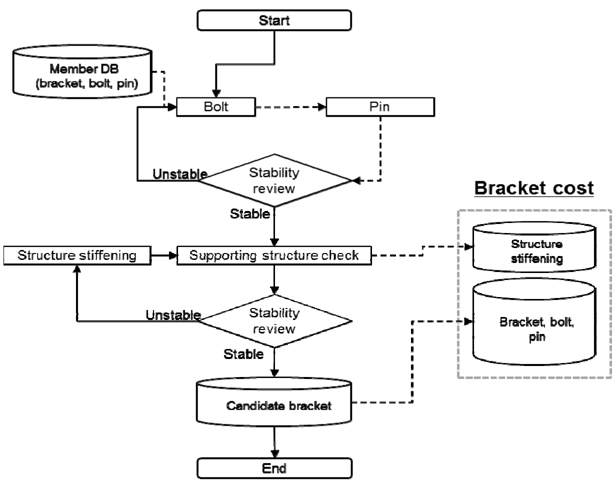

Figure 14. Economic Review Process for Brackets (step 2-2)

After the frame cost is reviewed, the bracket cost (C_b) is calculated by the prices (P_{bp}, P_{rp}, P_{st}, P_{bt}, P_p) of the quantity of base plates (Q_{bp}), rib plates (Q_{rp}), stiffeners (Q_{st}), bolts (Q_{bt}) and pins with the labour cost (C_l) added, as shown in formula 4.

$$C_b = (Q_{bp} \times P_{bp}) + (Q_{rp} \times P_{rp}) \\ +(Q_{st} \times P_{st}) + (Q_{bt} \times P_{bt}) \\ +(Q_p \times P_p) + C_l \quad (4)$$

6. Foundation Design

The foundation design process represented as step 3 of Figure 8 proceeds in two parts. The first part is to determine the foundation specifications by examining the stability of the soil bearing capacity of the foundation and the pile foundation. In particular, the geological conditions of the given site should be analysed when selecting the pile foundation, and if it lacks in soil bearing capacity or if the foundation cannot be enlarged to a certain size, a pile foundation is designed in the second part. A stability review of the foundation design is conducted following the procedure demonstrated in Figure 15. Concrete strength is examined as basic data for the stability review of the soil bearing capacity that meets the site conditions. In addition, an allowable soil bearing capacity is the bearing capacity of the loaded ground, where the load per unit area is applied. The foundation size and thickness are analysed to determine the foundation specifications. The first priority is to review the stability of the soil bearing capacity; if it exceeds the allowable soil bearing capacity, the foundation may settle, overturning the tower crane. Thus, its risk should be reviewed. Several reviews should be carried out by changing the pile design or foundation specifications. Furthermore, the shear strength related to the foundation specifications needs to be reviewed. For a stability review of the pile, the maximum loading force and allowable loading force on the pile are examined. Foundation and pile reviews are intended to minimize the required cost, and the cost is calculated as shown in formula 5.

$$Minimize\ \{ C_F \} \quad (5)$$

Subject to:

$\sigma_{conc} \leq f_{conc}$ (Bearing capacity)

$e \geq l_s/3$ (Overturning)

$V_u \leq \Phi V_c$ (Shear)

$P_{max} \geq P_a$ (Pile capacity)

where

σ_{conc}: ***Bearing capacity of concrete,***

f_{conc}***: Allowable bearing capacity,***

e: Eccentricity,

L_s***: Length of foundation,***

V_u***: Shear strength affecting concrete foundation,***

ΦV_c***: Nominal shear strength of concrete foundation***

P_a***: Allowable loading force on a pile,***

P_{max}***: Maximum loading force on a pile,***

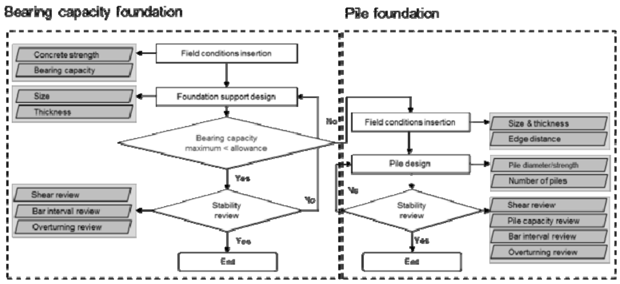

Figure 15. Review Items upon Foundation Design

Since tower cranes are selected in consideration of lifting load and working radius, the lifting load and free-standing height are imported from the tower crane selected during foundation design, which is utilized in the design standards. As illustrated in Figure 16, when tower crane selection is completed, the tower crane information and foundation design standards are applied to design the foundation, and rebar specifications and reinforcement of rebar spacing are established. Here, the rebar specification and reinforcement of rebar spacing are generated based on the RC design information proposed in the study by Kim [6], and the minimum quantity of rebar is applied to prevent over-design of rebar. The next step is to review the stability of overturn and shear, and if it is proven to be unstable, the foundation size and reinforcement of rebar should be changed. After this process is repeated to secure the stability of overturn and shear, the bearing capacity is reviewed to determine whether to install the pile. Information pertaining to the economic review of the foundation includes the form installation cost, the quantity of reinforced rebar and concrete. The method used to calculate the foundation cost is similar to that applied to general reinforced concrete construction, so it is discussed further here.

If it is impossible to secure the bearing capacity because the foundation size is limited due to the site conditions, or if the foundation size is too large to secure the bearing capacity, its efficiency and economic feasibility decrease. In such a case, the foundation size is restricted and the pile is reinforced to generate an efficient foundation design. Pile specifications and quantity should be established to ensure there is sufficient bearing capacity. The foundation size is considered for the designed pile to review spacing, pile bearing capacity, and pile pulling, and the bearing capacity of the completed design is reviewed once again. Moreover, information concerning the pile specifications and quantity are required for an economic review, which should be saved for each case. The cost for pile and foundation work (C_f) is calculated by multiplying the quantity of the foundation (Q_f) by the unit price (P_f) and the price (P_{pf}) by the quantity of piles (Q_{pf}) with the labour cost (C_l) added, as shown in formula 6.

$$C_f = (Q_f \times P_f) + (Q_{pf} \times P_{pf}) + C_l \quad (6)$$

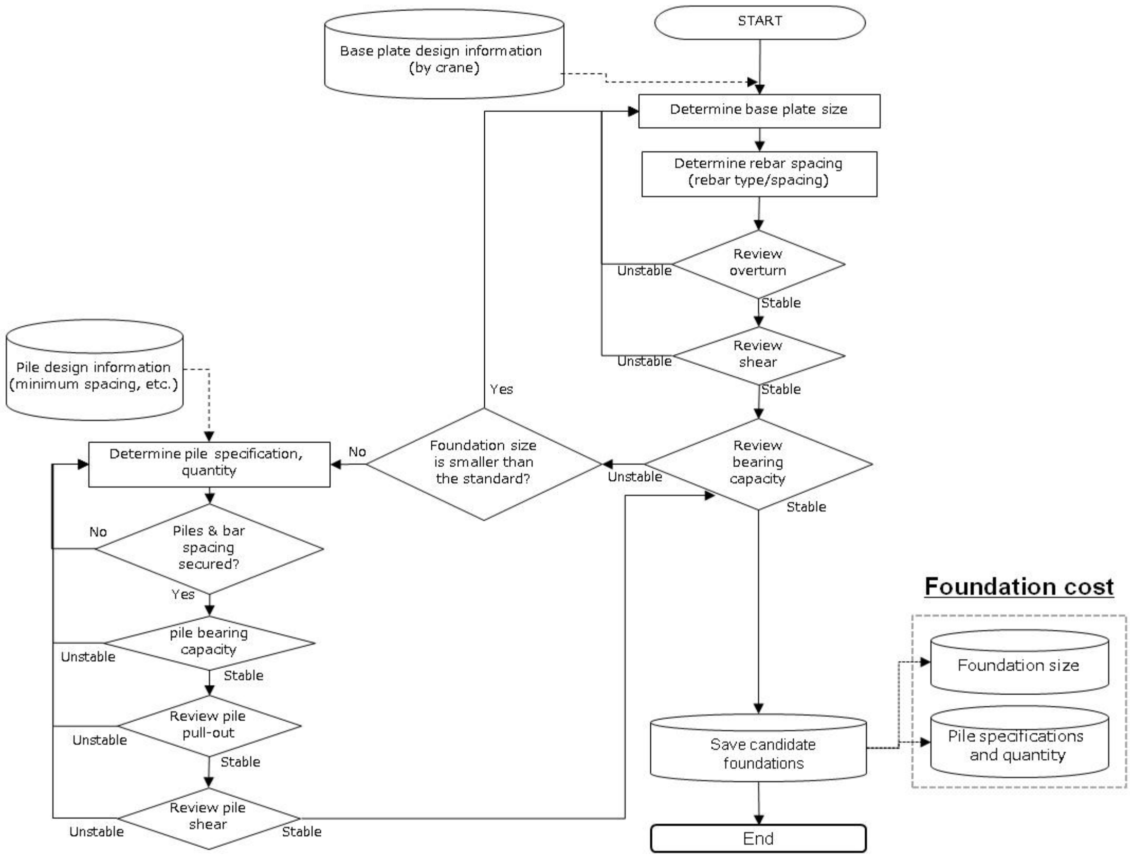

Figure 16. Process of Economic Review of Foundation (step 3)

7. Optimization Model

The issue of crane acquisition and management does not only require a study of economic feasibility which considers all the cost influence factors of each acquisition method, but also the policy of managing the equipment. The economic feasibility study is not complicated, but requires a series of cost analyses using cash flow charts and net present value analyses. The policy of managing equipment is a fairly complicated issue to deal with. This study, thus, aims to develop an optimization model for generating cases that require a minimized cost by examining multiple cases, where the stability is already ensured, and calculating the costs required, limited to the rental and installation costs. The optimization variables are the features used to evaluate the economic feasibility as deduced from formulas 3, 4, and 6, as well as the TC rental cost (C_{TC}).

Each item is generated from the TC selection and supporting design process (Figure 8) and the detailed steps (step 1, step 2 and step 3). The aim of the optimization is to minimize the sum of the tower crane cost (C_{TC}), wall bracing cost (C_{WB}), and foundation cost (C_F), as shown in formula 7.

$$\textit{Minimize}\ \{C_{TC} + C_{WB} + C_F\} \quad (7)$$

The optimization flow chart is illustrated in Figure 17, and step 1, step 2 and step 3 are consecutively executed to generate candidates. As described in the introduction, step 1 precedes step 2 and step 3, which is the critical standard for the lateral support and foundation designs, which affects the cost. The number of generated cases represented as , and step 1, step 2 and step 3 are consecutives, which varies according to the conditions. The number of cases generated by optimization based on the number of jibs applicable by TC type and the member information described in Tables 1-3 is approximately 3,000 ~ 15,000 times, which may increase depending on the number of members that can be reviewed. In addition, the number of cases and generated cases increase as the site requirements (like lifting load or working radius) become smaller. This optimization model gathers all cases to be saved as data, which makes it possible to review alternatives with reduced cost, not just the case with the minimized cost.

The causal relationship between candidates generated from the economic reviews of steps 1-3 is shown in the conceptual diagram in Figure 18. The TC type and jib length determined from the economic review process (Figure 9 in Chapter 4) of the tower crane selection are the first features of the cost review, which limit the features of the second cost review, including the foundation, pile, bracing and bracket types. The second feature of the cost review (foundation) is the review before that of the pile, bracing limits and the applicable bracket type.

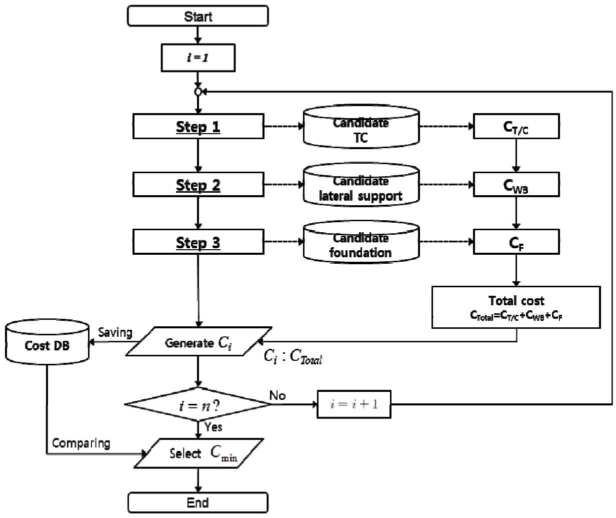

Figure 17. Optimization of Economic Feasibility

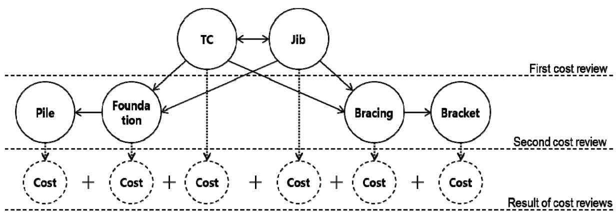

Figure 18. Causal Relationship of the Cost Review Items

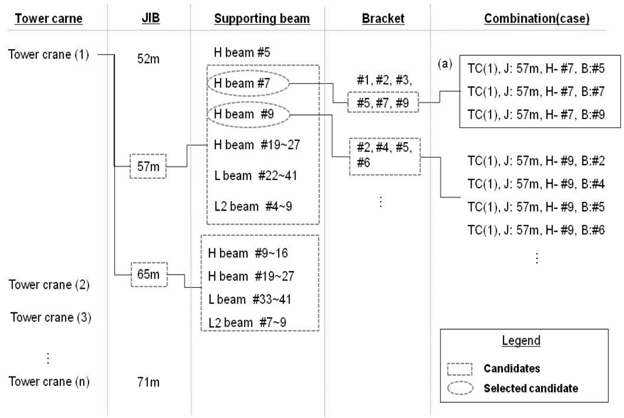

Figure 19. Example of Economic Optimization

Figure 19 shows an example of economic optimization developed from this study. First of all, there are four types of jibs applicable to TC(1) omic optimization developed from thtwo different types plicable to TC(1) omic optimization developed fromlifting load of the site. Thirty eight supporting beams including the H-shape steel are applicable to the 57 m jib, but H-shape steel #5 is excluded as a result of design lateral force review. There are six types of brackets applicable to steel shape #7, including type #1 and type #2, and three bracket candidates of type #5, type #7, and type #9 are selected in consideration of the supporting structure type and design lateral force. Accordingly, three cases are generated as shown in Figure 19(a). The economic optimization process enables us to generate cases by analysing the applicable TC, jib, bracing and bracket.

When analysing economic feasibility by case, the cost per type differs (including TC type, lateral support, and foundation), so all the costs should be converted into the net present value (NPV) for an accurate analysis. The installation cost of the foundation is calculated first, and there is no additional cost until its removal. However, TC and lateral support components have rental costs to be paid depending on the rental period after their installation, which is highly influenced by the installation and removal schedule. Thus, the tower crane rental cost (C_{TC}) as an installation point for pending on is calculated by adding together the current value of the installation cost (C_i) and the monthly rental cost (C_i) with the current value of the removal cost (C_d), as shown in formula 8.

$$C_{TC} = C_i + \sum_{n=1}^{m} \frac{C_r}{(1+r)^n} + \frac{C_d}{(1+r)^m} \qquad (8)$$

The same method of calculating the TC rental cost is applied to the lateral support. As illustrated in Figure 20, the lateral support cost is composed of the installation cost (x_1), member rental cost (x_2), and removal cost (x_3) depending on the installation schedule. The total cost (C_{Bra}) is the cumulative sum of all costs. Firstly, when the lateral support is installed (s illustrated in Figure, the installation cost (x_1) is the input and the rental cost (x_2) generated every month after its installation, increasing the rental cost as the lateral support increases. The removal cost (x_3) is the cost of removing all lateral supports, which is generated as soon as the TC is removed.

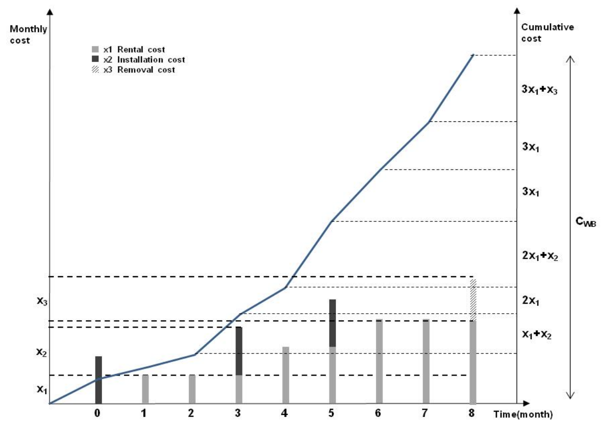

Figure 20. Cumulative & Monthly Cost (Lateral Support)

The cost for lateral supports should be calculated for each location, and the cost for lateral supports used for removal costC_{WB}) can be calculated by adding together the current value of the installation cost (C_i) and the monthly rental cost (C_r) with the present value of the removal cost (C_d), as shown in formula 9.

$$C_{WB} = C_i + \sum_{n=1}^{m} \frac{C_r}{(1+r)^n} + \frac{C_d}{(1+r)^m} \qquad (9)$$

where, $C_r = x_1$, $C_i = x_2$, $C_d = x_3$

Multiple cases should be generated in connection with the stability reviews as specified in the economic optimization. This should be conducted as shown in the flow charts of Figures 6, 8, and 9, and the costs required can be calculated simultaneously using consecutive selection. Figure 21 shows the relationship between the factors that are input during the stability review process and the cost generated by such factors. The lifting load and lifting height affect the tower crane rental cost as well as the installation/removal costs and telescoping cost. However, the additional mast delivery cost is unrelated to the lifting, and is instead affected by the lifting height, which is related to the quantity of additional masts.

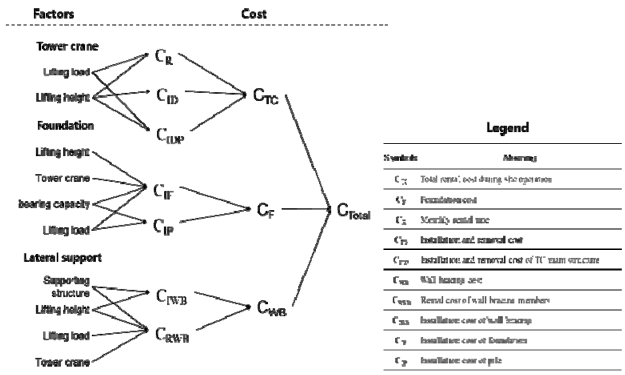

Figure 21. Relationship of Cost Influencing Factors

All the costs related to the tower crane are calculated to determine the total cost, which is the basis for the selection of the minimum cost. The stability of the optimum tower crane selection comes before price. This sequential flow in tower crane plans is clear and only cases where stability has been ensured will receive a cost calculation.

8. Conclusion

The optimum tower crane and supporting design management that provides stability and economic feasibility suitable for construction conditions should integrate and consider all the different factors, including engineering, economy, simulation and optimization methods. However, it is difficult for site engineers to have all the related knowledge and such work is time-consuming. If the related methods are built into a system, engineers will be able to perform the related works easily and promptly. This study establishes TC selection and support design processes and a related database to achieve this goal, and proposes a method to optimize economic feasibility (cost) assuming that lifting conditions and stability are satisfied. The results of this study are summarized as follows.

First, the database built from the available tower cranes in the market for optimum tower crane selection generated candidate cases in accordance with the lifting conditions, and we confirmed that it is capable of easily and quickly generating cases using a simulation afterwards.

Second, the design components required for lateral support and foundation designs with which to build a database were collected, which made it possible to easily and quickly perform stability reviews. Furthermore, the algorithm proposed for the optimum supporting design was confirmed as being able to generate the optimum design plan after calculating the costs of design plans that meet stability.

Third, we confirmed that the system run time can be reduced by examining the necessity of piles during the support design process related to the selected TC prior to foundation design, and then determining the bracing frame and the bracket details for lateral support.

Fourth, it was proven that even though the tower crane rental cost during cost reviews is minimized, increases in support system costs such as lateral support and foundation may not always minimize the total cost. This is because the TC selected with the minimum cost may require supplementary support systems to secure structural stability, which may increase the total cost.

Fifth, the algorithm proposed in this study simulates all the possible candidate cases, saves them in the database, reviews practical alternatives, and generates a case with minimized cost as the final solution. It should be checked whether the design components can be procured on-site.

Finally, all the costs used in the economic analysis should be converted into the net present value (NPV) for an accurate comparison, since all the costs are generated at different periods. In particular, TC and lateral support members (which are rental items) have rental costs to be paid according to the rental period, which is greatly influenced by the installation and removal schedule.

The economic optimization method developed from this study analyses correlations among the various tower crane performances, foundation designs, lateral support structures, and each member required during the lifting plan phase, which is helpful in systematic, optimum TC management.

9. Acknowledgement

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