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Potential and Insufficiency of Application of 4D-BIM for the Building Demolition Process

Suoao Wang*[1], Siyang Liu[2] and Yasushi Ikeda[3]

[1] Ph.D. candidate, Department of Architecture, Graduate School of Engineering, The University of Tokyo
[2] AQ group Co., Ltd.
[3] Project professor, Department of Architecture, Graduate School of Engineering, The University of Tokyo

* chesterwang111@g.ecc.u-tokyo.ac.jp

Abstract

The utilization of 4D-BIM in the demolition phase of buildings has not gained widespread attention. Therefore, this study aims to clarify the challenges faced in effectively utilizing 4D-BIM in the demolition project. The method of this study involves applying 4D-BIM in the actual demolition project, observing and evaluating its role in the process of demolition planning and execution, exploring the challenges faced, and the potential effects that can be achieved in the utilization of 4D-BIM during the demolition phase, and providing prospects for its future applications. During the process of creating the 4D-BIM for the actual demolition project, we encountered several challenges related to generating BIM data and utilizing BIM software. Although these issues required substantial time and effort to resolve, using 4D-BIM effectively discussed and created demolition solutions in the actual demolition project. It enables the visualization of multiple demolition schemes and enhances the intuitive understanding of these solutions. The results of attempting to use 4D-BIM in the actual demolition project show that, despite challenges such as issues with BIM data creation and inadequate BIM software functionalities affecting the efficient generation of 4D-BIM data, the effects demonstrated by 4D-BIM indicate its potential for application in the demolition phase.

Keywords

Building Information Modeling (BIM), 4D-BIM, Building Demolition, Demolition Process, Site Utilization

Type: Research article

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1. Introduction

1.1. Background

4D simulation connects a BIM 3D model of the facility to the scheduling of construction activities, enabling the visualization of the construction process over time [1]. 4D-BIM allows for smooth alignment among project participants and more intuitive comprehension of onsite processes, leading to improved constructability compared to traditional scheduling techniques [2]. During the construction phase of the building, the utilization of 4D-BIM represents one of the methods employed for evaluating the construction scheme. This approach facilitates a detailed assessment of various aspects, including safe and efficient construction methods and sequences, the construction schedule, and reasonable site utilization.

For the demolition phase of a building, creating a well-planned demolition scheme is crucial for effectively managing waste materials and meeting environmental protection requirements. Simultaneously, the reasonable demolition scheme can ensure that the project remains within reasonable schedules and budgets. Furthermore, a well-designed site plan can provide on-site demolition personnel with a safe working environment. Therefore, advanced planning of the demolition schedule, sequence, and site utilization can ensure that the building demolition proceeds smoothly, efficiently, and safely. However, for the demolition of most buildings, the schedule and sequence of demolition are typically outlined in the demolition schedule chart. Additionally, the layout of the demolition site is planned through using 2D drawings. Therefore, the abstract nature of numbers and text makes it difficult for demolition personnel to reach a consensus on the concept of demolition. This can lead to communication and operational discrepancies, resulting in risks such as project delays, increased budgets, and unsafe site utilization. Due to the numerous similarities in the evaluation of projects during both the demolition and the construction phases, there is significant potential for using 4D-BIM to provide detailed assessments of the schedule, sequences, and reasonable site utilization during the demolition phase.

1.2. The utilization of 4D-BIM

(i) Assessment of construction site utilization

Tak et al. [2] discussed the utilization plan for multiple cranes at the construction site based on the onsite operation management framework proposed using 4D-BIM. Chau et al. [3] developed a model using 4D simulation that integrates resource management and site space utilization, providing effective assistance to construction planners. Cheng and Teizer [4] developed a real-time tracking and visualization framework that effectively simulates and records construction sites, outdoor construction settings, and worker training environments. Bortolini et al. [5] developed a site logistics planning model using 4D-BIM to effectively manage logistics on a construction site.

(ii) Safety assessment of the construction site

Hosseini et al. [6] developed a model using 4D-BIM to analyze the risk of fire emergency occurrence and the risks associated with evacuation performance through an integrated approach in complex construction sites. Tran et al. [7] explored the coverage scheme of safety monitoring devices on construction sites using 4D-BIM. Zhang et. al. [8] proposed a new approach for conflict and safety analysis during construction through the integration of 4D-BIM in construction. Sloot et al. [9] presented 4D-BIM as useful in construction for the development of effective risk mitigation strategies.

(iii) Assessment of construction progress.

Han et al. [10] presented a new appearance-based material classification method using 4D-BIM for monitoring construction progress deviations at the operational level. Kropp et. al. [11] presented a novel method that increases the degree of automation for indoor progress monitoring using 4D-BIM. Moon et al. [12] developed an algorithm that can generate workspaces and can be applied in 4D-BIM to identify schedule and workspace conflicts. Jongeling and Olofsson [13] presented a process method for the planning of workflow by combining the use of location-based scheduling and 4D BIM to improve the usability of the 4D BIM for workflow analyses.

Based on previous studies, the exploration of site utilization, safety, and schedule planning at construction sites using 4D-BIM represents a prominent trend in the building construction phase. Similarly, during the demolition phase, the exploration of site utilization, safety, and schedule planning at demolition sites is also paramount. However, during the phase of building demolition, the utilization and research of 4D-BIM are still in an inadequate stage.

1.3. The purpose and the subject of the study

The purpose of this study is to clarify the challenges faced in effectively utilizing 4D-BIM in the actual demolition project. The number of architectural cases with BIM data is gradually increasing. Since BIM data contains all the information from the architectural design phase, its potential use during demolition is evident. For planning the demolition phase, three aspects need to be considered: the rationality of the demolition, the rationality of waste disposal, and the rationality of site utilization. Furthermore, the progress of demolition operations is closely related to time and space. Therefore, when discussing architectural demolition schemes, it is necessary to add a demolition timeline in the BIM data, transforming it into 4D-BIM data, to simulate the progression of the demolition process over time. Therefore, exploring the effectiveness of using 4D-BIM in formulating and executing demolition plans during the demolition process is an important topic.

For investigating and researching the effectiveness of 4D-BIM in the practical building demolition phase, this study chose Keio Co-Evolving House (CEH), located at Keio University in Japan, as the subject of the demolition investigation and research. CEH, the first dwelling house in Japan with cross-laminated timber (CLT) as its main structural material, had to be demolished due to significant aging (Figure 1).

Figure 1. The state before the demolition of the CEH.

The reasons for selecting CEH as the research subject are as follows:
(i) The CEH needed to be demolished due to its aging issues.
(ii) The CEH was not large in scale, and the period from demolition planning to implementation was relatively short. It could be observed and studied within a short period.
(iii) The design and construction of the CEH were related to the authors. BIM data was partially preserved during the design phase, enabling its utilization for discussing the demolition scheme in the demolition phase.
(iv) Since the budget for the CEH demolition project had been determined, it was necessary to develop a reasonable demolition plan.

The main objective of this demolition project was to investigate efficient methods for recycling and reusing CLT materials while also exploring effective and environmentally friendly treatments for other categories of building materials. Therefore, it was necessary to avoid damaging the CLT panels as much as possible during demolition. Due to budget constraints for this demolition project, the CLT panels had to be cut and recycled on the demolition site. Additionally, the classification of waste materials also needed to be done on the demolition site. Therefore, detailed planning is required for the placement of transport trucks and heavy machinery, the location for waste material classification, and the area for cutting CLT panels within the limited space.

Due to the need for this study to explore the rationality of demolition, waste disposal, and site utilization using 4D-BIM, to clarify the challenges faced by 4D-BIM in effective utilization. Therefore, for the CEH demolition project, the discussion on the rationality of demolition mainly includes methods to reduce damage to CLT panels during demolition, methods to complete demolition within a reasonable budget, and methods to achieve efficient demolition processes. Secondly, the discussion on the rationality of waste disposal mainly includes methods for recycling CLT panels and methods for classifying and disposing of waste materials. Finally, the discussion on the rationality of site utilization mainly includes the short-term placement and removal time of recycled and discarded materials, the location and timing of secondary processing of CLT panels, the utilization location and timing of heavy demolition equipment, and the safe moving line. Therefore, this study selected the CEH demolition project as the research subject and utilized 4D-BIM to plan and develop its demolition scheme. The demolition of CEH started on November 15, 2022, and was concluded on December 22, 2022 (Figure 2).

Figure 2. The demolition scene of the CEH.

1.4. Research methods

The method of this study involves applying 4D-BIM in the actual demolition project, observing and evaluating its role in the process of demolition planning and execution, exploring the challenges faced and the potential effects that can be achieved in the utilization of 4D-BIM during the demolition phase, and providing prospects for its future applications. The study utilized Autodesk's Revit 2022 (Revit) and Navisworks 2023 (Navisworks) to generate 4D-BIM data.

The specific composition of this study is as follows: The chapter Two mainly elaborated on the production process of 4D-BIM data used for demolition, as well as the challenges encountered during this process. The chapter Three mainly elaborated on the effectiveness of using 4D-BIM in formulating and implementing demolition plans. The chapter Four mainly evaluated the challenges encountered in the practical application of 4D-BIM in the demolition project, as well as the prospects for its application in the demolition phase of buildings.

2. The creation process and issues of 4D-BIM for demolition

Using 4D-BIM in the CEH demolition project was an experimental attempt. Therefore, it was unclear whether 4D-BIM was effective for devising and utilizing demolition plans during the demolition process in the initial stages of creating 4D-BIM data. Therefore, it was necessary to produce 4D-BIM data fully based on the important focus points of the CEH demolition project for effective utilization during the demolition phase.

For the CEH demolition project, some portions of the CLT panels needed to be recycled, so it was necessary to minimize damage to them during the demolition process. Simultaneously, it was necessary to use the circular saw to cut the CLT panels for segregating recycled and discarded portions within the limited demolition site, due to budget constraints and environmental considerations. Meanwhile, the recycled and discarded portions of CLT panels and other types of waste materials needed to be stored separately on-site for a certain period before being taken away from the demolition site. Additionally, cranes, heavy machinery, and transport trucks needed to be utilized within the demolition area. Therefore, the discussion of demolition solutions mainly focused on the efficient processes and methods of demolition, and the efficient method for recycling waste materials.

To enhance the efficiency of demolition, it is essential to first discuss the sequence and methods of building demolition. This not only ensures that the demolition process proceeds as planned but also minimizes potential safety risks. At the same time, building materials that need to be recycled can also be maximally protected from damage during the demolition process, thereby increasing the possibility of their reuse. Secondly, it is necessary to discuss the utilization of the demolition site. Planning the utilization of the demolition site can ensure the safety of the movement line. Furthermore, planning the utilization of the demolition site enables efficient sorting and processing of discarded and recycled materials based on their types. This improves the efficiency of handling various waste materials and helps reduce environmental pollution.

It is essential to explore methods for extracting and preserving recyclable materials from waste to enhance the efficiency of recycling discarded materials. In the CEH demolition project, it was crucial to plan the extraction method for recyclable materials because extracting recyclable parts required secondary processing of the demolished materials on-site. This planning can help determine the processing locations and required space for recyclable materials, thus avoiding low processing efficiency and safety hazards due to insufficient space. By strategically planning the placement of recyclable and waste materials on-site, it becomes easier to identify and handle recyclable materials, thereby reducing confusion and mistakes among workers.

This chapter provides a detailed explanation of the process of creating 4D-BIM data for demolition and discusses the challenges faced during the creation process. Creating 4D-BIM data for discussing demolition schemes involves three essential steps. First, supplement the existing building BIM data to align it with the pre-demolition conditions. Next, model all demolition elements that may appear on the demolition site. Finally, position the modeled demolition elements within the designated area of the demolition site and add timelines into the overall BIM model to complete the production of the 4D simulation.

2.1. Supplementing Existing BIM Data for CEH

During the design phase of CEH, assembly methods for CLT panels were explored using BIM data. As a result, the BIM data was preserved from the design phase (Figure 3a). The types of models presented in the BIM data during the design phase included CLT panels, columns and beams, load-bearing reinforced plywood, interior finishing plywood (partially), exterior finishing plywood (partially), decks, outdoor slope, furniture (desk, chairs), and equipment (dust system). However, due to numerous elements within the building were not created and integrated into the BIM data, there were many deficiencies in the BIM data saved during the design phase of CEH. Although a comprehensive CEH architectural model was created using Rhinoceros during the design phase (Figure 4), it was not feasible to convert these models into BIM models in Revit. At the same time, due to numerous changes during the construction and usage phases of the building, there were many discrepancies between the actual condition of the building before demolition and the design drawings, as well as the initial 3D models.

In the initial stage of the demolition discussion, since it was unclear which BIM data would be required for the demolition phase, we supplemented the BIM data to resemble the actual condition of the building before demolition. Therefore, this study conducted a detailed BIM modeling of the condition before the demolition of CEH by utilizing Revit based on the construction drawings of CEH and condition surveys (Figure 3b).

The types of BIM models needed for the demolition phase included exterior finishing plywood(supplement), interior finishing plywood(supplement), outdoor and indoor stairs, terrace handrails, insulation panels (roof, exterior walls, foundation, underfloor), green earth wall, concrete foundation, windows and doors, roof waterproof FRP, furniture (beds, chairs, etc.), equipment (hot water storage unit, pipes, solar panels, bath unit, etc.), home appliances (lights, air conditioners, TV, microwave, toilet, refrigerator, etc.). While creating the BIM model for the building, a separate BIM model of the site was also created for demolition site planning (Figure 5).

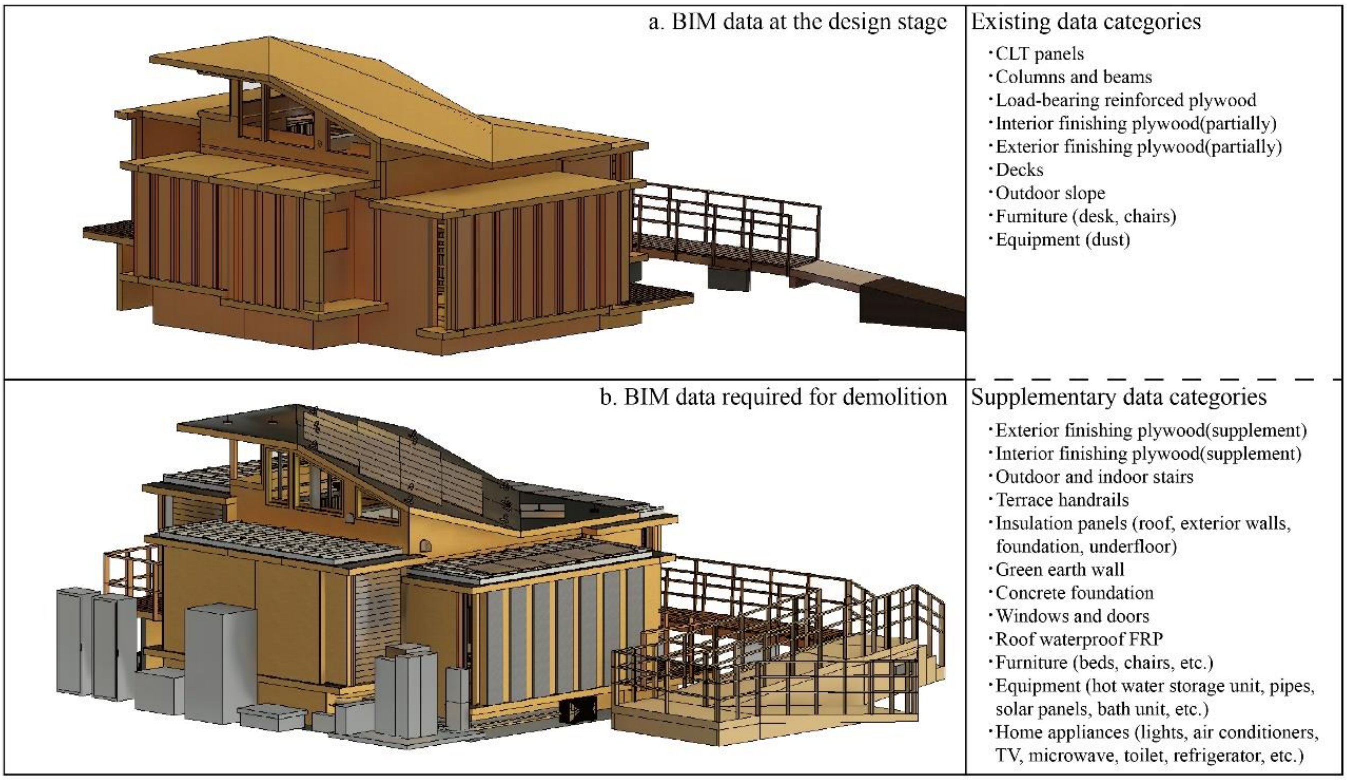

Figure 3. The BIM model of CEH.

Figure 4. The Rhinoceros model of CEH.

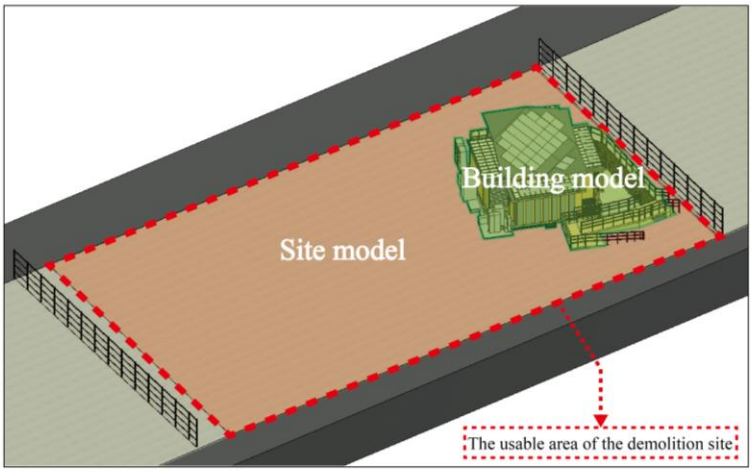

Figure 5. The site model of CEH.

2.2. The creation of demolition elements for demolition site layout

The discussion on the rationality of site utilization is essential for achieving safe and smooth demolition. Therefore, it was uncertain which elements would appear within the demolition site in the initial stage of planning for site utilization in the CEH demolition project. Therefore, before creating 4D-BIM data, it was necessary to model all the demolition elements that might be placed on the demolition site based on the shape, size, and material of each component within the building model.

The reason for modeling according to the actual shapes, sizes, and materials of the elements that might appear on the demolition site is as follows:
(i) It enables observation of the utilization within the limited area of the demolition site, thereby aiding in the formulation of a reasonable demolition plan.
(ii) Materials after demolition need to be placed on the site according to their types, and a model with material information facilitates easier planning of material classification schemes.
(iii) It allows for observation of the volume of various waste materials on the site, making it easier to devise personnel allocation and heavy machinery usage plans.
(iv) Placing models of waste materials that require secondary processing on the site helps to visualize the space needed for processing.
(v) Distinguishing between models of recyclable parts obtained after secondary processing and models of waste parts becomes easier. Additionally, determining the volume of each part is simplified, thereby enhancing the efficiency of site utilization and material recycling.

As shown in Figure 6 (a), it was necessary to model the elements used for demolition on the site. These elements include the scaffold, temporary enclosure, crane, truck, waste container, tent, temporary toilet, and temporary iron plate. Additionally, temporary placement of indoor and outdoor equipment was required within the demolition site. Since these models already exist and are available for direct download, they can be imported into the demolition site model for positional adjustments. As shown in Figure 6(b), it was necessary to model the waste materials that needed to be placed for a certain period within the demolition site. These elements to be modeled include CLT panels (including or excluding recycled portions), columns and beams, insulation units, and indoor/outdoor plywood. During the CEH demolition project, it was necessary to cut the demolished original CLT panels and then extract the parts that needed to be recycled. Therefore, the recycled and discarded portions of CLT panels must be modeled and placed at the demolition site.

Since these waste materials were removed from buildings, the most efficient method to generate them is by directly extracting the corresponding components from building models and placing them horizontally on the demolition site model. When implementing this method, it was found that components horizontal to the ground could be directly extracted from the building model and placed on the demolition site model. However, when attempting to extract and place the models that were perpendicular to the ground, it was discovered that in Revit software, they cannot be rotated and placed on the ground. Therefore, it was necessary to remodel the elements that were perpendicular to the ground to match their original shape and materials, ensuring they could be placed parallel to the ground.

The recycled and discarded portions of CLT had different shapes, as they were cut from the demolished CLT panels. Due to the limitation of dividing one model into multiple models of various shapes in Revit software, it was necessary to create new 3D models for the recycled and discarded portions of CLT (Figure 7).

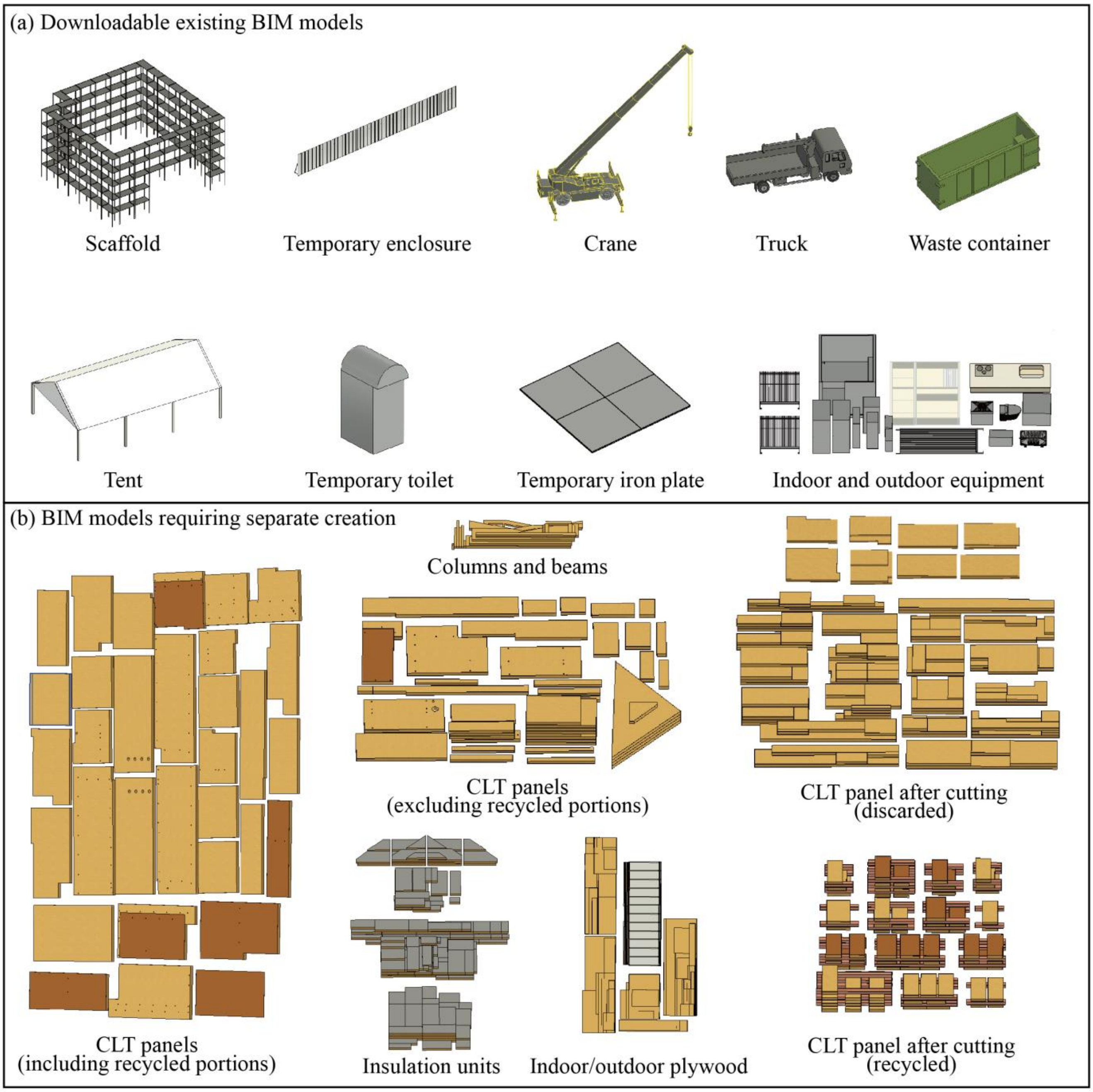

Figure 6. The BIM model of demolition elements.

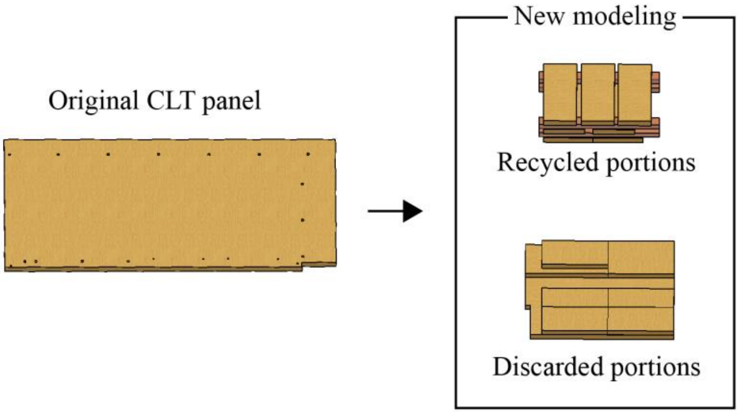

Figure 7. The creation of recycled and discarded CLT panels.

2.3. The process and issues of creating 4D simulations using BIM data

To produce a 4D simulation for demolition, it is necessary to incorporate a demolition timeline into BIM data. While BIM data is created using Revit, the software does not support the integration of the demolition timeline into BIM data. Therefore, Navisworks was employed to add the demolition timeline within the BIM data. Within Navisworks, a new task needs to be established, and specific information from the BIM model needs to be imported. After that, a timeline is manually added to this task. This method accurately adds the demolition timeline to specific components within the building. However, due to the diverse nature of property information within BIM and the presence of identical property information across different BIM components, confusion and difficulty may arise when adding the demolition timeline. Therefore, integrating the timeline in Navisworks and correctly assigning it to various components within the BIM model can be intricate and cumbersome. This process can require a significant time investment to ensure precision, especially when dealing with large or complex BIM models. Particularly in the creation of 4D simulations for CEH, each proposed plan discussed during demolition required a distinct 4D simulation. Therefore, relying solely on the BIM data used for demolition site planning to generate 4D simulations can be cumbersome. Therefore, to simplify the complexity of operations within Navisworks, it is necessary to create unique property information for all components within the BIM model. This will enable the demolition timeline to be easily added to the specified component (Figure 8).

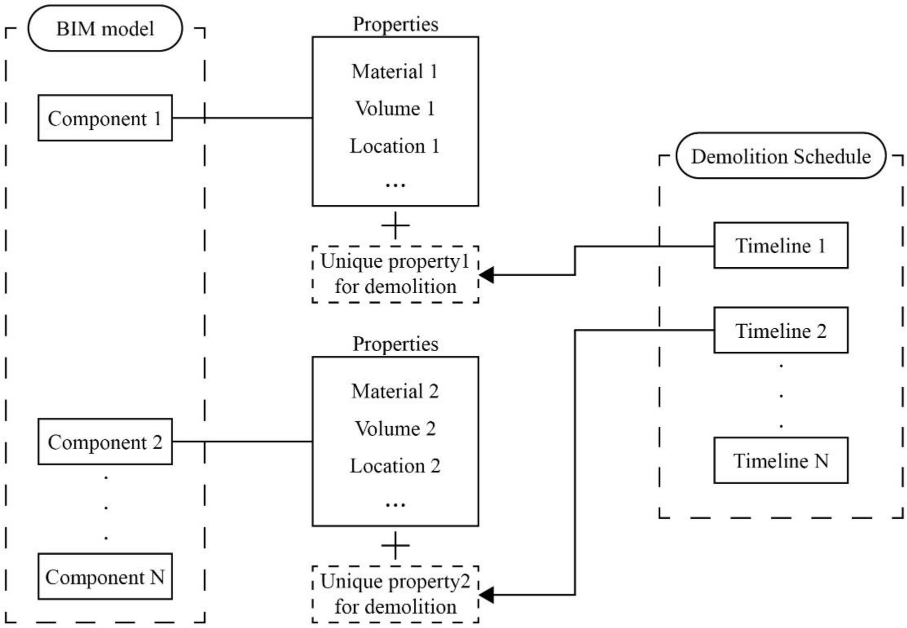

Figure 8. The method for integrating the demolition timeline into each component of the BIM model.

Corresponding names were assigned to each demolition step to accomplish the purpose of creating unique properties. By increasing the number of demolition steps generated, the visualization of the demolition process will become more detailed. Consequently, in the CEH project, over 250 demolition steps were created to accomplish the 4D simulation in detail for demolition. This was essential for a comprehensive evaluation of the demolition scheme (Figure 9). After creating the demolition steps, it is necessary to assign the properties of the demolition steps to the corresponding components of the BIM model. The specific method of operation is to select one component that needs to be assigned the demolition step and then select the corresponding demolition step in “Phase Demolished” under “Properties” (Figure 10). Continue with the same process as described above until all elements of the BIM model are assigned the demolition step. The time required to add the demolition step in the BIM model depends on the number of steps created.

There were compound walls and roofs in CEH. A single compound wall contains multiple layers of various materials. Generally, the compound elements of the BIM model are created as individual model elements with multiple layers of material and thickness, such as walls [14]. As shown in Figure 11a, because the BIM model of CEH was created using a general method, this approach cannot perform the moving, editing, or adding demolition property information for individual component layers within compound elements. This limitation makes it difficult to create the 4D simulation in detail for demolition and to discuss the schemes of demolition methods and sequences, schedule planning, and waste classification. Hence, as shown in Figure 11b, to create compound elements like compound walls, it becomes necessary to model each layer of the compound element one by one and add materials to each model individually. This approach enables the selection and independent operation of each layer of the compound elements.

In the CEH demolition project, the process of creating a 4D simulation for discussing demolition schemes is as follows: first, place the created demolition element models in the model of the demolition site according to the specified positions. Next, add a timeline to the created BIM data to observe the entire dynamic demolition process. Subsequently, decision-makers evaluate the demolition process and methods depicted in the 4D simulation based on actual situations and budgetary constraints, and then provide suggestions for modifications. Based on the suggestions provided, rearrange the components and demolition timelines in the BIM data to generate a new 4D simulation for reference by decision-makers. Repeat this process until decision-makers devise a relatively reasonable demolition plan.

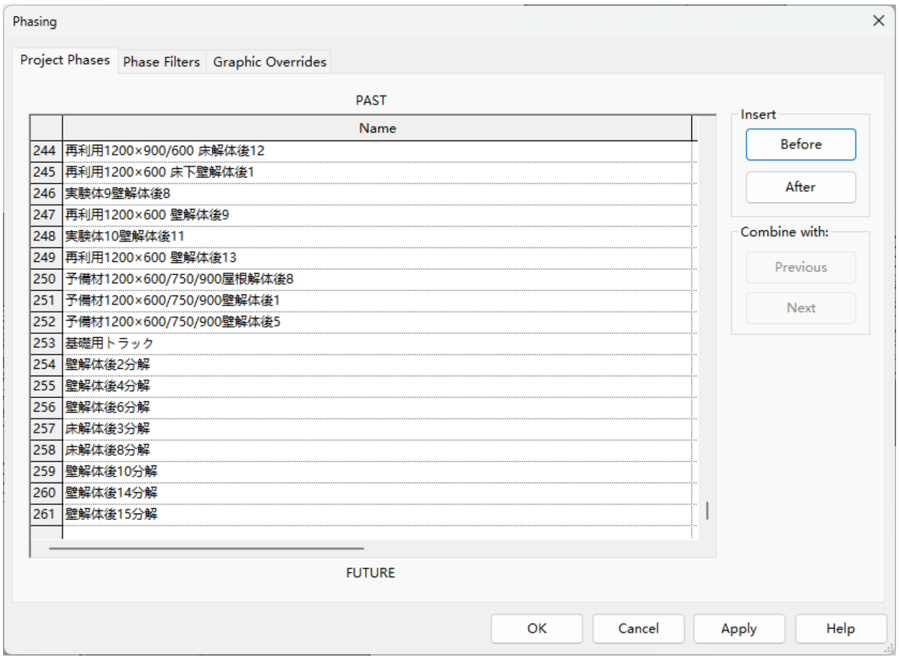

Figure 9. Phasing dialog.

Figure 10. Properties dialog.

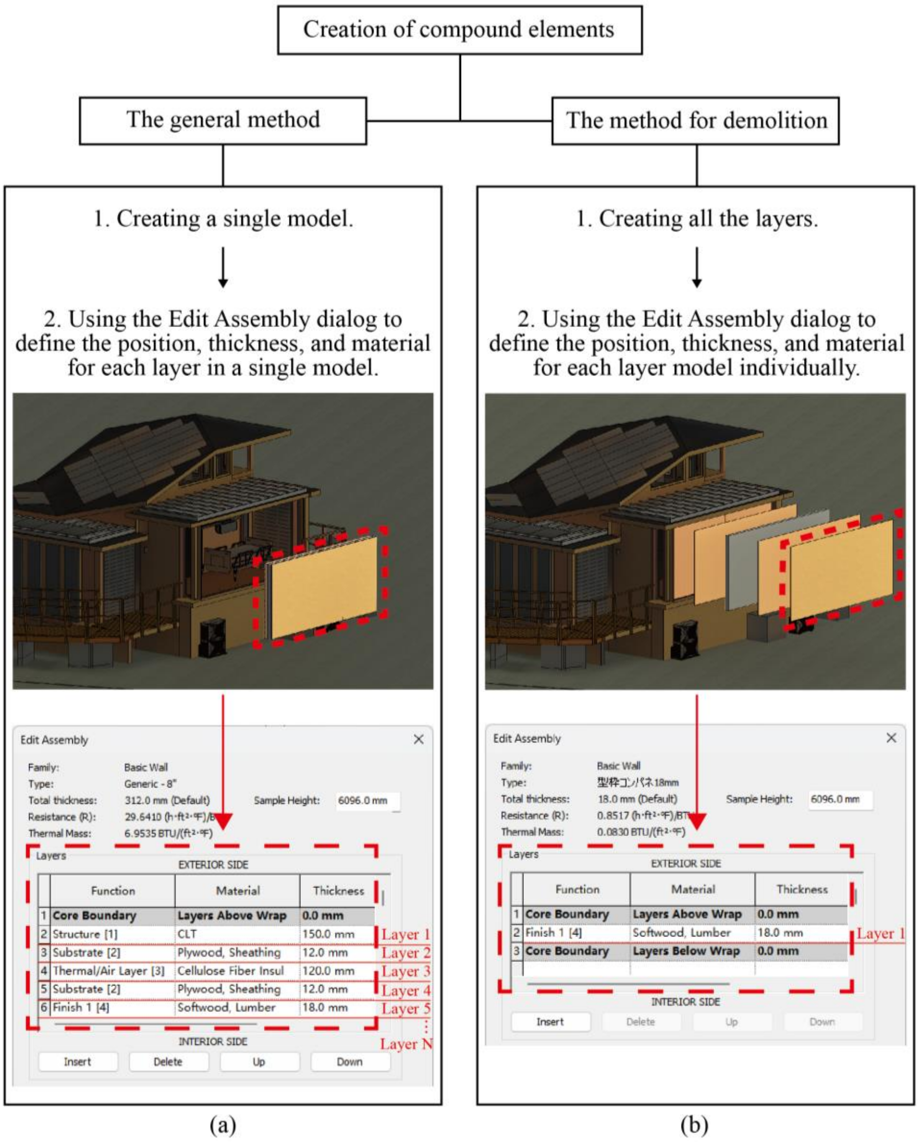

Figure 11. The methods of creating compound elements.

In the CEH demolition project, the utilization of the demolition site, demolition process, and methods were discussed using 4D-BIM data. Throughout the discussion process, we made three revisions to the demolition plan and arrived at the optimal demolition solution ultimately (Figure 12). The modification process of the demolition plan is as follows:

The goal of the demolition project at CEH was to recycle and reuse CLT panels while sorting different types of demolition waste. In the initial plan, the idea was to transport all the CLT panels of CEH together to a cutting facility for cutting and recycling. Therefore, the demolished CLT panels had to be temporarily stored on the demolition site until all CLT panels were demolished from CEH. Simultaneously, other types of waste will be placed in separate waste containers according to their respective categories to ensure proper sorting for processing. The demolition waste was categorized into four types: wood, metal, discarded plastic, and mixed materials. Hence, the demolition site required four large waste containers for sorting purposes. Therefore, by placing the models of CLT panels and waste containers, and adding a demolition timeline, a successful 4D simulation of Plan 1 was created (Figure 12). However, this simulation did not demonstrate the use of demolition elements such as cranes, trucks, etc. Hence, it needed to position the models of heavy machinery, transport trucks, temporary iron plates, portable toilets, and temporary fencing within the site model. This would enable decision-makers to develop the most efficient site utilization scheme. Due to budget constraints, the recycling of CLT panels involved on-site cutting using circular saws. During the planning discussions, it was proposed to set up a tent on the site to shield the cutting process from direct sunlight and rain. However, as shown in Plan 2 in Figure 12, the initial placement plan of the tent obstructs the movement path of the transport trucks. Therefore, as shown in Plan 3 of

Figure 12, it was decided to relocate the tent to the corner of the demolition site. This adjustment ensured the work area remained unaffected while facilitating a smooth cutting process operation.

At the final stage of the scheme discussion, it was discovered that the existing budget could not support the previously discussed demolition scheme. Consequently, the utilization of waste containers, the tent, and the temporary toilet was discontinued in the final scheme. This led to the need to re-plan the cutting location for CLT panels, determine the placement location for recycled and discarded portions of CLT panels, sort and place other types of waste materials, and the placement location for heavy machinery. Therefore, as shown in Plan 4 of Figure 12, all potential elements that could arise at the demolition site were re-planned and positioned within the site. After incorporating the demolition timeline into the final site layout plan, the final 4D simulation for demolition was completed.

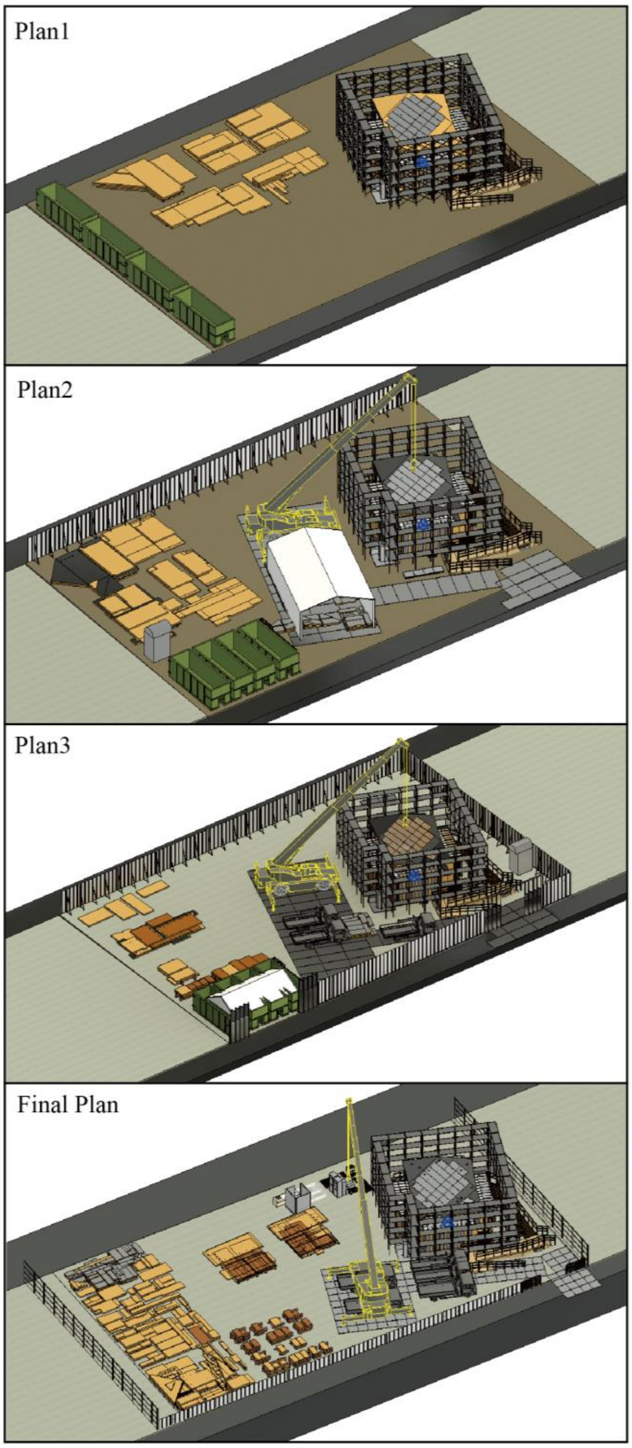

Figure 12. The various BIM models with different layouts.

2.4. Summary of issues and solutions identified during the creation of the 4D-BIM for the demolition

The summary of the problems encountered in creating 4D-BIM data to achieve CEH demolition goals, and the solutions adopted for effective discussion of demolition schemes, are as follows:
(i) During the process of creating demolition elements for demolition site layout, two issues were identified, and the corresponding solutions in this study are as follows (see Table 1):
Problem 1: In the Revit software, components that are perpendicular to the ground cannot be rotated, which makes it impossible to extract them directly from the 3D model of the building and place them horizontally on the ground.
Solution: In this study, the components that were perpendicular to the ground were re-modeled based on their original material, shape, thickness, and other information, enabling them to be horizontally placed within the model of the demolition site.
Problem 2: The extraction method for recycled CLT panels required cutting them from the original CLT panels at the demolition site. As a result, the shape of the recycled and discarded CLT panels was inconsistent with the CLT panels in the CEH BIM model. Additionally, it is impossible to directly cut a component model and divide it into multiple arbitrary shapes in Revit. Therefore, the new CLT panel models generated at the demolition site in CEH cannot be directly extracted from the original BIM model.
Solution: In this study, new models were created for the discarded and recycled portions of CLT panels that were integrated horizontally into the demolition site model.
(ii) During the process of creating the 4D simulations for discussing the demolition solution, two issues were identified, and the corresponding solutions in this study are as follows (Table 1):
Problem 1: The diverse nature of property information within BIM data and the presence of identical property information across different BIM components can lead to confusion and difficulty when adding the demolition timeline.
Solution: This study created unique property information for components in the BIM model to assign demolition time information.
Problem 2: The general method of creating compound elements cannot perform the moving, editing, or adding demolition property information for individual component layers. This limitation makes it difficult to create the 4D simulation in detail for demolition and to discuss the schemes of demolition methods and sequences, schedule planning, and waste classification.
Solution: It is necessary to model each layer of the compound element one by one and add the property information to each model individually.

Table 1. Issues and solutions encountered in 4D-BIM data creation.

	Challenges	Solutions
Creating the demolition elements	(i) Vertical components in the BIM model cannot be rotated.	(i) Recreate component models to allow for horizontal placement.
	(ii) The component model cannot be segmented freely.	(ii) Create new models based on the segmented shape.
Creating the 4D demolition simulation	(i) The existing properties of components are challenging to identify.	(i) Create a unique property for integrating the demolition schedule.
	(ii) The general modeling method for compound elements does not support layer-by-layer operation.	(ii) Model compound elements layer by layer.

3. The application effects and evaluations of using 4D-BIM for demolition

3.1. The evaluation of 4D-BIM data creation

Although demolition schemes can be developed using 2D drawings, when it comes to the need for in-depth analysis and improvement of the scheme, the use of 4D-BIM has significant advantages. Firstly, 2D drawings lack temporal information, making it impossible to comprehensively demonstrate the time progression and operational workflow during the demolition process. In contrast, 4D-BIM combines building information modeling with a timeline to achieve dynamic time visualization, making the planning and adjustments of the demolition process more precise and effective. Secondly, modifying 2D drawings can be relatively cumbersome. When there is a need to enhance and refine the demolition plan, making changes to 2D drawings requires numerous manual operations and redrawing, which is time-consuming and energy intensive. In contrast, 4D-BIM can quickly and accurately update demolition schemes by moving component positions or adjusting the timeline. Therefore, applying 4D-BIM offers advantages over 2D drawings when there is a need for in-depth analysis and improvement of demolition schemes.

Although 4D-BIM data is superior to 2D drawings in terms of scheme improvement and creation efficiency, the process of producing 4D-BIM data suitable for demolition scheme discussions took some time and effort due to incomplete existing BIM data and the imperfect functionality of BIM software.

The efficiency of 4D-BIM data production is primarily affected by two main factors: challenges encountered in supplementing existing BIM data and limitations in the functionality of BIM software.

Regarding the evaluation of challenges encountered in supplementing BIM data, they are as follows: Firstly, the construction and utilization phases of the CEH underwent numerous changes compared to the design drawings and the existing 3D data. During the process of supplementing BIM data, only observable differences could be addressed. However, portions of the building that were not visible cannot be supplemented in BIM data. This limitation was also highlighted by the decision-maker during the interview. The BIM model of CEH was created based on construction drawings and condition surveys. During the construction phase, some long screws were driven into the interior of the CLT panels to secure them. The positions and quantity of these long screws were temporarily determined based on the site conditions. Therefore, these nail locations could not be found on the construction drawings, and the interior condition of the building panels could not be observed during condition surveys. Therefore, these long nails were not included in the BIM model, making it impossible for 4D-BIM to visualize the detailed process of removing them. This resulted in a significant amount of time consumed during the demolition process to determine the positions of the long nails. Thus, the decision-maker pointed out that if the BIM model is solely created based on the initial construction drawings and the building condition survey, the accuracy of the demolition evaluation will be limited. Secondly, while adding different timelines to BIM data to simulate various demolition scenarios rapidly, it was essential to create unique property information for each component before adding timelines to facilitate identification. This also reduced the efficiency of creating 4D-BIM data in the CEH demolition project.

Regarding the evaluation of the imperfect functionality of BIM software is as follows: Firstly, components corresponding to the building model can be directly extracted and placed at the demolition site when creating models of waste materials. This method is fast and efficient. However, due to the limitations of Revit software, which does not support the rotation of vertical elements and their placement horizontally on the ground when extracting vertical components within the building, it becomes essential to create a new model that aligns horizontally with the ground based on the shape, size, and material of the vertical elements. Secondly, for the CEH demolition project, recycled materials were obtained by cutting from demolished materials. However, it is impossible to directly cut a component model and divide it into multiple arbitrary shapes in Revit to create models of the recycled and discarded portions. Hence, new modeling work was required for the recycled and discarded portions. Therefore, the above two issues reduced the efficiency of creating 4D-BIM data in the CEH demolition project.

3.2. The effectiveness and evaluation of 4D-BIM in exploring demolition schemes

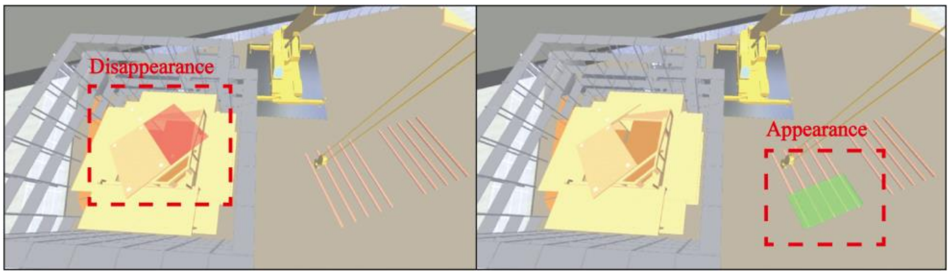

Figure 13. The visualization form of 4D-BIM.

By adjusting the placement of components within the site and adding various demolition timelines to the BIM data, different demolition schemes can be quickly and efficiently discussed, providing effective references for producing the most reasonable demolition plan. Furthermore, 4D-BIM can illustrate the demolition and generation of components within a specific time frame through the disappearance and reappearance of the component models (Figure 13). This presentation format allows for intuitive observation of the quantities of waste and recycled materials generated at the demolition site at different times. This prompts the accurate formulation of personnel deployment plans and equipment usage schemes, thereby saving costs, improving work efficiency, and ensuring the safety of the demolition site. Simultaneously, this enables decision-makers to engage in a more comprehensive discussion about the demolition process and potential plans in a more intuitive manner. Through interviews with one of the decision-makers, we learned that 4D-BIM, which can visualize the demolition process, played a highly effective role in discussing the layout plans for cranes, recycled materials, discarded materials, and truck arrangements at the demolition site.

When discussing the detailed demolition process of buildings, we found the CEH has compound elements. Revit software provides an efficient modeling method for compound elements, allowing users to add multiple layers of component information to the same model. However, this method does not allow for the addition of separate demolition timelines for each layer, thus hindering the detailed simulation of the demolition sequence of compound elements. This limitation, in turn, impedes detailed scheme exploration. Although creating multiple layers in a single model is very efficient, Revit software cannot segment the compound element model created by this method layer by layer. Therefore, in the demolition project of CEH, we modeled each layer of the compound element individually. Although this method can discuss the detailed demolition process of compound elements, it is inefficient compared to general methods for creating compound element models.

3.3. Evaluation of the effectiveness of implementing the demolition plan developed with 4D-BIM during the demolition

The 4D-BIM can display the demolition process, the generation time and placement of waste and recyclable materials, and the duration and location of demolition equipment such as cranes. Hence, during the initial phase of CEH demolition, a comprehensive explanation of the demolition process and site utilization was presented to the participants using the 4D-BIM (Figure 14). This allowed the participants in the demolition to gain a more intuitive understanding of the demolition plan and enabled all relevant personnel to reach a consensus on the demolition process. Simultaneously, 4D-BIM can also display the types of work required daily and the amount of work. This feature allows decision-makers to schedule the necessary personnel effectively for the demolition project. The effectiveness of the above has also been confirmed in interviews with decision-makers.

Figure 14. Using 4D-BIM to illustrate the demolition scheme to the relevant personnel (Left: Initial phase of demolition. Right: Phase of demolishing CLT panels).

In addition, 4D-BIM allows observation of the demolition process of buildings from any angle and at any time. During the demolition phase of CLT panels in the CEH demolition project, the demolition personnel were provided with a detailed explanation of the process and methods of demolishing CLT panels using 4D-BIM (Figure 14). For example, as depicted in Figure 15, the 4D-BIM provided detailed information about the installation time and location of the hanging hardware fittings used to hoist the CLT panels. This made the installation of hanging hardware at the demolition site smooth and efficient.

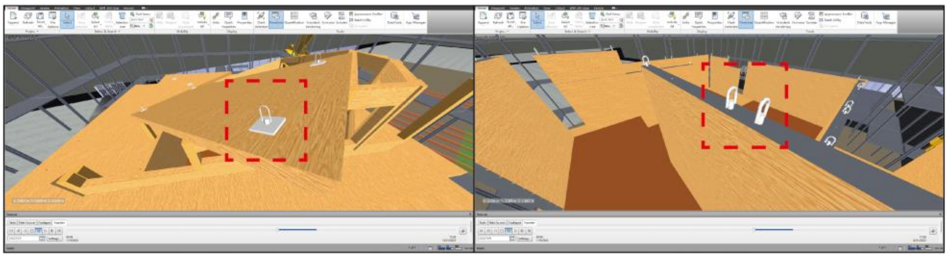

Figure 15. The installation time and location simulation of hanging hardware fittings.

Although detailed demolition plans can be communicated to demolition personnel through 4D-BIM data on the computer screen and consensus can be reached on the demolition plan, during the demolition process, demolition personnel may not be able to always watch demolition simulations. Additionally, unpredictable situations may occur at the demolition site, leading to a series of problems such as reduced demolition efficiency. Therefore, although the demolition plan made through 4D-BIM can enable demolition personnel to reach the same consensus, it does not ensure that the demolition will progress entirely as per the planned 4D-BIM scheme.

4. Discussion

4.1. The prospects for 4D-BIM data creation and 4D-BIM software functionality

Although the CEH demolition project has demonstrated the potential of using 4D-BIM to some extent during the demolition phase, there are also various shortcomings. The attempt in the CEH demolition project suggests that to enhance the efficiency of using 4D-BIM during the demolition phase, it is primarily necessary to focus on two aspects: first, the approach to creating BIM data needed for demolition, and second, the software functionality used to generate 4D-BIM data. The specific content is as follows:

(i) The creation of BIM data for demolition

When creating 4D-BIM data, it is necessary to add a timeline for demolition within the BIM model. It is essential to assign unique properties to each component in the BIM model to associate the timeline with the corresponding components more efficiently. However, it is an ineffective task to create and assign properties to each component after creating the BIM model. Therefore, utilizing BIM for modeling and assigning unique category properties to each component simultaneously during the design phase of a building can save a significant amount of time and effort during the demolition phase. Hence, assigning unique category properties to components using the BIM model in the early stages of architectural design is a crucial step in enhancing efficiency during the demolition phase. This not only aids in saving time and resources but also ensures consistency and traceability of data throughout the entire building lifecycle.

Furthermore, the discrepancies between the actual condition of the building and the construction drawings, particularly those that are challenging to confirm through condition investigation, pose an obstacle to creating accurate BIM data. Therefore, timely recording of building changes and updating the BIM model during the construction, maintenance, and utilization stages can enhance the accuracy of the model creation. This practice can improve the efficiency of the 4D-BIM utilization during the building demolition phase.

(ii) The utilization of BIM software for demolition

Generally, BIM data is created before construction begins. Therefore, during the demolition phase of a building, if one wishes to utilize the BIM model to plan the placement of waste and recyclable materials on the demolition site, a quick method is to directly copy and extract the portions needed for planning from the BIM model and then place them on the site model for positional adjustments. However, some elements are perpendicular to the ground within the building, which Revit prohibits from being rotated and placed horizontally with the ground. Therefore, recreating these vertical elements is a time-consuming and labor-intensive task during the planning process of site utilization for demolition.

In this study, we used the TimeLiner function in Navisworks to create timelines for components in the BIM model, aiming to achieve the production of the 4D demolition simulation. We discovered that simulating the rotation of vertical components and their horizontal placement at the demolition site within the model can be accomplished using the Animator function in Navisworks (Figure 16a). The specific steps are as follows: First, create a movement path or rotation animation for a component in the Animator. Next, find the task in the TimeLiner's Tasks that corresponds to this component. Then, import the animation created in Animator into the Animation section of the Tasks (Figure 16b). This approach enables the direct extraction of vertical elements from the building model and simulates the process of placing them on the ground. However, we encountered certain limitations in using Animator to depict the demolition process of vertical elements in the production of the 4D demolition simulation.

In the 4D-BIM model, a component model can only be assigned a “Demolish” or “Construct” timeline, which means they can only appear or disappear within specified periods. The animations created in Animator can only be displayed within the set time frames in the TimeLiner. This representation is effective during the construction phase of a building. When a component is assigned the "Construct" simulation attribute in the Task Type of the TimeLiner, the component continues to exist in the 4D simulation image after the motion trajectory and rotation animation have ended. However, if a component is assigned the "Demolish" simulation attribute in the Task Type of the TimeLiner, the component will disappear from the 4D simulation image after the demolition simulation animation. As a result, it cannot reflect its placement status on the demolition site (Figure 16c). Therefore, it is impossible to accurately simulate the placement location and time of the demolished waste materials and recycled materials. This limitation makes it impossible to discuss the utilization plan for the demolition site. Hence, it was deemed essential in this study to create models of waste materials in Revit before establishing a demolition timeline for the BIM model.

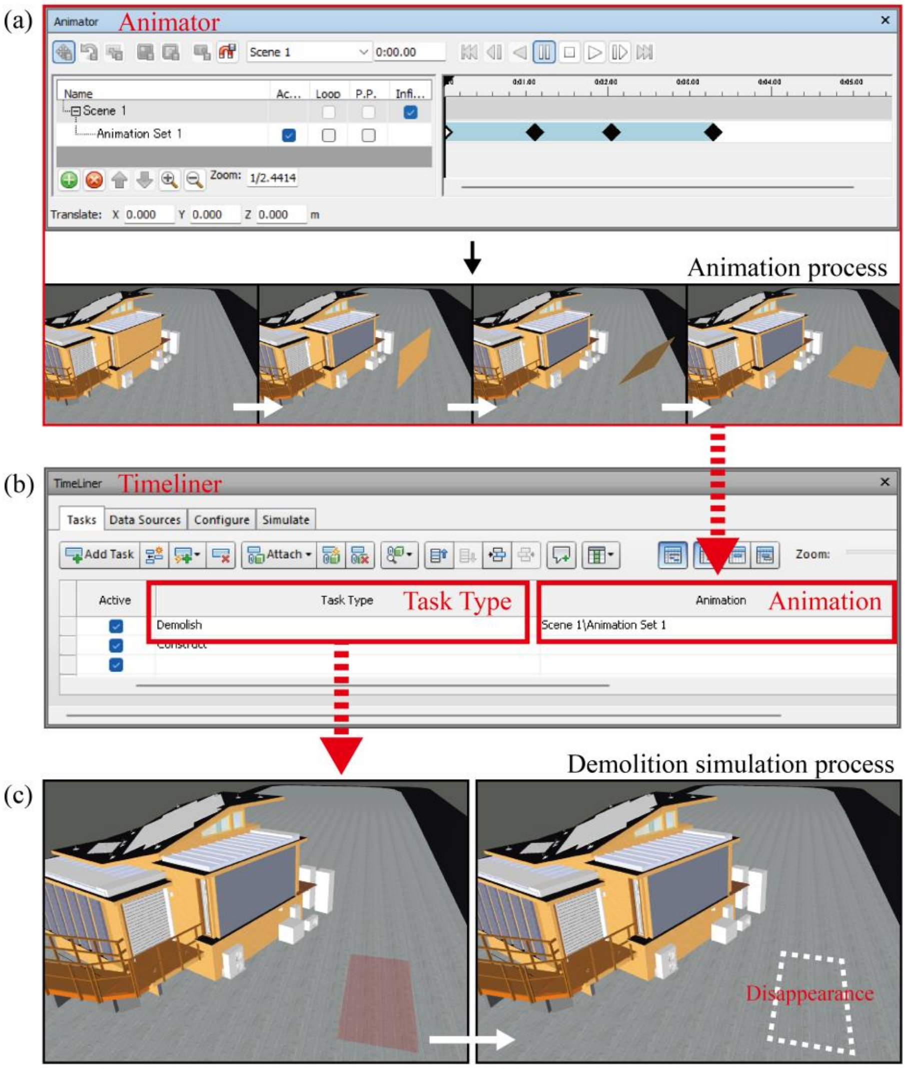

Figure 16. The presentation effect of Animator in Timeliner.

Furthermore, neither Revit nor Navisworks has the capability to divide the component model into an arbitrary shape. In the CEH demolition project, the recycled and discarded portions of the CLT panels, after being cut, still needed to be modeled again in Revit according to the cutting shapes and placed at the designated locations.

Simultaneously, to facilitate the more efficient creation of compound elements, Revit offers the capability to add multiple layers to a single model and define thicknesses and materials for each layer. However, the current capability provided by Revit does not allow for individual operation and selection of each layer of compound elements, which is highly disadvantageous when discussing detailed demolition schemes.

In summary, creating new models for demolished materials can partially address these issues, but it certainly adds to the complexity and workload of modeling. This also highlights the limitations of 4D-BIM when dealing with complex demolition projects.

Therefore, we expect to have the capability in BIM software where each layer in compound elements created through a single model can be separated from each other and become independent models (Figure 17a). Secondly, we hope that the BIM software can define waste properties, allowing models with waste properties to rotate in any direction and be placed in any position. Moreover, it should allow for easy conversion of models with any properties into models with waste properties. This enables the direct extraction of any element from the building model for waste element conversion (Figure 17b).

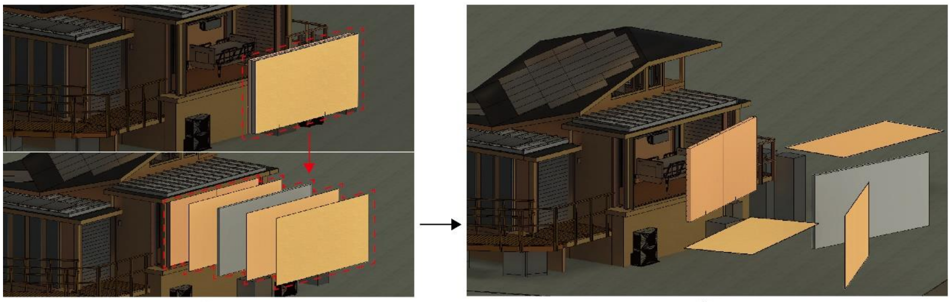

Figure 17. Expected function of BIM software (a): Each layer within a compound element generated by a single model can be transformed into an independent and operable model. Expected function of BIM software (b): Elements transformed into waste properties can be rotated in any direction and placed in any position.

4.2. Further research

Recording and feedback are crucial during the demolition implementation phase to address various issues and changes that may arise during project execution. Accurate records need to be maintained during the implementation phase to clearly understand the differences between the demolition plan and its actual execution.

Sometimes, it is challenging to utilize 4D-BIM data correctly during demolition implementation. This issue could be attributed to insufficient BIM data or a lack of appropriate methods to accommodate changes and adjustments during the demolition execution phase. To address this issue, a method needs to be developed to continuously compare 4D-BIM data with actual demolition progress during the demolition process, identifying discrepancies and issues. If demolition is not proceeding as planned or changes are required, communication and coordination within the team are necessary to assess the impacts of plan changes and consider appropriate measures.

Therefore, recording the progress of demolition execution at the demolition site and assessing the effectiveness of utilizing 4D-BIM for demolition execution is a future topic of interest.

5. Conclusion

This study evaluates the challenges of effectively utilizing and the effectiveness of 4D-BIM in demolition through its practical application in an actual demolition project.

During the data creation phase of 4D-BIM, although the efficiency of using 4D-BIM is superior to 2D drawings in scheme production and modification, challenges were encountered in supplementing BIM data and utilizing BIM software effectively to achieve detailed discussions on demolition objectives. This resulted in a decrease in the efficiency of producing 4D-BIM data for the demolition. Therefore, if the demolition requirements are fully considered during the creation process of BIM data in the design, construction, and maintenance phases of buildings, and if the functionality of BIM software can efficiently address these requirements, the efficiency of creating 4D BIM data for the demolition phase will be greatly improved.

During the exploration and formulation phase of demolition plans, 4D-BIM can illustrate the demolition and generation of components within a specific time frame by showing the disappearance and reappearance of the component models. Furthermore, multiple demolition simulations can be created by modifying the placement of components in the BIM model and adding various demolition timelines. These simulations can provide decision-makers with valuable insights for discussing and evaluating demolition strategies. Moreover, through interviews with one of the decision-makers, we learned that 4D-BIM, which can visualize the demolition process, played a highly effective role in discussing the layout plans for cranes, recycled materials, discarded materials, and truck arrangements at the demolition site.

Based on the utilization effect of the demolition plan developed with 4D-BIM during the demolition implementation, since 4D-BIM can visualize the demolition process and the amount of work required each day, it can enable relevant personnel at the demolition site to reach a consensus on the demolition plan by observing the demolition simulation. At the same time, it can also allow decision-makers to develop a reasonable plan for personnel arrangements at the demolition site. However, it is impossible for workers to confirm the 4D-BIM data at any time during the demolition process. Simultaneously, unforeseen circumstances during the demolition process may lead to discrepancies between the actual situation at the demolition site and the demolition plan created by 4D-BIM. Therefore, finding a real-time recording method for the demolition process at the demolition site and comparing it with the demolition plan in the 4D-BIM data is the next important research topic for conducting real-time discussions and solutions regarding the conditions that arise at the demolition site.

Although this study evaluated the effectiveness of applying 4D-BIM only in one specific demolition project, the key issues it discussed include the rationality of demolition, the rationality of waste disposal, and the rationality of site utilization. These aspects are commonly considered in demolition projects. Therefore, through the case analysis of the CEH demolition project, exploring the feasibility of utilizing 4D-BIM to formulate the demolition plan, and assess the rationality of the demolition process, waste disposal, and site utilization, has universal reference value. Nevertheless, due to the relatively small scale of the CEH demolition project, unique demolition requirements may arise in different demolition cases. Due to the difficulty in finding architectural demolition cases that have created BIM data, and due to limitations in research budget and time, this study could only attempt to utilize 4D-BIM to analyze the demolition project of CEH, in which the authors participated during the design phase. Therefore, further practical use of 4D-BIM may be needed in various demolition projects in the future to identify challenges for effectively implementing 4D-BIM technology across different scales and requirements.

While creating 4D-BIM data to explore demolition plans effectively, we encountered challenges related to BIM data creation and utilizing BIM software. Although it required extra time and effort in the initial stages to address these challenges, the solutions proposed in this study enable the effective utilization of 4D-BIM in exploring and creating demolition plans. If the issues identified in this study can be effectively addressed in the future, the efficiency of producing 4D-BIM data for demolition will improve. This will lead to a broader application of 4D-BIM in the demolition phase of buildings.

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Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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