ICCEPM 2024 https://dx.doi.org/10.6106/ICCEPM.2024.0002
The 10th International Conference on Construction Engineering and Project Management
Jul. 29-Aug.1, 2024, Sapporo

Construction Method Research Using BIM: A Focus on the Precast Concrete Partitioning Method Leveraging Genetic Algorithms

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Abstract: In Japan, when constructing frames using Precast Concrete (PCa) methods, unique building components are used. These include integrating column tops with beam ends or using cast-in-place concrete in the panel zone. Planning these components requires considering various factors such as the loading capacity of trailers, crane lifting capacity, joining methods, and equipment penetrations. Building Information Modeling (BIM) technology has become increasingly common in construction planning. However, extracting the necessary information for construction planning directly from the design BIM model is challenging. This difficulty arises because the design BIM model organizes columns and beams in different division units than those used in construction. To address this issue, our study models the concept of the "panel zone" and proposes a method for representing a PCa BIM model composed of panel zones, columns, and beams as PCa products. The study decomposes and combines columns and beams, with parametric changes applied to the panel zone range. Additionally, our study analyzes factors related to the design and planning of column and beam PCa products through interviews and questionnaire surveys conducted with general contractors. An evaluation mechanism for the proposed column and beam division was also established. Based on the findings, a BIM-based method was developed for planning the PCa construction method of the frame using a genetic algorithm. This approach provides a technological solution that supports the planning of frame division, considering the construction rationale at the early design stage.

Key words: Building Information Modeling (BIM), precast concrete (PCa), panel zone, PCa products, construction planning, Genetic Algorithm (GA)

1. INTRODUCTION

1.1 Precast concrete construction method in Japan

The key to enhancing productivity and creating top-notch products with minimal staff lies in the concept of labor-saving. Streamlining operational efficiency and guaranteeing repetitive tasks can significantly cut down the construction timeline, commonly referred to as shortening the construction period[1]. Precast concrete (PCa) is an approach that can help achieve these goals. This method entails fabricating the structural elements and building members in a dedicated factory, and then utilizing cranes to piece them together on the construction site. Unlike conventional construction methods such as in-situ concrete, this construction method ensures the quality of the precast concrete elements, which are not affected by the weather. This not only shortens the construction period but also reduces labor at the construction site. In Japan, high-rise residential buildings are increasingly adopting a practice known as "structural PCa", in which primary structural components such as columns, beams, and load-bearing walls are made of PCa elements. This practice is becoming more widespread due to its advantages in terms of structural stability, cost-effectiveness, and reduction of work at height[2][3].

The construction of precast concrete structures varies depending on the precast parts and the location of column and beam members. There are four types of connections, each with unique features and costs. As shown in Figure 1 below, Type A involves a single PCa beam spanning between columns, with the main reinforcement of the beam joined at the column-beam joint and followed by concrete casting. Type B is a beam-center connection type, where the main reinforcement of the beam is joined at the center of the span between columns, followed by concrete casting. Type C is an integrated column-beam joint type, where the column-beam joint and the beam are precast as one unit, and the main reinforcement of the beam is joined in the middle, followed by cast-in-place concrete. Finally, Type D is an end-of-beam connection type, where the column is fully PCa up to the slab top, and the main reinforcement of the beam is joined at both ends of the beam, followed by cast-in-place concrete[4]. Choosing the right construction method is crucial, as it affects both the manufacturing and labor costs and the overall construction period and cost.

To seek the rationalization of construction methods, it's necessary for designers, contractors, and technicians from PCa-specialized construction companies to repeatedly experiment and deliberate on the design proposals. This process is not only time-consuming but also heavily depends on the know-how and experience of the involved parties. In some cases, the finally decided construction method may not be the most optimal in practice. One critical element identified to solve this issue is Building Information Modeling (BIM).

Figure 1 Example of construction method for structural PCa [5]

1.2 The research problem and study purpose

The BIM process entails creating a digital representation of a building's physical and functional attributes using 3D objects[6]. This technology has enabled the creation of a three-dimensional BIM model on a computer before the actual construction project commences, providing crucial information on design, structure, and facilities to aid in construction planning. However, traditional BIM models consist of objects that represent "building elements" such as columns and beams. These "building elements" are conceptual in design and differ from the "components" used in precast concrete construction methods. Consequently, calculating the information necessary for process planning is challenging. As a result, the use of BIM has been limited to interference checks and drawing generation, and its potential in the planning stage is yet to be fully realized[7].

When devising a plan for constructing a building, one frequently considered approach is precasting the structural frame and using cast-in-place concrete for the panel zones where columns and beams intersect. However, if on-site work is arduous or it is challenging to ensure the quality of the panel zones, another approach is to precast the panel zones and take into account the division of the remaining columns and beams. This study posits that there is a rule for planning these construction methods and suggests modeling the concept of "panel zones". By parametrically altering the range of panel zones, this method proposes a way to disassemble and reassemble columns and beams as "building elements" and express a construction BIM model composed of panel zones, columns, and beams as "PCa products". Additionally, it offers a method for planning PCa structural techniques using BIM, which uses a Genetic Algorithm (GA). This method allows for the support of body division planning that considers construction rationality at an early design stage, providing a technical solution.

2. PREVIOUS STUDIES

Facing the challenge of converting design BIM models into construction method BIM models, Koike proposed a method that utilizes the "work area division" function of 5D-BIM software to redefine the division of building elements in the design BIM model and create a construction method model[8]. This approach enables the division of a structural body into components by creating a vast number of minuscule regions, each corresponding to a single component, through Boolean operations. However, while technically feasible, this method is labor-intensive and complicates the management of information related to part division, making its application in practice challenging.

Kitano pointed out the necessity for simulations based on multiple construction methods for a single design and proposed a method for comparing two different processes for one building[9]. Tazawa et al used 5D-BIM software and synchronized multi-site scheduling to optimize structural plans for high-rise buildings through simulations based on task relations and site/component divisions. However, these methods involve manually dividing into components and conducting simulations, and proposals for its automation have not yet been presented[10].

Kataoka targets the integrated approach of building construction method and technique, termed "construction method," and proposes the packaging of related knowledge into "construction method templates." Utilizing these templates enables the application of multiple construction methods to a single building and facilitates the selection of the optimal method through simulation[11]. This approach is similar to the methods presented in this research. However, the "construction method template" is described in a design-independent manner, necessitating the preparation of numerous construction method data in advance. There are also questions about the scope of handling information related to construction components. For example, decisions to enhance construction efficiency, such as precasting panel zones, may precede, and the division of the remaining members may be based on component weight, stiffness, and transportation constraints. This trial-and-error process could indicate that using "construction method templates" may lack flexibility.

3. RESEARCH METHOD

In this study, a system for automatically generating construction method models is conceived by utilizing Autodesk's Revit and Dynamo, along with the programming tool Python. The process involves reading information from design models created in Revit and executing a component division algorithm developed in Python. This innovative approach facilitates the automatic generation of construction method models, leveraging the strengths of Revit for detailed architectural modeling, Dynamo for extending Revit's capabilities through visual programming, and Python for its flexibility and power in gorithm development. This combination of tools enables a more efficient and accurate translation of design intent into practical construction methods, embodying a significant advancement in the field of construction planning and BIM technology.

To ascertain the optimal construction method model from a variety of options, it is imperative to conduct a thorough evaluation of each automatically converted construction method model. Regrettably, there is currently no established methodology for appraising construction methods in Japan, and the process mainly depends on the acumen of general contractors. To address this issue, a survey was carried out among five general contractors with a proven track record in adopting structural PCa. The survey (shown in Table 1) employed open-ended questionnaires that were sent in advance, allowing the companies to carefully consider their responses before conducting face-to-face interviews to verify their answers. The questions were designed to focus on the design and construction planning of structural PCa, including columns and beams. The survey results were analyzed and elaborated upon in Chapter 4. This approach aims to bridge the gap in evaluating construction methods by leveraging direct insights from industry experts, which could ultimately lead to the development of a more systematic and comprehensive evaluation framework.

Table 1. Details of Survey

No.	Content
1	When adopting the structural PCa method, what guidelines or standards do you use in design and construction planning? Do you have any company-specific guidelines or standards?

2	Are there any internal rules regarding the allocation and division of structural PCa? What factors influence the decision on allocation and division?
3	How do you specifically evaluate the constructability of structural PCa members? Is it possible to evaluate this numerically?
4	Do you consider the number of times formwork can be reused when studying the allocation of structural PCa?
5	Regarding PCa member division patterns, such as panel zone PCa, beam-panel zone joint type, and beam center joint type, how do you evaluate the advantages and disadvantages of these patterns?
6	Do you consult with PCa factories regarding the planning of PCa division patterns? If so, what kind of issues do you discuss?
7	Do you use BIM or ICT to plan the allocation patterns of structural PCa? If so, what are the advantages compared to not using BIM or ICT?

Based on the research results concerning the automatic conversion from design BIM models to construction method BIM models and the evaluation mechanism for automatically converted construction method models, this study has developed a method for planning the structural PCa construction method using BIM, optimized automatically at the early stages of design through the use of GA. This approach aims to facilitate the efficient and effective planning of body division, leveraging the power of GA to explore a wide range of possible solutions and identify the most optimal construction method configuration, thereby streamlining the decision-making process in the context of structural PCa construction planning.

4. RESEARCH FINGDINGS

4.1 Automatic conversion program from design model to construction model

The system is distinguished by its ability to load a design model, automatically identify the positions of beam ends, beam centers, and column-beam joints, and automatically place two types of joint objects. The prepared joint objects are categorized into two types, as shown in Figure 2. By positioning these joints and accordingly automatically cutting the original design model's column and beam objects to align with these joints, the program, implemented in Python, facilitates this process. The following details the placement of joint objects and the automatic generation of construction method models, with a focus on these steps. Additionally, Figure 3 illustrates the overall flow of the program is provided.

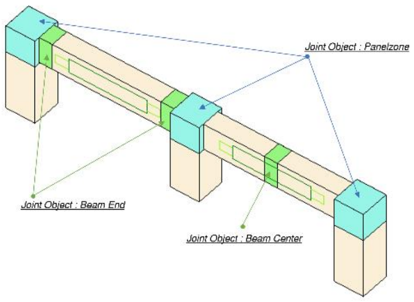

Figure 2 About joint object

4.1.1 Algorithms in programming

1) The spatial information of beam and column objects from BIM model designs is read, and joint objects are automatically placed at the ends and center of the beams, as well as at the junctions between columns and beams. 2) Parameters named "Joint_On_Left," "Joint_On_Center," and "Joint_On_Right" are prepared in advance for the beam objects to control the visibility of joint objects placed on the beams through these three parameters. For instance, if "Joint_On_Left" is true, the joint object on the left side of the beam is displayed, and if false, it is not displayed. 3) Columns and beams perform Boolean subtraction and intersection operations with their respective joint objects. Subtraction operations work by removing one shape from another, and intersection operations find the common parts of two geometries. In this study, the column and beam objects obtained through subtraction are referred to as

column (Difference) and beam (Difference), while those obtained through intersection are referred to as column (Intersection) and beam (Intersection). Then, column (Difference) and beam (Intersection) are converted into "Column PCa" and "Joint" objects, respectively. 4)The beam (Difference) that was in contact with the column (Intersection) is combined to generate a new irregular geometry (hereinafter referred to as new geometry). However, it is considered that it cannot be determined solely by geometry which PCa object this geometry should be converted into. This is because both the "central connection type beam" and the "column-beam integral type" can be represented by a shape composed of one cube and two rectangular bodies. Therefore, to determine the construction method object into which the geometry should be converted, this study adds a parameter called "Is_Panelzone_PCa" to the column objects, indicating whether to precast the beam panel zone or not. 5)If "Is_Panelzone_PCa" is false, it is determined whether there is a joint object corresponding to the beam part in the new geometry. If not, the beam part of the new geometry is converted to "Beam PCa" and the column part to "joint". If there is, the beam part of the new geometry is not processed, and only the column part is converted to "joint". 6)If "Is_Panelzone_PCa" is true, the new geometry is converted into "Panelzone PCa".

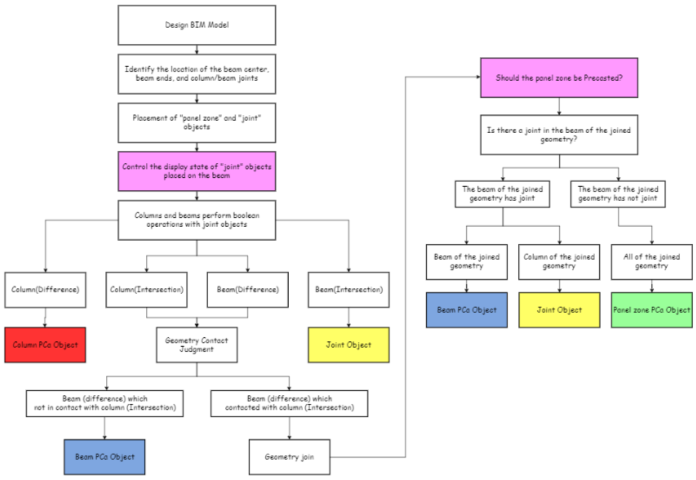

Figure 3 The overall flow of the program

4.1.2 Conversion results of the construction method model

By controlling the existence of parameters such as "Joint_On_Left," "Joint_On_Center," and "Joint_On_Right" for beams, and "Is_Panelzone_PCa" for columns, joint objects enable the automatic conversion of a single design model into four types of construction models, as depicted in the Figure 4.

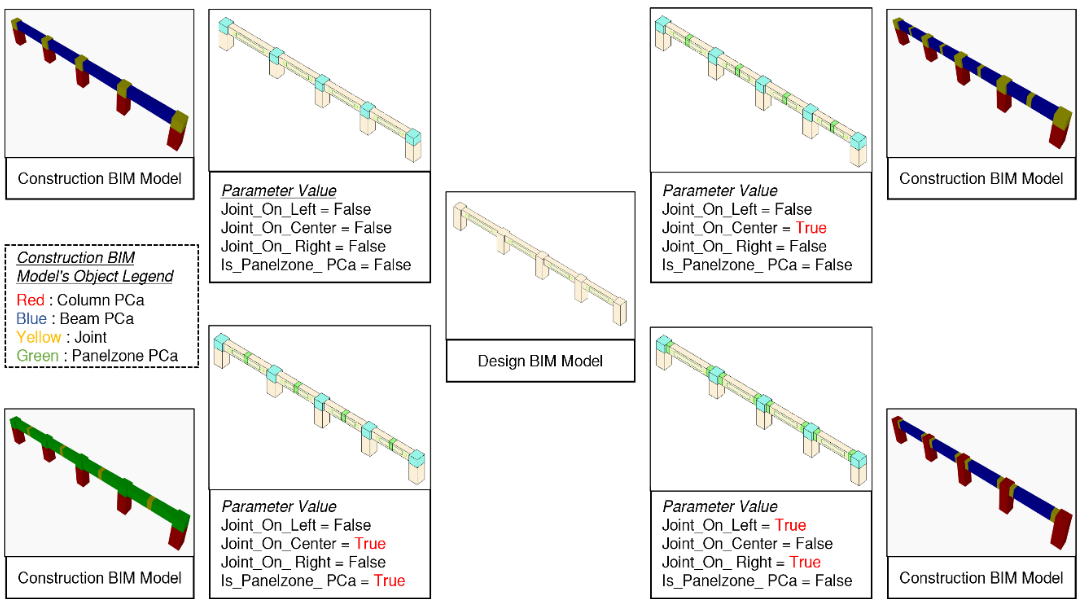

Figure 4 Conversion result

4.2 An evaluation mechanism for the proposed column and beam division

4.2.1 Survey results

According to the survey results, concerning precast concrete (PCa) construction methods, companies are advancing their design and construction planning while referring to their own guidelines or general structural guidelines. In particular, while some companies use guidelines they have developed themselves, others refer to existing structural guidelines. A lack of clear guidelines on the methodology for dividing columns and beams has been pointed out, with crane specifications and transportation conditions cited as significant influencing factors. Additionally, there is a focus on standardizing parts and the reusability of steel forms to reduce costs and improve efficiency. Companies adopt different methods for evaluating division plans and conduct reviews on manufacturing, logistics, and cost aspects through consultations with PCa factories. On the other hand, it has been revealed that the use of BIM and ICT technologies in PCa construction is still limited.

4.2.1 Analysis of survey results

As shown in Figure 5, This study identifies key indicators for evaluating construction methods, including the weight and dimensions of members, the position and number of joints, the number of pieces of precast concrete (PCa) members, and the reusability rate of forms. These indicators can be divided into limiting factors, such as weight and dimensions, and optimizable factors, such as the number of joints and the formwork reuse rate.The construction method evaluation mechanism involves converting the design BIM model into various construction BIM models, determining the maximum weight and dimensions of members based on crane and transport vehicle specifications, evaluating construction models based on these indicators, calculating the number of joints and member pieces, deriving an estimated construction period, classifying PCa members of the same shape and calculating the formwork reuse rate, calculating the estimated cost, and finally deriving the optimal construction method by changing the position of joints based on the estimated construction period, cost, and formwork reuse rate.

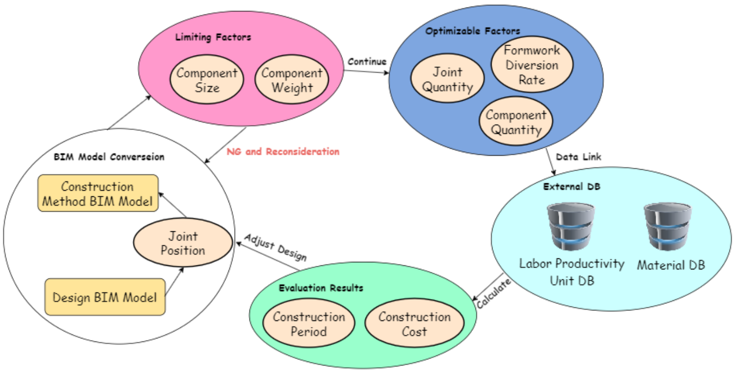

Figure 5 Schematic diagram of the evaluating mechanism

4.3 PCa construction method planning technique using genetic algorithms in BIM

4.3.1 Why Genetic Algorithms

In the design model, theoretically, there can be a diverse range of construction method models. Particularly, when focusing on the integrated column-beam joint PCa (precast concrete) construction method and assuming three types of beam joint positions: at the end, in the middle, or without a joint, the number of construction method patterns is based on the theory of permutations and combinations, amounting to 3 raised to the power of N variations. Here, N represents the total number of beams. For instance, in the case of a medium to large building with 60 beams per floor, theoretically, there exist 3 to the power of 60 different construction method patterns. This number significantly exceeds the current computational capabilities of computers, making a brute-force search to calculate all possible construction method patterns and select the optimal one impractical.

GA is an optimization method that mimics the evolutionary process of biological organisms to solve optimization problems[12]. It is particularly useful when there are numerous variable combinations, making it impossible to analyze all of them exhaustively. In this study, we use the Simple Genetic

Algorithm (SGA) as a representative model and provide a detailed description of the process for generating the initial population, evaluating fitness, and performing GA operations in the computational flow.

4.3.2 Population, fitness evaluation, and GA operation

To apply GA in (PCa) construction planning, we need to determine the chromosome representation. The joint position for each beam can be represented by a 1x3 binary matrix, where 0 indicates no joint and 1 indicates a joint. One construction pattern is treated as an individual with n chromosomes, where n is the total number of beams. The initial population is randomly generated by creating multiple such matrices.

In this study, a fitness function evaluates each individual's fitness based on research findings. The function calculates the fitness threshold of each individual, mimicking natural selection. The evaluation is conducted in two stages: an assessment based on limiting indicators, and an evaluation of optimizable indicators. For the evaluation of limiting indicators, the length, volume, and weight of members are calculated, and points are awarded based on pre-set constraints. The evaluation of optimizable indicators considers the number of members from the perspective of the construction period, with fewer members receiving higher scores. The algorithm's feasibility is verified based only on the construction period due to the lack of manufacturing cost data.

4.3.2 Verification results

The verification results are illustrated in the graph. In line graph 1, the horizontal axis represents the number of program executions, while the vertical axis shows the scores of each individual. In this experiment, an initial population of 10 individuals was generated, with the maximum length of PCa members set at 10 meters and the maximum weight at 15 tons. At the initial stage of execution, the scores of each individual varied, reflecting the randomness of the generated solutions. However, as the number of executions increased, there was a trend of rising scores for each construction method. This indicates that the algorithm is selecting superior individuals and that the population is continuously evolving. Line graph 2 more clearly demonstrates this trend, with the horizontal axis representing the number of program executions and the vertical axis the average score of the population. Moreover, while each individual from the initial population eventually converged, the number of executions required for convergence varied. For example, Method-10 converged after a maximum of 20 executions, whereas Method-8 only required 10 executions. As a result, a construction method with a score of 104 was calculated as the optimal solution, and the representation of that individual and its BIM model is shown in the graph 1.

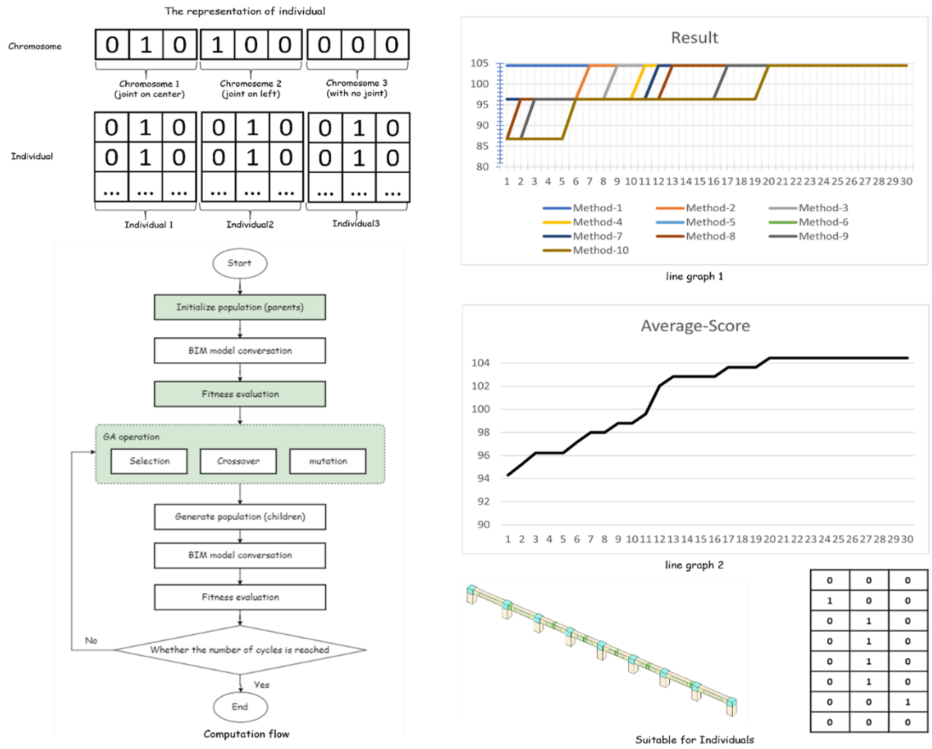

Figure 6 The logic of GA in PCa construction method

5. CONCLUSIONS AND FUTURE WORK

In this study, we proposed a method for modeling the concepts of "panel zones" and "joints" in connections, allowing for the parametric alteration of the locations where connections occur. By decomposing and combining columns and beams as "components," we developed a construction BIM model composed of panel zones, columns, beams, and joints as "PCa products." This BIM model, rather than being a mere 3D shape corresponding to each construction method, is made up of objects in the same division units as the actual construction. By linking with appropriate construction method information, it can compute the information necessary for construction planning.

Additionally, by conducting interviews and surveys with general contractors, we analyzed factors related to the design and planning of column and beam PCa members and devised an evaluation mechanism for column and beam division plans. This survey clarified the constraints and construction challenges on actual construction sites, laying the foundation for proposing optimal column and beam division plans that consider these factors. Valuable feedback obtained from general contractors provided insights that led to efficient use of PCa members and cost reduction, contributing to the precision of architectural planning.

Building on these findings, we developed a method for planning PCa construction methods using BIM with a genetic algorithm. This method established a way to automatically identify construction patterns close to the set goals while conducting multifaceted examinations along multiple evaluation axes. By applying genetic algorithms to PCa division planning, we established a new method that can replace the division planning traditionally based on designers' experience, demonstrating the potential to find solutions that may not be conceived through conventional thought processes.

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