Automated Layout Planning of Climbing Formwork System Using Genetic Algorithm

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Abstract –

Layout planning of climbing formwork system is a prerequisite for executing efficient and cost-effective structural framework in a high-rise building construction. However, most of the formwork system layout is operated manually under heuristic approach of the supervisor, and thus is prone to errors that affect constructability of the entire construction. Furthermore, inflexibility of the current method to changes in building design also results in unexpected variability during system utilization. Automated formwork layout method that considers essential factors such as configurations on unit module of the form as an input data, information on building parameters for specifying possible areas of system installation, and configurations on working platform for optimal arrangement of unit systems can be suggested as an alternative to the current manual execution of formwork layout. Therefore, this study proposes an automated layout planning method of climbing formwork system by using genetic algorithm. The method developed in this study is to be utilized for reasonable decision making of the construction worker in control of the automated layout planning.

Keywords –

Automated layout planning; Climbing formwork system; High-rise building; Genetic algorithm

1 Introduction

Climbing formwork system is applied in a high-rise building construction as an appropriate facility for vertical erection of a rigid structure. As structural framework is the single largest cost-related activity in a building construction [1, 2], framing a high-rise structure by attaining economic feasibility becomes a major concern. Equipment and material utilization associated with concrete formwork are prerequisite for a successful construction performance. Thus, layout planning of climbing formwork system must be preceded for executing efficient and cost-effective structural framework in a high-rise building construction.

However, current layout planning method of climbing formwork system encounters several factors in need of improvement. First of all, current system layout is operated under heuristic approach of the supervisor by relying on personal experience in managing climbing formwork system. Not only is manual operation of formwork layout inevitably prone to errors, but also does it consume excessive work duration and workload in actual construction site. Furthermore, current layout method cannot instantly reflect changes in design of the building, and thus results in higher variability in both quality and constructability. Therefore, this study proposes a flexible, automated layout planning method of climbing formwork system that serves as a framework of a decision support model for optimal climbing formwork system layout in high-rise building construction.

2 Theoretical Background on Climbing Formwork System and Related Work

2.1 Climbing Formwork System in High-rise Building Construction

Built environment of a dense area prefers buildings to be erected vertically rather than spread horizontally for efficient construction within limited space. In response to this shift of paradigm on building construction, ensuring rigidity of highly erected structure with minimum cost input on framework construction became a primary concern [3].

Compared with traditionally applied facilities for vertical framework such as gondola and gang form, a climbing formwork system of which scaffold components and wall formwork are all fabricated as one unit can adopt various forms of structure with higher versatility. By executing construction processes with standardized components, system formwork method offers a systemized operation processes with positive effects on improving quality, safety, and constructability [4]. As a result, current trend of high-rise building construction prefers to form a high-rise building structure by operating either crane-lifted-, or self-climbing formwork system during structural framework [5, 6].

Even with the benefits associated with utilizing climbing formwork system in vertical framework construction, the system requires relatively high cost input distributed during three main phases of system utilization - fabrication, erection, and removal [7]. If an error is discovered while comparing the planned layout with applied formwork system to an actual construction site, rework associated with re-adjustment of the system causes variability in both constructability and project cost. Thus, material components of a climbing formwork system should be assembled to minimize workload related to system re-adjustment and also to maximize economic feasibility.

2.2 Major Configurations of Climbing Formwork System

As configurations related to size of climbing formwork system components are adjustable according to site conditions and needs of client, there is no fixed modular form of climbing systems with standardized unit size and specification. For instance, size and elevation level of working platform in a scaffold are adjustable according to the decision-maker in charge of system design. Nevertheless, certain major configurations are chosen to be considered unconditionally in the upmost priority for optimal use of climbing formwork system, and also for its resulting constructability of workers.

The system has maximum allowable length of a working platform that one bracket can endure. Platform is designed to satisfy performance in both work efficiency and safety. Modular aluminium sub-elements of equal size are assembled to form a unitized platform, and combination of the elements for fabrication determine the length of one platform. Combination of aluminium sub-elements are determined under the possibility that elements are cut off in case of need for re-adjustment to a new wall configuration.

One unit of a climbing formwork system is determined by one set of two brackets that supports the working platform and also eventually the entire system. Brackets must be positioned in optimal location with appropriately designed platforms to endure high load-bearing capacity and ensure structural safety of the system. In addition, bracket set is deemed important in formwork layout, since cost on one bracket set accounts for a considerable portion of total cost on climbing formwork system.

Brackets also have a main role of connecting the climbing rail and anchoring shoe for installation of the system to wall surface. Whether the climbing cone can be anchored to a surface insinuates availability of system arrangement within the boundary.

Figure 1 depicts an exemplary climbing formwork system and its major components.

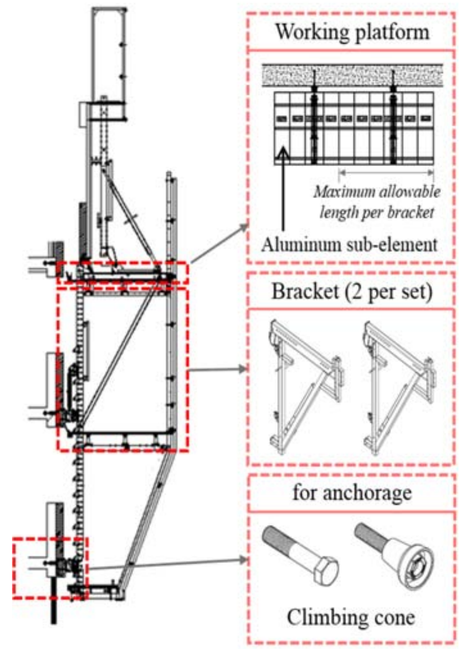

Figure 1. Configuration for climbing formwork system with major components

2.3 Layout Planning of Climbing Formwork System Compared with Other Facilities

Current formwork layout planning method provides alternatives for decision makers, but it does not guarantee whether the chosen alternative is the optimal decision. In a structure with equal parameter, total number of units and associated bracket sets can differ according to the decision made by the supervisor. If the supervisor chooses a layout plan with higher total number of system units to be applied in construction, it means total number of bracket sets becomes proportionally higher. Not only additional installation of bracket results in higher cost, but also re-fabrication of working platforms for adjustment to uneven configurations results in additional workload.

It has been deduced from literature review and interview with experts who majored in building structure that researches on automating layout planning of horizontal formwork and vertical temporary facilities have been previously proposed [4, 8-10]. In case of horizontal formwork, layout planning has been automated based on imported floor plans of building solely by focusing on interior space, not the outer boundary of the building. In case of vertical temporary facilities, few construction corporations have developed their own automated software programs to draw formwork around a building structure and create a bill-of-materials based on the planned layout. However, developed programs for vertical formwork facility are dictated under highly limited conditions, and are applicable to structures with smaller magnitude. Also, the developed programs for automating layout planning of vertical facilities are not intended for 'optimal' layout with targets on specific performances.

In case of climbing formwork system, formwork experts rely on manually planned formwork layout for decision-making. Based on the fixed floor plan, working platform of a system with the longest width are stationed in building parameters and visualized as a layout. In case more than one type of temporary facility must be used in a building construction, decision makers encounter difficulty in finding the optimal set. This insinuates that considerable amount of work hour is consumed for manually planning the layout demonstrated as exemplary on Figure 2.

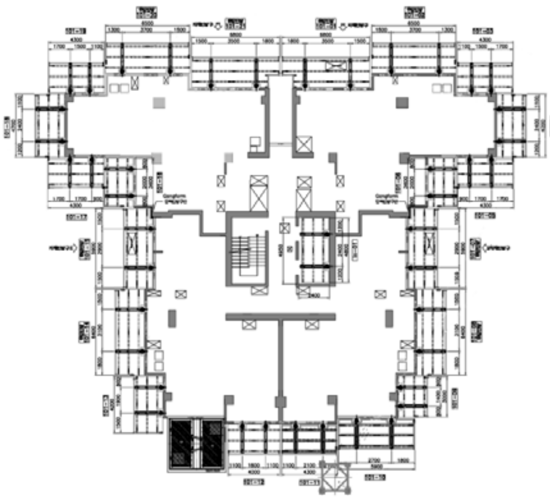

Figure 2. Layout planning of formwork systems

Layout planning dependent on heuristic approach results in higher cost input on labor during planning and design phases. In addition, total cost increases during structural framework of construction phase if any errors occur in any of the formworks that have been fabricated based on the designed layout. Therefore, an automated layout planning model is needed for optimal layout execution of climbing formwork system based on a clear objective in construction performance.

3 Automated Layout Planning of Climbing Formwork System

3.1 Consideration Factors and Assumptions for Optimal Layout Planning

As a decision supporting model for optimizing the use of an appropriate formwork system, automated layout planning method of climbing formwork system has been defined as the objective of this study. The proposed automated method for formwork layout should identify the best arrangement of the systems within the constraints imposed by various conditions. However, simply contributing to cost reduction for formwork construction does not satisfy the conditions of an 'optimal' model.

Since standardization of resources results in operational stabilization in construction, maximizing the use of standardized systems with modular size is efficient in both cost and work constructability. Thus, solution to this optimization problem aims to minimize formwork cost through minimizing material usage for special units or any form of rework associated with system utility. Since cost associated with bracket installation has been determined as the most cost-consuming factor, minimizing quantity of bracket sets by maximizing number to platform installation with minimum variability in modular sub-elements is another definition of the optimization problem. A set of parameters is considered in order to optimize a set of variables set for achieving the specified targets [11].

During this study, the two major components critical for optimal arrangement of the system - length of working platform and distance between two supporting brackets that are connected to the anchoring shoe for system anchorage – are design parameters for configuration of formwork layout and arrangement. In addition to information related to the materials composing a unit module system, information related to construction site acts as the key for space modelling. Imported shop drawings related to the building structure set constraints for system installation. For example, information on location and dimension of window opening and columns serve to determine the resultant possibility of anchorage for formwork system. Also, information on retaining wall and column is also critical for determining availability of platform installation.

Another important controlling factor of climbing formwork system installation is specification of tower crane in construction site. Regardless of whether crane-lifted or hydraulically lifted, the system requires use of tower crane for erection and removal. Also, components of scaffold attached to the system have to be re-adjusted from the previously used modular system if location of tower crane or its turning radius interferes with formwork construction. Although lifting load of tower crane is not additionally reflected in this study, constructability on fabrication, erection, and removal of the system by assistance of tower crane has to be ensured [12, 13]

3.2 Relationship between Structural Safety and Design Parameters of Climbing Formwork System

Optimal solution set should be derived within a reasonable boundary, in both physical workspace perspective and structural safety perspective [14]. Constraint set in this problem requires: (1) a set of brackets to not be installed in window openings, (2) length of working platform to be deduced based on maximum allowable length per bracket, and (3) designed platform to have sufficient capacity to endure the system load.

After the configurations above are fixed, total length of platform is deduced based on the locations of anchorage and their resultant distance between two brackets. However, the two brackets are not always positioned to share the same amount of loading capacity with equal projecting length of platform. Consequently, fitness of anchorage location for two brackets to support a working platform is evaluated in this study by: (1) whether platform length satisfies maximum allowable length of platform per bracket, (2) whether locations of anchorage and capacity of one bracket are compromised to deduce optimal number of aluminium sub-elements of platform for each system arrangement, and (3) whether total length of platform is designed to satisfy the structural limits.

Structural safety verification of the utilized climbing formwork system is applied for satisfying all the above constraints related to the design of platform. Thus, locations of anchorage for brackets should satisfy the maximum deflection of the platform (δ_{max}) , and maximum allowable unit stress in bending (F_b).

Considering total vertical load in a platform (W) as summation of dead load and permissive live load under extreme working condition, safe transfer of bearing forces into the building structure is verified under the constraint of maximum allowable length of platform per bracket l_{max} as:

$$\frac{w{l^2}_{max}}{8Z} \leq F_b \tag{1}$$

$$\delta_{max} = \frac{5w{l^2}_{max}}{384EI} \leq {}^{l}/_{240} \tag{2}$$

in which uniform loads(w) are calculated as total vertical load multiplied by maximum length of platform. Maximum deflection of platform should also satisfy the fundamental equation on allowable deflection of an element. The two inequality functions are to be converted and accommodated as a constraint set during search for optimal arrangement of climbing formwork system by using genetic algorithm.

3.3 Genetic Algorithm Formulation for Optimal Solution to Formwork Layout

3.3.1 Framework for Developing Automated Layout Planning

An optimization problem for construction layout has been commonly interpreted as arrangement of a set of predetermined target into appropriate locations. Likewise, developing an automated layout planning of climbing formwork system is not only concerned with providing multiple alternatives of formwork layout. Primary objective of incorporating automation technology for layout planning of climbing formwork system is to provide an optimal solution with definite standards for decision-makings to supervisors.

Development of automated layout planning of climbing formwork system through incorporation of search algorithm contains the following procedures depicted on Figure 3.

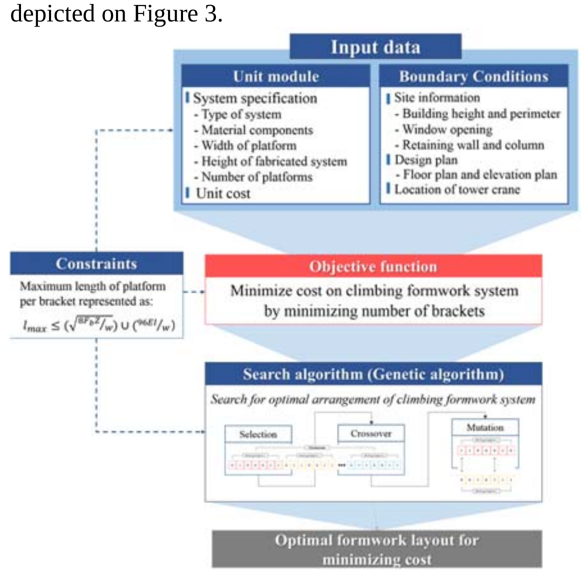

Figure 3. Framework for developing automated layout planning

First, classification of formwork – including size, location of use with different performance requirements, type of climbing formwork system and its material components for high adaptability to all shapes, should be clarified. Unchangeable information on unit module of a climbing formwork system including width of working platform, size of wall formwork, total height of the fabricated system, and number of platforms serve as input data. Unit cost of the climbing system estimated by unit cost of material components is also an input value and a determinant factor for the ultimate output.

Second, shop drawings of construction site with information on building dimensions, including building height and perimeter, are imported for space modelling. Boundary conditions, which in this case interpret possible areas of layout plan, are implemented on a grid with x and y axis. Whether a climbing formwork system can be arranged in an area is determined by availability of anchorage of the brackets to the wall. Location of anchorage considering areas incapable of system installation is first reflected in the space, such as wall surface with openings for window installation. As previously mentioned, imported plans should also include information on number of tower cranes installed along with their locations.

Shop drawing of a building structure is implemented on a grid with information on axis for possible anchorage of climbing formwork system, as demonstrated on Figure 4. Within the boundary space that enables arrangement of the system, a set of optimization algorithm is employed for random search. In this study, locations of anchorage for the two brackets in a unit module of the system are ultimately searched and imported on the grid with (x_i, y_i) and (x_j, y_j) coordinates, respectively. The two coordinates determine distance between two brackets. Prior to derivation of optimal location for anchorage, grid array portraying installation areas of platforms around the building is constructed with length (cl_{ij}) and width (cw_{ij}).

3.3.2 Genetic Algorithm Formulation

Genetic algorithm is applied as a search algorithm to provide optimal solution for arranging climbing formwork system in high-rise building construction. Genetic algorithms employ random search for locating the globally optimal solution through parallel processing [15], and represent schemes that provide alternatives for layout plans in this study. Applying principles of genetic algorithm involves five primary aspects: (1) setting the chromosome structure, (2) deciding the evaluation criteria (objective function), (3) generating an initial population of chromosome for initial solutions, (4) selecting an offspring generation mechanism as a process to generate new potential solutions by mutation, and (5) schematizing the results [16].

Building structure with information on openings, columns, and retaining wall is set as the optimization area for installation of climbing formwork system. Data structure is first established in order to derive the ultimate

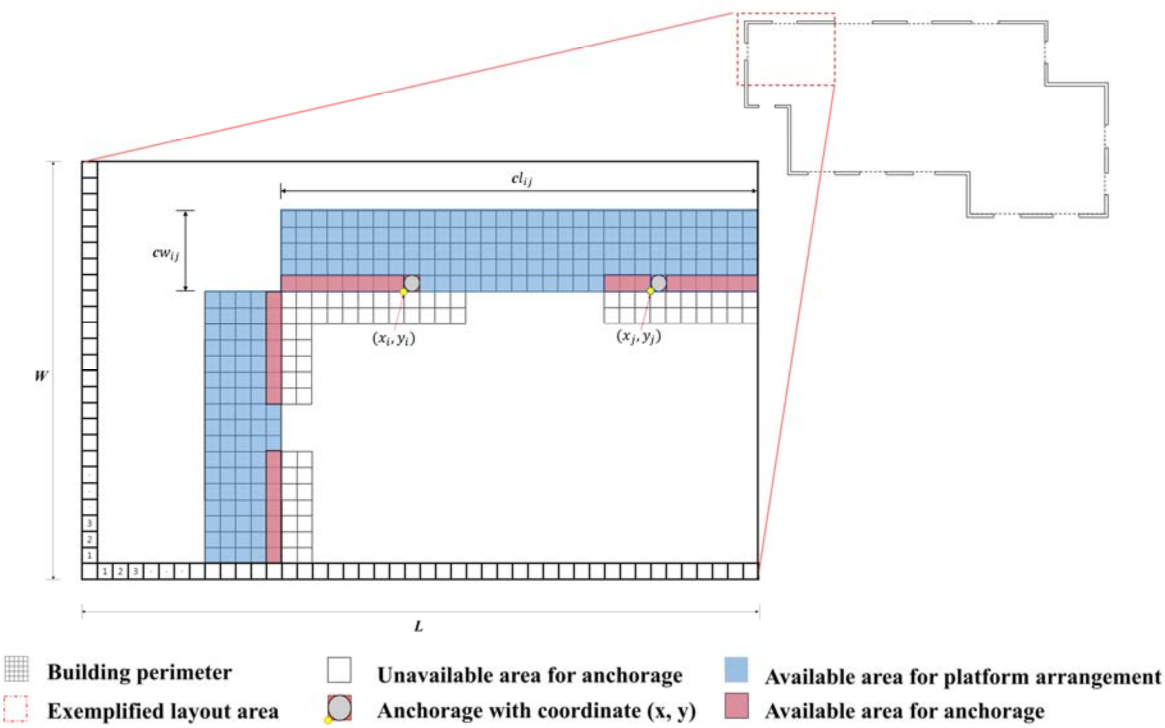

Figure 4. Geometry of allowable area for system installation (reference to [14])

optimal solution [17, 18] based on the available area for installation. Design variables that affect optimization objective are represented as chromosomes with various genes. Prior to the setting of fitness based on objective function, objective function parameters are coded in binary codes.

With reference to Figure 4, possible areas for installation of platforms with predetermined modular width are coordinated around the building surface. Parameter p_{xy} recognizes whether an entire modular platform of unit *i* with length (cl_{ij}) and width (cw_{ij}) can be placed within the rectangular grid coordinates with length *L* and width *W*. Reflecting the binary parameter implemented based on openings or any other areas that disallow anchorage, parameters (a_{xyi}, a_{xyj}) are plotted for possible installation of two anchoring shoes within the platform area coordinated as (x_i, y_i) and (x_j, y_j). Binary parameters (p_{xy}, a_{xyi}, a_{xyj}) are given a value of 1 if the system is installed, and 0 if otherwise.

During the search for optimal solution in this study, location of anchorage for system installation to the wall surface is coded, and length of working platform is to be determined based on maximum allowable length of platform per bracket and additional information on anchorage information. Considering that brackets serve to connect anchoring shoe and scaffold in order to support the system, locations of climbing formwork system anchorage convey allowable length of working platform that one bracket can endure.

After continuous search for feasible layout, arrangement of climbing formwork system is executed based on imported boundary conditions of building perimeter and location of the tower crane that confine the boundary set. Parameters on anchoring location converge after searching for optimal locations, and yields to position in which the resultant length of platform satisfies the constraint on maximum allowable length of platform per bracket. Thus, the automated layout planning method of climbing formwork system is operated to search for a solution that minimizes cost input by minimizing use of brackets and associated material components under the following objective function:

$$Minimize \sum_{x=1}^{L}\sum_{y=1}^{W} p_{xy}\left(\sum_{i} a_{xyi} + \sum_{j} a_{xyj}\right) \qquad (3)$$

4 Conclusion

As a preliminary study, this paper presented an algorithm that serves as a framework of a decision-support model for optimal layout planning of climbing formwork system. Through an extensive study on formwork layout that takes place during planning and design phases, it has been deduced that optimal layout method for vertical formwork system has not been yet proposed. Multiple factors have been defined to be under consideration, including specification on major components of climbing formwork system such as working platforms and brackets for installation to a wall surface. Based on the derived decision variables that are applied as input data, flow chart defining input data, boundary conditions related to the building structure, and constraints such as maximum allowable length per bracket of a system was produced.

'Optimal' layout of a facility has responded to greater demands for higher-quality construction delivered on lower cost, higher constructability of workers, and enhanced work efficiency. Likewise, optimization problem of this study has been defined as arrangement of climbing formwork system with minimum cost input and maximum material usage during system utilization. Considering the modelled space of the building structure, specification on anchorage with its resultant total length of platform have been determined through random search within constraints. Genetic algorithm has been chosen as the optimal form of algorithm for providing alternatives of formwork layout planning and facilitating construction workers to make a rational decision.

The following conditions should be additionally considered in future study for reliability assessment of the proposed model:

1. The proposed method views the construction space in two dimensions. Since layout planning of climbing formwork system should provide both horizontal and vertical layouts based on shop drawings from various perspectives, providing the solution in three axis (x, y, and z) is expected to provide a clear vision.
2. Some of the conditions that are considered important in actual construction site are not reflected in the current algorithm. Thus, future study is to complement the proposed layout method, and is expected to extend from a framework to an actual automated layout planning that provides optimal solution to the defined problem.

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References

[1] Peurifoy R.L, and Oberlender G.D. *Formwork for*

Concrete Structures, Fourth Edition. McGraw Hill, New York, 2011

[2] Lab R.H. Think Formwork – Reduce Costs. On-line:, Accessed: 10/02/2016

[3] Lee C., Ham S., Lee G. The Development of Automatic Module for Formwork Layout using the BIM. In *The 3rd International Conference on Construction Engineering and Management/The 6th International Conference on Construction Project Management (ICCEM/ICCPM 2009)*, pp. 1266-1271, Jeju, Korea, 2009

[4] Kim T. Advanced system formwork and construction planning model for tall build construction. Doctorate thesis, Korea University, 2013

[5] PERI GmbH. 2015. Climbing system. On-line: www.peri.de, Accessed: 16/02/2016

[6] Yang S-H, Cho J-Y, Cho J-W, Lee J-H, Kim Y-S. A Study on the Development of Automated Gangform Climbing System for Apartment Housing Construction. Korean Journal of Construction Engineering and Management, 13(1), pp. 53-66, 2012

[7] Mawdesley M., Al-jibouri S., Yang H. Genetic Algorithms for Constriction Site Layout in Project Planning. Journal of Construction Engineering and Management, 128(5), pp. 418-426, 2002

[8] Lee D., Lim H., Kim T., Cho H., Kang K.I. A Formwork Layout Model based on Genetic Algorithm. In *The 31st International Symposium on Automation and Robotics in Construction and Mining (ISARC 2014)*, pages 474–479, Sydney, Australia, 2014

[9] Cha M. A Decision Support Model for Optimal Formwork Layout in High-rise Building Construction. Master's thesis, Korea University, 2012

[10] Kannan M., and Santhi M. Constructability Assessment of Climbing Formwork Systems Using Building Information Modeling. Procedia Engineering. 64, 00. 1129-1138, 2013

[11] Whitley D. A Genetic Algorithm Tutorial. Statistics and Computing, 4, pp. 65-85, 1994

[12] Cai P., Cai Y., Chandrasekaran I., Zheng J. Parallel genetic algorithm based automatic path planning for crane lifting in complex environments. Automation in Construction, 62, pp. 133-147, 2016

[13] Ahn B., Kim J., Kim K., Kim S. A Study on the Optimization of Site Layout in the High-Rise Building Construction. Journal of the Architectural Institute of Korea – Structure & Construction, 15(12), pp. 107-118, 1999

[14] Kim T., Lim H., Lee U.K., Cha M., Cho H., Kang K.I. Advanced formwork method integrated with a layout planning model for tall building construction. Canadian Journal of Civil Engineering. 39:1173-1183, 2012

[15] Conway D., and Venkataramanan M. Genetic Search and the Dynamic Facility Layout Problem. Computers & Operations Research, 21(8), pp. 955-960, 1994

[16] Hegazy T. Optimization of Construction Time-cost Trade-off Analysis using Genetic Algorithm. Canadian Journal of Civil Engineering, 26(6), pp. 685-697, 1999

[17] Koo C., Hong T., Kim S. An Integrated Multi-Objective Optimization Model for Solving the Construction Time-Cost Trade-off Problem. Journal of Civil Engineering and Management, 21(3), pp. 323-333, 2015

[18] Park U-Y, Cho S-S, Kang K-I. A Study on Rebar Detailing Optimization Using Genetic Algorithm. Journal of the Architectural Institute of Korea – Structure & Construction, 19(10), pp. 125-132, 2003