buildings

Article

Collaborative BIM-Based Construction Coordination Progress Modeling Using Extended Collaborative Process Modeling (exCPM)

Jae-Hyung Shim [1], Nam-Hyuk Ham [2,*] and Jae-Jun Kim [1]

[1] Department of Architectural Engineering, Hanyang University, 222, Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea; sjh060400@hanyang.ac.kr (J.-H.S.); jjkim@hanyang.ac.kr (J.-J.K.)
[2] Department of Digital Architecture and Urban Engineering, Hanyang Cyber University, 220, Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea
* Correspondence: nhham@hycu.ac.kr; Tel.: +82-2-2290-0861

Abstract: Agile project management pursues repetitive and continuous management through an empirical process control method considering the complexity of the project. This study aimed to propose a collaborative Building Information Modeling (BIM)-based work process, focusing on construction coordination tasks among participants during the construction phase of a project. The theoretical framework chosen for this endeavor was the Scrum framework, selected after analyzing previous research to align with the specific characteristics of construction coordination. Using the Scrum framework as a foundation, the study employed the exCPM methodology to model the collaborative BIM-based construction coordination progress. To validate the model, it underwent a transformation into a Petri-Nets model through the marked graph building block (MGBB) along with established rules for model conversion. The converted model was then subjected to validation through reachability tree analysis. The findings of this study hold applicability to diverse collaboration processes that leverage BIM in the construction industry.

Keywords: Agile project management; Scrum framework; construction coordination; BIM; exCPM

check for updates

Citation: Shim, J.-H.; Ham, N.-H.; Kim, J.-J. Collaborative BIM-Based Construction Coordination Progress Modeling Using Extended Collaborative Process Modeling (exCPM). *Buildings* **2024**, *14*, 358. https://doi.org/10.3390/buildings14020358

Academic Editor: Osama Abudayyeh

Received: 5 January 2024
Revised: 14 January 2024
Accepted: 25 January 2024
Published: 28 January 2024

1. Introduction

The requirements of a construction project are complex, depending on the size, type, and other characteristics of the project. Moreover, the final product of a construction project, a building, is created through the collaboration and coordination of participants with various interests [1]. This process is iterative and progressive throughout the lifecycle of the construction project. Rework issues, such as frequent design errors, redesigns, and reconstructions, that occur during this process are a major obstacle to achieving project goals [2]. Traditional construction project management methodologies focus on meeting project objectives with constraints, such as scope, schedule, and cost, and existing studies have solved problems through explicit and theoretical modeling [3].

Building information modeling (BIM) technology, which is expected to improve the management of construction projects, focuses on achieving the goals of traditional construction projects and related technologies, such as model authoring, using BIM S/W directly related to tangible project deliverables [4], 3D BIM model representation level (e.g., level of development (LOD)) [5], and information exchange, such as the information delivery manual and model view definitions (MVDs) [6–8]. Furthermore, 3D BIM is expanding into multidimensional (nD) BIM by fusing concepts, such as schedule, cost, sustainability, facility management, and safety [9–14]. However, the techniques suggested by these studies may conflict with existing processes or may not work well when introduced into traditional construction project management methodologies [15]. In this regard, various approaches have been proposed to improve the way construction projects are procured, including integrated project delivery (IPD) [16], virtual design and construction [17], design for manufacturing and assembly (DfMA) [18], and off-site construction (OSC) [19]. However, these prior studies either work properly only for specific targets and processes or focus on local optimization, so it is difficult to have a significant impact on meeting the constraints of construction projects.

Meanwhile, in the case of software development, the complexity of projects makes it difficult to adopt a defined process control approach; hence, it is preferable to choose an empirical process control approach [20]. It has also been shown that, in the long run, getting it right the first time with empirical process control is far more cost-effective than reworking defective products produced with explicit process control [21]. Therefore, advanced construction companies, such as Tidhar [22] and DPR [23,24], recognize BIM as a tool for managing construction projects and focus on the aspects of fusing it with traditional lean construction concepts for its effective functioning. This study aimed to model and verify BIM-based construction coordination progress that enables continuous and iterative collaboration in order to improve the collaboration process in the construction phase of construction projects.

2. Literature Review

2.1. Agile Project Management Approach

Various Agile methods are used in software development, including the eXtreme programming development process, Scrum development process, crystal family of methodologies (CM), and dynamic system development method [25–27]. These methods are utilized to satisfy customers, support interactions, communicate, and produce high-quality products. Among them, the Scrum development method assumes that the uncertainty in the early stages of a software development project is high, the requirements can change sufficiently during the process, and the risks and uncertainties of such projects are the same as those of construction projects. For this type of project management, it is crucial to understand how to run a team in a changing environment. Scrum is a way of responding to customer needs in an agile, iterative, and incremental way through strong, highly skilled teams [28].

Meanwhile, Toyota's lean philosophy states that continuous improvement activities should go hand in hand with the elimination of waste. In development organizations, the value ratio is no more than 7%, and over 93% of the time is wasted [29]. As the amount of time that adds value across the entire timeline is very small, i.e., roughly 5%, improving this time will not have a significant effect. However, there is a significant amount of time wasted in the process, and eliminating it can improve the value ratio. Several studies have been conducted in construction to identify and quantify non-value-added efforts to eliminate this waste [30,31]. Lean focuses on the baton, the value of the project, not the runners—workers, machines, etc. It does not produce a suboptimal optimization that maximizes the utility of the worker or machine. Instead, bottlenecks are removed to accelerate value throughput for customers. This is the focus of Scrum, producing valuable features in short time-boxed iterations [29].

2.2. Lean Construction and BIM-Based Construction Project Management

A manufacturing production line and a construction project site are different in several ways. Various lean construction tools and elements are still in their infancy, as the lean production theory and practice are not a perfect fit for the construction industry [32]. Nevertheless, lean construction techniques are gaining popularity because the approach of lean production can have a significant impact on the profitability of a project [33]. In addition, a study proposed a lean assessment scale to quantify lean implementation, which evaluated six lean construction factors (last planner, increased visualization, huddle meeting, first-run studies, five S's, and fail safe for quality) [34]. Lean construction is a management paradigm that tends to disrupt traditional project management [22].

The convergence of lean construction and BIM-based construction project management has been conducted in various previous studies [35–37]. BIM is a key technology in lean construction for changing the management paradigm, requiring the adoption of BIM-appropriate workflows that differ from traditional ways of working. DPR E&C utilizes an IPD approach for project management to bring lean thinking to its construction projects. To apply the IPD approach to construction projects, construction coordination progress, including data collection, work planning, BIM modeling appropriate for work plan review, plan review using the BIM model, adjustment, and execution, is carried out repeatedly and continuously every three weeks. The BIM model is used to support smooth collaboration between participants in this process. Lean management techniques are also adopted to execute and manage planned work. Through an iterative, incremental process of aggregating all the information required for planning into a single BIM model, then sharing that BIM model with everyone involved in the planning process, and modifying and supplementing it, a specific and realistic plan for the actual construction can be created. This approach can maximize productivity and quality by minimizing issues, such as mid-course corrections and rework, compared with the execution of incomplete plans resulting from traditional project management methods [38].

2.3. Properties of BIM-Based Construction Coordination Progress

Construction coordination is defined as a process by which a project manager provides services to the stakeholders involved in a construction project [39]. There are eight methods of coordination required for construction project management: meetings, informal discussions, site visits, written correspondence, plans, schedules, reports, and contract documents [40]. On-site construction coordination can be varied and complex, from one-time to ongoing. Therefore, BIM-based construction coordination does not simply involve implementing nD BIM [9–14] or BIM-based clash detection and design validation [41,42].

BIM-based construction coordination progress is a process to achieve BIM goals through various BIM uses that can be utilized in the construction phase [43]. Professional BIM staff helps reduce design errors, improve constructability, and enable better communication during this process [44–46]. Professionals involved in a project often make a request for information (RFI) from the BIM staff to improve construction coordination progress based on BIM. Depending on the type of RFI, the amount of time required for BIM staff to provide BIM services to support construction coordination varies widely. Therefore, if the focus is on BIM use rather than BIM goals, it is likely to result in the same narrow optimization as before.

Ham and Yuh (2023) classified BIM RFIs for BIM-based construction support and conducted a performance analysis of prioritizing high-priority RFIs [47]. Huh et al. (2023) also analyzed the effectiveness of applying a prioritization policy to improve the performance of a BIM-based design validation process [48]. These studies utilized a priority queue, an empirical process control approach from the field of management science. However, BIM-based construction coordination progress is built as an abstract queue, which has limitations in managing iterative and incremental collaboration processes. This study aimed to establish an iterative and gradual BIM-based collaboration process that reflects the characteristics of BIM-based construction coordination progress, and to verify the process and present implications through a case analysis of the BIM-based construction coordination process in the construction phase.

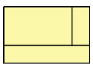
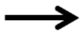
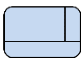
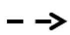
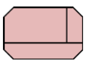
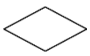
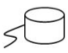
2.4. Business Process Modeling Methodology

The business process modeling method involves creating a simplified and abstracted form of the model to represent the progress of the work according to a certain representation format [49]. Tasks are also defined by process and participant, and the flow and correlation of data generated through diagrams are visually expressed [50].

Various business process modeling methods have been applied to represent the BIM-based construction process. The Integration DEFinition 0 (IDEF0) modeling method consists of activity, input, control, output, mechanism, and call arrow. This method is useful for understanding the information flow in a task and has been used to represent information flow in BIM and extended reality [51]. Business process modeling notation enables the design and diagramming of various processes by dividing activities into organizations or participating entities and notating the flow of information between activities according to the time flow of the process. It has been used to represent processes for various BIM uses and was developed by Penn State [43]. The unified modeling language (UML) is a general-purpose modeling language that leverages object-oriented concepts to model systems and provides a standard way to visualize system designs. This language has been used to model the requirements and specifications for the cloud-based BIM governance platform [52]. Al Hattab and Hamzeh (2013) developed swim-lane process flow diagrams to show the flow of design output deliverables across different design stages and respective teams under ideal BIM-based and traditional designs to demonstrate the differences in information flows qualitatively at a macro level using BIM [53]. Petri-Nets can be used to model systems with asynchronous elements that are tightly connected to one another, and are composed of places, transitions, arcs, and tokens. Places represent the state of a system, its behavior, etc., and transitions represent events that cause change. Tokens can represent the state of the system at a particular point in time [54]. However, these process modeling methodologies have limitations for modeling collaborative processes that represent multiple actors.

Collaborative process modeling (CPM) is a methodology for modeling collaborative processes between multiple performers and other organizations [55]. CPM is process-centric and consists of eight components based on UML notation. The general process, internal collaborative process, and external collaborative process are organized with different symbols, allowing for an intuitive understanding of the process by indicating the actors who perform the work. In addition, the model completed through CPM can be converted into a Petri-Nets model through marked graph building blocks (MGBBs) and rules for model conversion, enabling model analysis and validation. However, there are limitations to the real-time monitoring of collaborative processes and the representation of information exchanged between collaborative processes and between actors. Extended CPM (exCPM) maintains the advantages of the CPM method and consists of 10 elements, reflecting the state token of Petri-Nets, the color token of colored Petri-Nets, and the ICOM concept of IDEF0 [56]. exCPM divides processes into three types: general, internal collaboration, and external collaboration, and each process is represented by three areas. Collaborative processes are intuitively monitored by displaying process information in the first area, the execution status of the process in the second area, and the actors as color tokens in the third area. The representation of information flow adopts the IDEF0 concepts of input, output, and control, and takes the form of a dotted line to distinguish it from process transitions. The other elements follow the components of a traditional CPM methodology, as shown in Table 1.

Table 1. exCPM elements.

Symbol	Description	Symbol	Description
	Normal Process		Process transition
	Intra-collaboration Process		Input/Output/ Control
	Inter-collaboration Process		Synchronization
	Decision		State token
	Resource		Color token

Lee et al. (2010) introduced exCPM, an expanded version that can increase the collaborative process modeling and analysis capabilities of existing CPM methods [56]. One of the distinguishing features of exCPM is that it supports model validation by converting exCPM models into Petri-Nets models. Through case analysis, this study confirmed how exCPM contributes to clearly explaining collaborative work in the manufacturing and business areas. Additionally, this study showed that the exCPM method is useful for improving productivity by capturing and validating collaboration between collaboration partners. Park et al. (2014) applied exCPM, which was proposed to model the collaboration process in the industrial engineering field, to research in the construction field in order to improve the collaboration process in the BIM-based early design stage [57]. The exCPM model was proposed by analyzing the collaboration process between architectural design subjects and structural engineering subjects in the early design stage of an actual construction project. In addition, the proposed exCPM model was converted to a Petri-Nets model and analyzed to validate whether the process model was properly constructed.

3. Problem Statements of Real-World BIM-Based Construction Project

As shown in previous studies, from a lean perspective, the focus of project management should be on the production output, which is the value of the project, rather than on the main players, such as workers and machines. Therefore, local optimization that maximizes the utility of workers or machines is avoided. Previous approaches to BIM research have focused excessively on the form of BIM as an information tool or the level of detail in information rather than on improving the quality of production outputs or optimizing processes. For example, by increasing the LOD of the BIM model to calculate material quantity information, the primary goal of obtaining bill of quantity (BoQ) can be achieved. However, when 5D BIM is constructed by linking cost breakdown structure (CBS) and BIM model to manage costs at the project management level, the complexity of information management increases, making it difficult to utilize for actual cost management. Additionally, when configuring 4D BIM, additional BIM models for necessary construction, equipment, materials, and personnel are required in addition to the building components being constructed. Even if 4D BIM is created by visualizing process information by linking the BIM model and work breakdown structure (WBS), it is possible to recognize the progress of the work, but it does not make a significant contribution to managing the actual process. In other words, BIM models built with a lot of investment are not recycled for various purposes, but are often not properly used for the single purpose they were originally intended for. Therefore, through the case analysis of this study, this study seeks to establish the justification that it is important to model collaboration and information flow between various entities centered on work rather than building a process centered on the BIM model.

As a methodology for modeling collaborative processes between multiple performers and different organizations, the exCPM methodology can provide solutions for iterative, continuously managed work processes. To examine the field applicability of the exCPM methodology reviewed in the literature, this study conducted a case analysis of a real construction project where BIM was applied and operationalized. Figure 1 shows a bird's eye view of a case project. As an apartment building construction project with a total of 12 buildings and 908 units, the site is so complex that construction coordination progress is being managed through BIM.

Figure 1. Bird Eye View of Case Project.

The construction phase of a construction project refers to the phase wherein the building is built as a result of the production carried out by various participants. Therefore, the form and type of information generated by BIM vary greatly depending on the user's purpose for utilizing the information and the form of utilization. The problems addressed in theoretical studies and the approaches to applying BIM to solve them are limited. There is no generalized concept of LODs and MVDs that can be applied to real-world projects. While the goal is the same, the production process is varied and complex. In fact, construction coordination between the general contractor (GC), who manages the construction project, and the subcontractor (SC), who directly performs the construction, is carried out through the BIM model as shown in Figure 2 to proceed with the structure of the basement floor after the earthwork is completed. For the overall process management, the BIM model visualizes the process information of pouring leveling concrete (pink model), pouring foundation concrete (yellow model), pouring basement concrete (green model), and pouring main building concrete connecting to the basement (red model). Owing to the large scale of the project, it is separated based on process information to manage the resources put into the construction efficiently. Furthermore, the locations of tower cranes for on-site construction operations, pump cars for concrete pouring, and ready-mixed concrete are laid out in the BIM model. During production, various project stakeholders are involved in the collaborative process, including design, process, and construction teams.

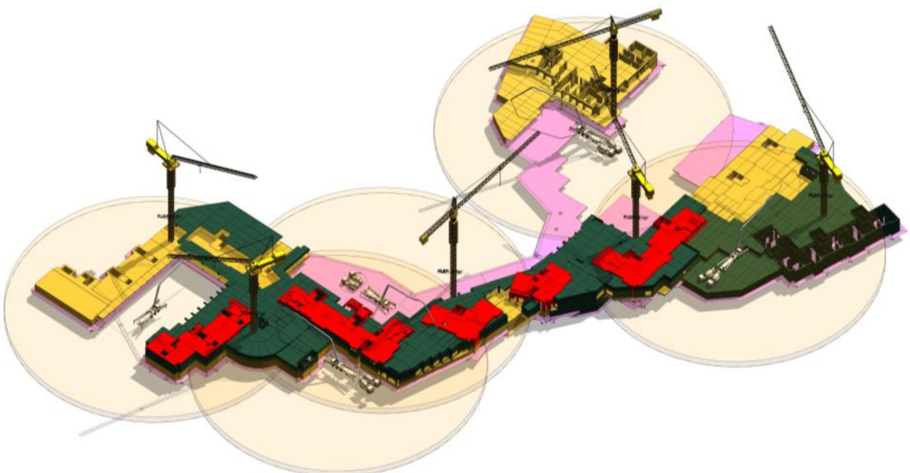


Figure 2. Discipline BIM model for structural construction process management.

In traditional project management, the excuse for not using BIM in the field is that there are no participants who can work directly with the BIM model. However, as in previous studies, construction sites can support BIM RFIs by having BIM staff who are familiar with BIM and by making information extracted from BIM available in various forms to those who are not familiar with BIM [44,45]. If BIM RFIs are not properly processed by professional BIM staff, it may delay the work of project participants who are responsible for making decisions or executing work in the project [47,48]. The information required for the communication, coordination, and decision-making processes required to carry out a construction project is not limited to the original BIM model created in the actual BIM authoring tool. Figure 3 shows a contractor coordination meeting led by the project manager, where on-site participants use the BIM model to discuss a complex structure plan for an apartment building before construction. At this site, not only does the construction of 12 main buildings need to be managed simultaneously, but the ground level is different for each main building, and all available information, such as level information and section information from BIM, is utilized to ensure the construction quality of the main building of the apartment building connected to the basement floor.

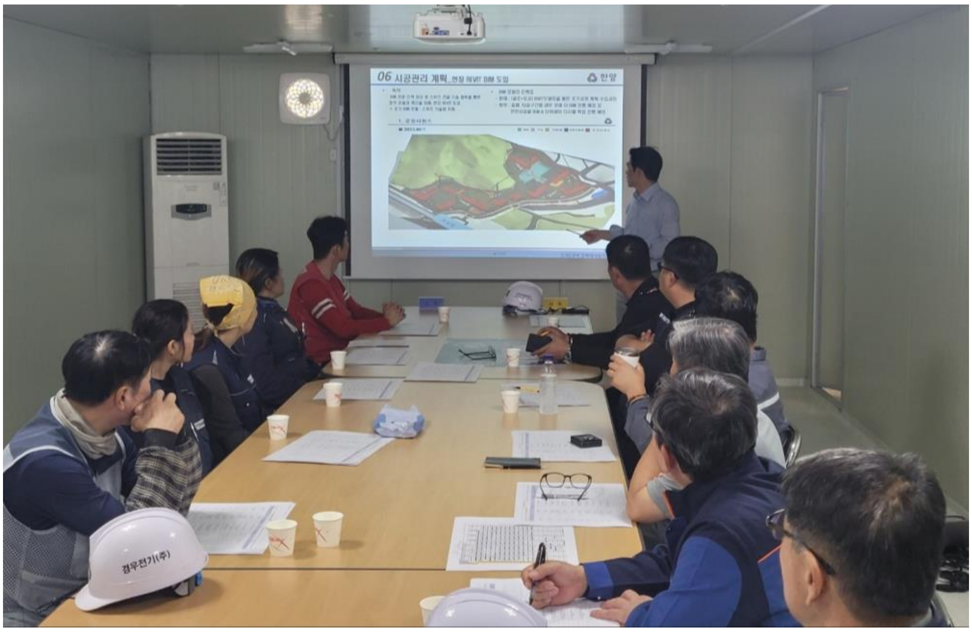


Figure 3. Contractor Coordination Meeting.

Figure 4 shows a scene where the BIM model reflecting the results of construction coordination is used for on-site construction inspection to verify the construction quality. In this case site, a detailed BIM model was built and utilized for the cost control of the structural construction work. This shop model was created in Builder Hub for cost control purposes, but was also utilized for quantity takeoffs and to review construction results by viewing the 3D geometry on a smartphone.

The structural construction work of an apartment building project involves several simultaneous activities that need to be managed, and a BIM model, shown in Figure 5, can be applied to monitor the construction progress. As shown in Figure 4, reviewing construction quality for a specific area and monitoring the entire construction process require two different approaches to project management. Consequently, the type and form of BIM model required to achieve these objectives will vary. This indicates that a BIM model for process management and a BIM model for reviewing construction quality may be defined differently, not only in terms of LOD but also in terms of the scope of implementation. The BIM models of the typical floor, where the same shape is repeated, and the lower floors and rooftop floors, where the existing Euro-form is applied, can be constructed differently in the main building unit. For the lower floors and rooftops, the goal is not to build a BIM model but rather to identify and eliminate areas where the basement structure and the primary structure may interfere. For the typical floor, once the gang-form is set, the structural construction sequence is a typical one-cycle process. Consequently, a detailed BIM model that serves as a baseline can be used repeatedly, rather than a BIM model for every baseline floor. The more important management factor is the grouping of tasks so that there is no waiting or waste through BIM-based construction coordination. At this site, there were a total of 12 main building structural construction works to be managed simultaneously, and the process was managed in groups of six buildings.

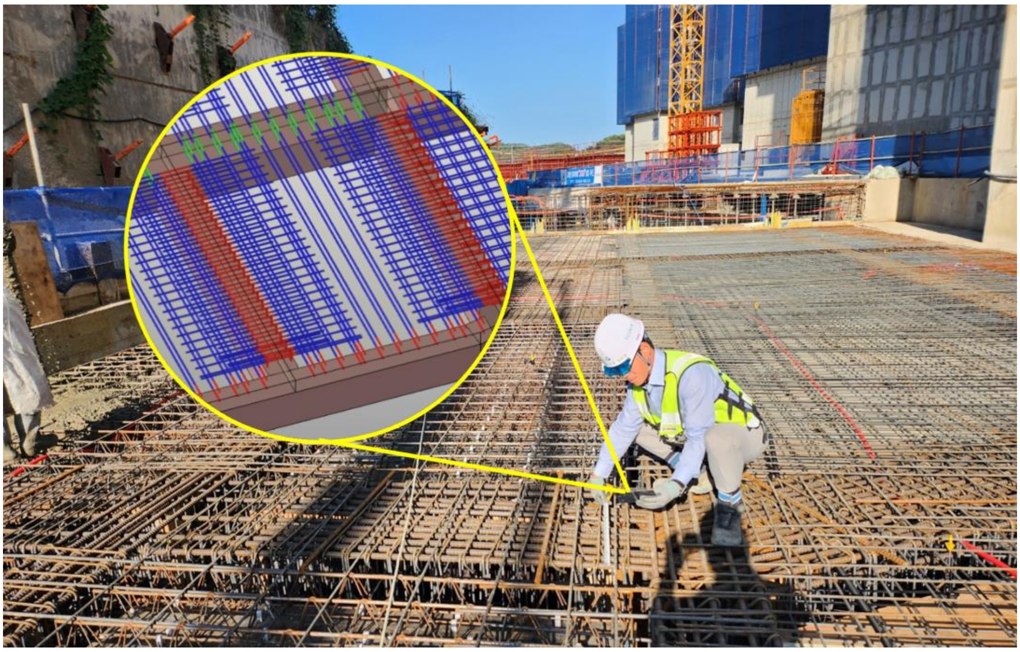


Figure 4. Inspection using shop model created in Builder Hub.

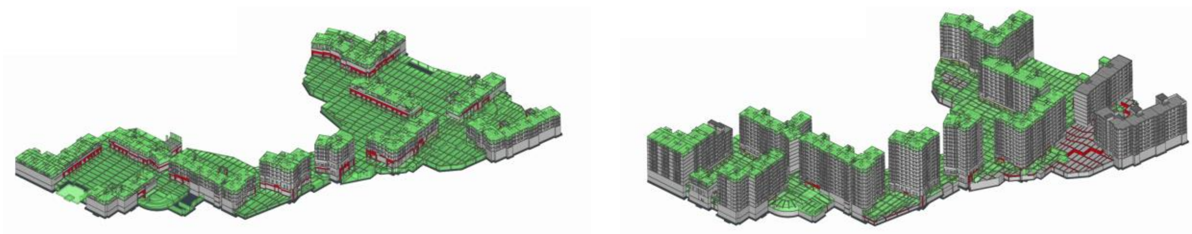


Figure 5. Structural construction progress management using BIM.

Table 2 shows the floor area, type composition, and number of units in the case project. Finishing work management can be achieved for each main building. Unlike structural construction, the type and order of construction are different based on the space within the unit. For the cost analysis of the finishing works, detailed BIM models of different types of floor areas and shapes can be used as representatives, as summarized in Table 2. However, building a BIM model for every generation to manage the process can cause difficulties in creating and managing data. The GC assigns tasks to SCs in batches of several floors to manage the process of finishing work. BIM models should be built and utilized for these management purposes and methods.

Table 2. Floor area type and number of households.

House Type	39 m^2	45 m^2 A	45 m^2 B	59 m^2 A	59 m^2 B	75 m^2 A	75 m^2 B	84 m^2	Total
General sale unit	42	164	32	110	1	26	52	58	485
Union member unit	1	4	21	219	15	17	37	71	385
Rental unit	38	-	-	-	-	-	-	-	38
Total	81	168	53	329	16	43	89	129	908

Figure 6 shows a spatial BIM model for managing the finishing work process for an 84 m^2 type building. One floor of this main building has four units of the same type. A dedicated space in a unit is divided into 12 color-coded spaces. As each space is subject to some construction, managing the sequence of work and interference becomes the focus of process management. A spatial BIM model is lighter than an object-based BIM model, and there is no need to consider whether to model the materials applied to an area through a complex input method or on a material-by-material basis. The spatial BIM model acts as an identifier for what finishes are being completed in which space. This indicates that the progress of finishing work can be managed by vertically integrating the spatial BIM model, enabling three-dimensional process management.

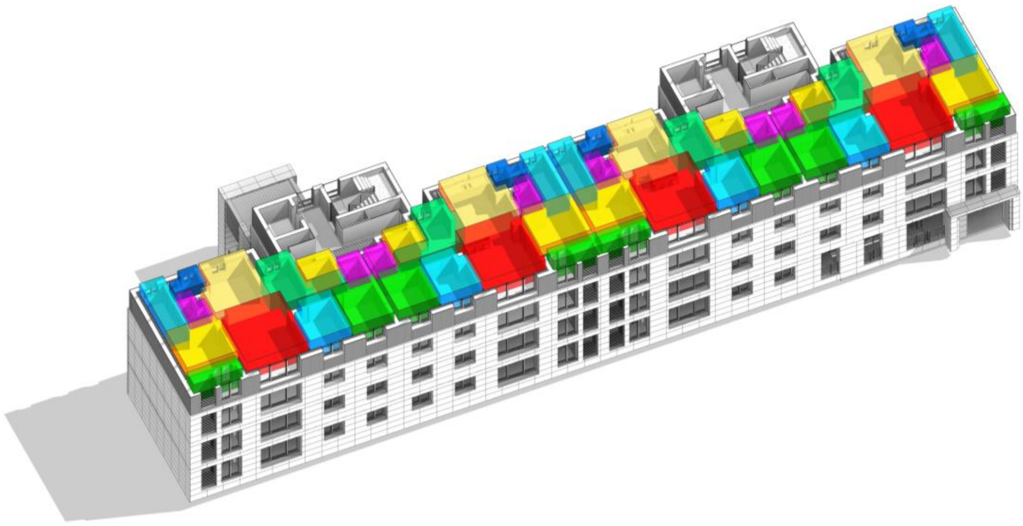


Figure 6. Spatial BIM model for finishing construction process management.

As seen earlier, work-centered BIM models are very diverse in form, and it is difficult to specify the LOD. The BIM models reviewed above are not models created directly by the construction company, but are models created by a professional construction company for collaboration, communication, and coordination with the construction company. Therefore, BIM models that focus on work inevitably have different forms. When analyzing the performance of an apartment complex, material values and performance data entered into the BIM model can be used. However, through this model, rather than the construction company directly analyzing environmental performance (e.g., carbon emissions), analysis is performed through collaboration and information exchange with service entities that analyze environmental performance. In addition, the BIM model for operation and maintenance must add not only as-built information but also information about the users and management entities that occupy the household. Rather than separate additional modeling work, a system should be created in which information is extracted from the BIM model according to a data classification system suitable for operation and maintenance purposes based on a standard format such as Construction Operation Building information exchange (COBie). As a result, BIM model-centered process modeling inevitably has limitations.

Applied to complex construction projects, BIM models can support construction coordination in several ways. As observed from the case analysis, it is difficult to formulate criteria for a BIM model that can be applied universally in the field. Therefore, at the project management level, it is necessary to apply a methodology that can visualize and manage the collaborative relationship between participants and the process of iterative work. By applying these methodologies, an empirical management system that is process-driven rather than information-driven can be built.

4. Research Framework

4.1. Scrum Framework of BIM-Based Constrution Coordination Progress

As shown in the literature review, BIM-based construction project management requires a new way of managing projects that is different from traditional project management. In particular, the construction phase should be managed through an empirical process control method, as the BIM-based construction coordination progress, which is the process of achieving BIM goals through various BIM uses, is iterative and continuous.

Visibility, inspection, and reconciliation are critical for effectively utilizing an empirical process control approach. First, visibility indicates that process elements that affect outcomes must be visible to those who control the process. Not only must these elements be visible, but the visible values themselves must be real. Second, inspection indicates that frequent inspections of different elements of the process are required for the prompt detection of any unacceptable level of error that occurs during the process. Third, adaptation indicates that, if an inspection of a process reveals that one or more elements (tasks) have exceeded acceptable limits and the end result is expected to be nonconforming, the inspector should immediately adjust the process or the resources at work, and these adjustments should be made as quickly as possible to minimize further damage. In this study, the BIM-based construction coordination progress based on the Scrum framework among Agile project management methods is shown in Figure 7.

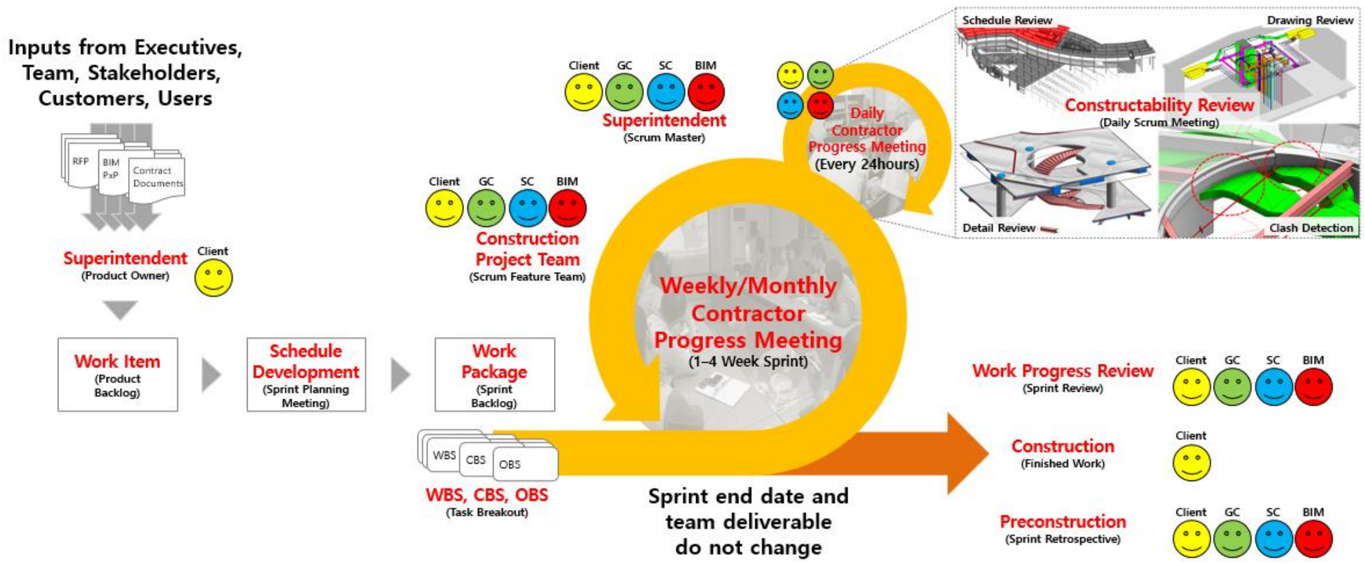


Figure 7. Scrum Framework of BIM-based Construction Coordination Progress.

4.2. Application of Extended Collaborative Process Modeling (exCPM)

The Scrum framework proposed in this paper is a powerful and concrete practice for iteratively and continuously improving construction project management through BIM-based construction coordination progress. To implement and verify this in practice, this study utilized exCPM, a process modeling methodology that is effective in monitoring and improving collaborative processes. In addition to modeling processes, exCPM can transform them into Petri-Nets models to find waste in the process, such as deadlocks. It is also useful for work management, as it allows the real-time monitoring of the exchange, flow, and status of information required to improve the collaboration process. The key features of exCPM are summarized as follows:

- Process-centric modeling methodology;
- Based on the components of CPM, there are 10 components in total;
- Color tokens allow for the representation of complex actors;
- It is easy to recognize general, internal collaboration, and external collaboration processes intuitively with separate symbols;
- Dynamic representation is possible by applying tokens from Petri-Nets, enabling the real-time monitoring of processes;
- IDEF0′s ICOM concept enables clear representation of collaborative data flows.

5. Collaborative BIM-Based Construction Coordination Progress Modeling

5.1. BIM-Based Construction Coordination Progress

The final BIM model and data from the design phase are delivered in various forms to the client or CM, GC, and SC participating in the construction phase, and there may not be any BIM data available [8]. To achieve project objectives in the construction phase, information with different levels and types of detail can be provided to project participants from BIM [46]. Eastman (1999) described this process through the concept of "information exchange architectures", and stated that internal mappings and external mappings are required to utilize the centralized BIM model in various aspects [58].

In the long run, various organizations participating in the project should have BIM staff with specialized competencies to provide BIM services required for various construction coordination activities in the construction phase. However, previous studies have shown that BIM staff are outsourced from companies with specialized competencies [42,43]. BIM staff contribute to construction coordination by converting BIM into various detail levels and types in response to the information requirements of project participants during the construction phase, and their specific tasks include the following [46,47]:

- Revision of work set to manage large data;
- Revision of sheets/view for user interface;
- List for the entry and use of data;
- Addition of BIM model properties to enhance its application in the construction stage;
- Revision of material properties for accurate calculation;
- Addition of engineering data considering technologies available on the project site;
- Other elements to improve communication on the project site;
- System for data input/output in the construction stage.

5.2. Modeling and Description

The results of modeling the collaboration process using exCPM, a process modeling method selected through the analysis of prior research on BIM-based construction coordination progress, are shown in Figure 8.

Table 3 provides information about the organizations and departments that participate in the process in Figure 8 through the color token.

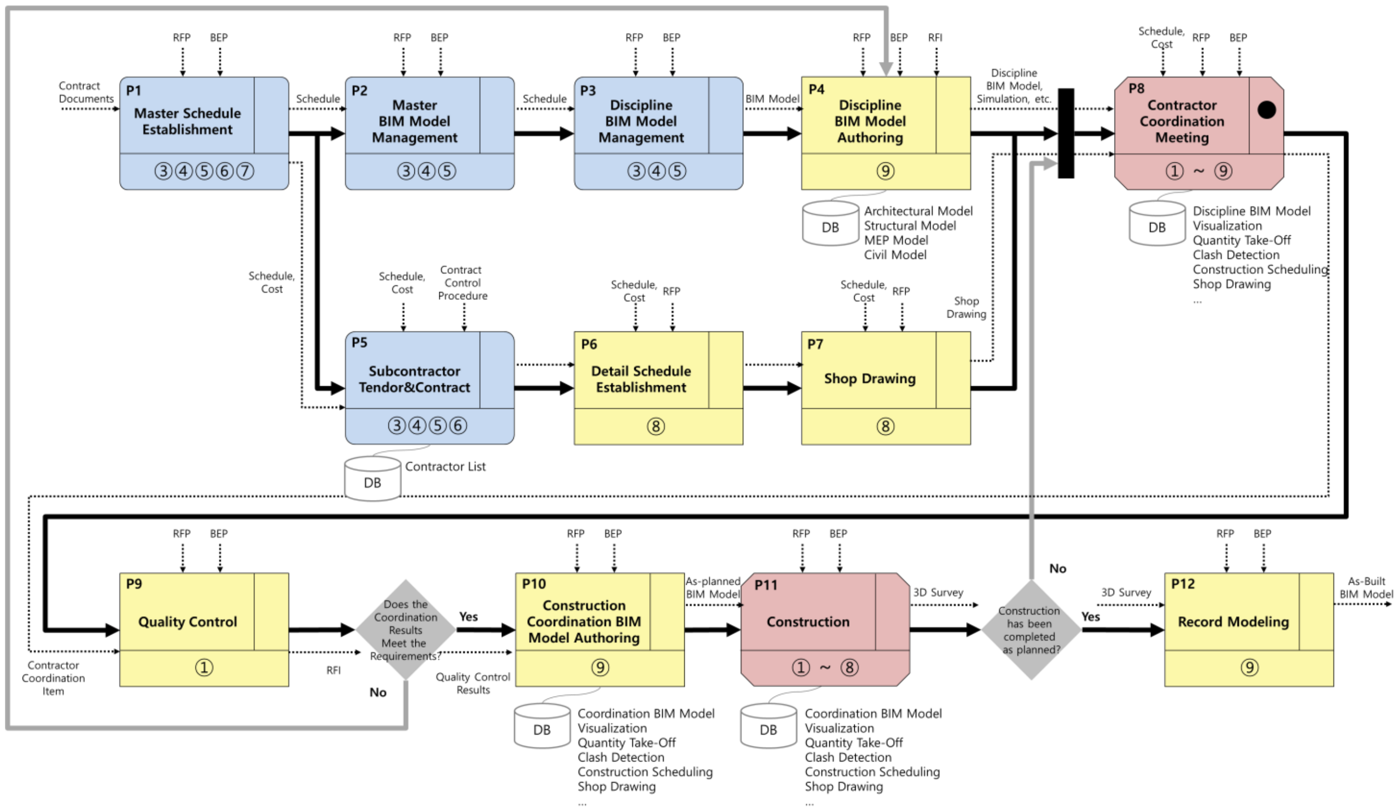


Figure 8. exCPM Model of BIM-based Construction Coordination Progress.

Table 3. Company and Departments for model in Figure 8.

Company	Color Token	Company/Department
Company A		Facility Owner
	①	Client (or CM) Team
	②	Facility Management Team
Company B		Construction Engineering Department
	③	Design Team
	④	Construction Planning Team
	⑤	Construction Team
	⑥	Finance Team
	⑦	Safety Team
Company C		Sub-Contractor
	⑧	Sub-Contractor Team
Company D		BIM Consulting Company
	⑨	BIM Coordination Team

P1 is the "master schedule establishment" task. The rounded square process type indicates that it is an internal collaboration, and the color token defined in Table 2 makes it easy to identify the related departments participating in the process. This study used numbers that did not appear in the components of exCPM to improve the readability of the color tokens. Once the schedule of the construction project is finalized according to the P1 process, the master BIM model is modified for detailed construction work.

P4 is the "discipline BIM model authoring" task. It is a generic process as indicated by the rectangular process type, and it is led by a BIM consulting company. In addition, BIM models by discipline (architecture, structure, MEP, civil) at the existing stage are used as inputs, with the discipline BIM model and BIM-based information (visualization, quantity takeoff, clash detection, construction scheduling, shop drawing, etc.) as outputs, and various requirements, such as RFP, BIM execution plan, and RFI, are applied as control elements.

P6 ("detail schedule establishment") and P7 ("shop drawing") are rectangular process types, indicating that they are regular processes and are led by an SC. This process involves creating a detailed shop drawing that considers the overall process and cost, and is planned to reflect the requirements of the client and GC. It also presents and reviews design alternatives that reflect the situation on site when the design is changed by the client, and the output of this process is utilized for smooth decision-making by the client and GC through the P8 ("contractor coordination meeting") process.

P8 is the "contractor coordination meeting" task, which is an angled square process type, intuitively showing that it is an external collaboration process, with the presence of a status token indicating that this process is currently in progress. In this process, all the companies and team members participating in the BIM-based construction coordination progress are involved, and various information outputs from the previous P4 process are utilized as resources. This process can be a daily process with a small number of people depending on the workload, or it can be a weekly or monthly process depending on the degree of impact on other construction types and subsequent processes. For this process, weekly and monthly process progress reviews should be conducted in conjunction with existing processes, and construction movement and management plans should be established to minimize interference between other construction types. In addition, parts that require consultation with other trades and parts with high construction difficulty shall be shared with the relevant stakeholders (client, GC, SC, and BIM consultant) through this process. The construction company that is the subject of this process should review the scope of work between separately ordered construction types, and allocate the work efficiently to minimize the risks of delays and construction performance degradation owing to disputes between contractors. This process also serves to communicate the discipline BIM model to site workers and safety managers, including the layout and planning of safety facilities, scaffolding plans, and equipment locations.

P11 ("construction") is also an angled square process type. It can be intuitively observed that this is an external collaboration process. In this process, periodic field measurements are required to ensure that the design contents and changes are accurately reflected in the construction, and field measurements are carried out for efficient site management, producing an as-built BIM model as the final result in connection with the general process, P12 "record modeling."

There are constantly recurring processes that take a certain amount of time (days, weeks, or months), as shown in Figure 9, which is part of Figure 8. These are not wasteful aspects of the project to be eliminated, but should be managed in a way that maximizes the value of the project. In Figure 9, in the P8 process ("contractor coordination meeting"), the information requirements of various stakeholders involved in BIM-based construction coordination progress are generated, and the BIM consultant takes the lead in responding to them. Enabling collaboration and coordination between professionals working on a project on a construction site is critical. This interparticipant collaboration and coordination tends to happen randomly in the form of RFIs, and needs to be supported by specialized BIM staff.

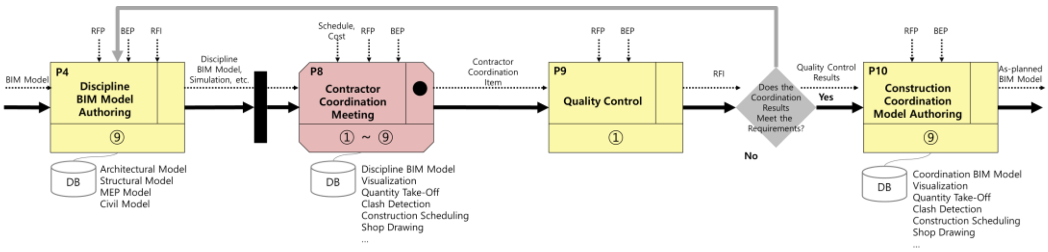


Figure 9. Iterative BIM-based Construction Coordination Progress.

5.3. Model Validation

This study used the MGBB of the existing CPM methodology and the rules for model transformation to validate the previously modeled exCPM. For the validation of the exCPM model, a modified or supplemented MGBB reflecting components not defined in CPM (status tokens, color tokens, etc.) and conversion rules reflecting them were used [56]. The MGBB applied in this study is shown in Table 4, and the conversion rules are as follows:

- Rule 1: Any input, output, and control elements in the exCPM model that are not defined as MGBBs are removed.
- Rule 2: The level of the marked graph to be converted (company, department, or individual) is determined.
- Rule 3: Each element of the exCPM model is converted to a Petri-Nets model using the defined MGBB. Here, the MGBB component selection for the process selected in Rule 2 is based on Table 3.
- Rule 4: The Petri-Nets model is completed by adding an ending mark between the place of the building block representing the last process in the converted Petri-Nets model and the transition of the building block representing the first process.
- Rule 5: If a process in an exCPM model has a state token, it places the state token in all the first appearances of the corresponding building block.

Table 4. Marked graph building blocks (MGBB) [53].

Symbol	Marked Graph Building Block	Symbol	Marked Graph Building Block
Normal Process	[P0] (Input for extension / Output for extension)	Synchronization	(Split-type) (Join-type)
	[P1]	Decision	(linked from a place)
Intra-collaboration process	[P2]	Process transition	(link places to transition)
		Resource	(link to transition)
Inter-collaboration process	[P3]	Ending mark (additional)	(start) - link to the first transitions (end)

When converting an exCPM model to a Petri-Nets model, the MGBB can be applied at the company, department, and individual levels to maintain consistency, as shown in Table 5. In this study, the exCPM model was converted in Figure 8 to a Petri-Nets model at the company and department levels using the transformation rules and the MGBB defined in the exCPM methodology. Figures 10 and 11 show the results.

Table 5. MGBB selection rules for transformation.

Level / Process	Company	Department	Individual
Normal Process	[P0]		
Intra-collaboration process	[P0]	[P1]	[P2]
Inter-collaboration process	[P1]	[P2]	[P3]

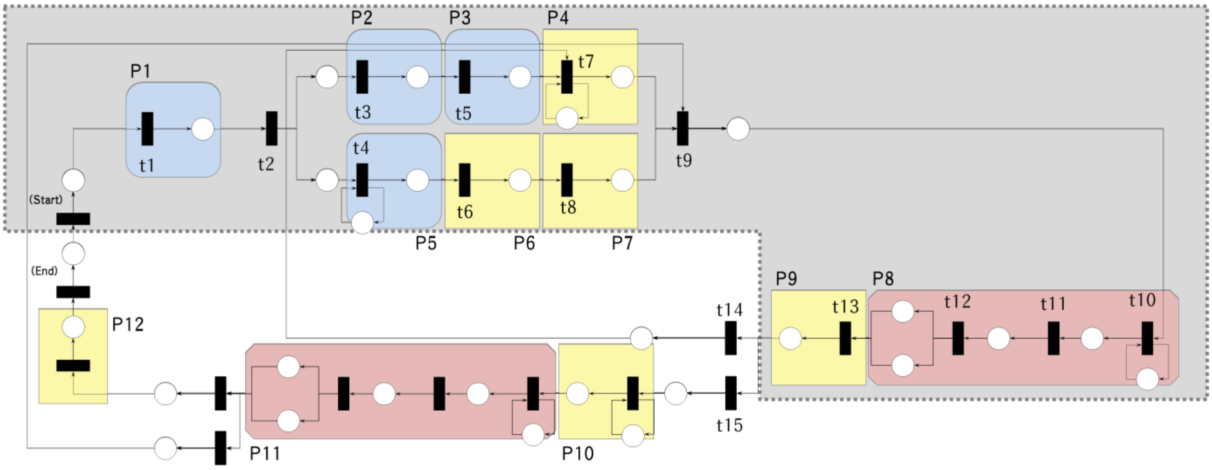


Figure 10. Company-leveled Petri-Nets model.

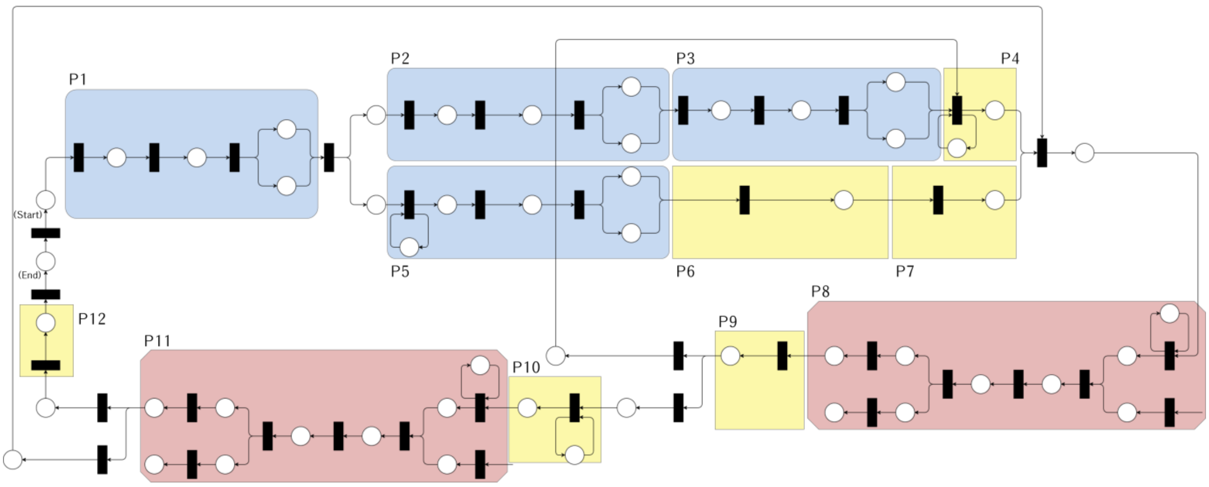


Figure 11. Department-leveled Petri-Nets model.

While direct validation methods for exCPM models have not yet been developed, exCPM models can be verified indirectly by verifying models converted to Petri-Nets. This study used a reachability tree to analyze the Petri-Nets model. The reachability analysis method enumerates all cases of reachable markings in a modeled system, and is a powerful normalized methodology for analyzing systems that are simultaneously occurring and distributed over an infinite number of states [59].

This study analyzed only the part marked as a dotted line in Figure 10 to simplify the validation, and the reachability tree was constructed based on the analysis as shown in Figure 12. While constructing the reachability tree, iterative sections with the same state mutation occur. For example, in Figure 12, M_{10} in the dotted line represents a state, such as M_{10} = (000001100000000000), which in a process model represents the first part of a process that repeats after a decision is made. As the states that can change afterward are also the same, the subsequent states are omitted from Figure 12. The reachability tree analysis shows that, in all states of the converted Petri-Nets model, deadlocks, i.e., states where no work can be performed, do not occur, and the flow of work is decentralized. Additionally, as the process is performed, all states ultimately result in one state (M_{17}). This indicates that the converted Petri-Nets model based on the exCPM model is considered reversible, enabling iterative work, as the company-level Petri-Nets model can eventually return to the initial state. Therefore, the transformed model is considered to have consistency. The results of these analyses confirm that the exCPM model has been built correctly.

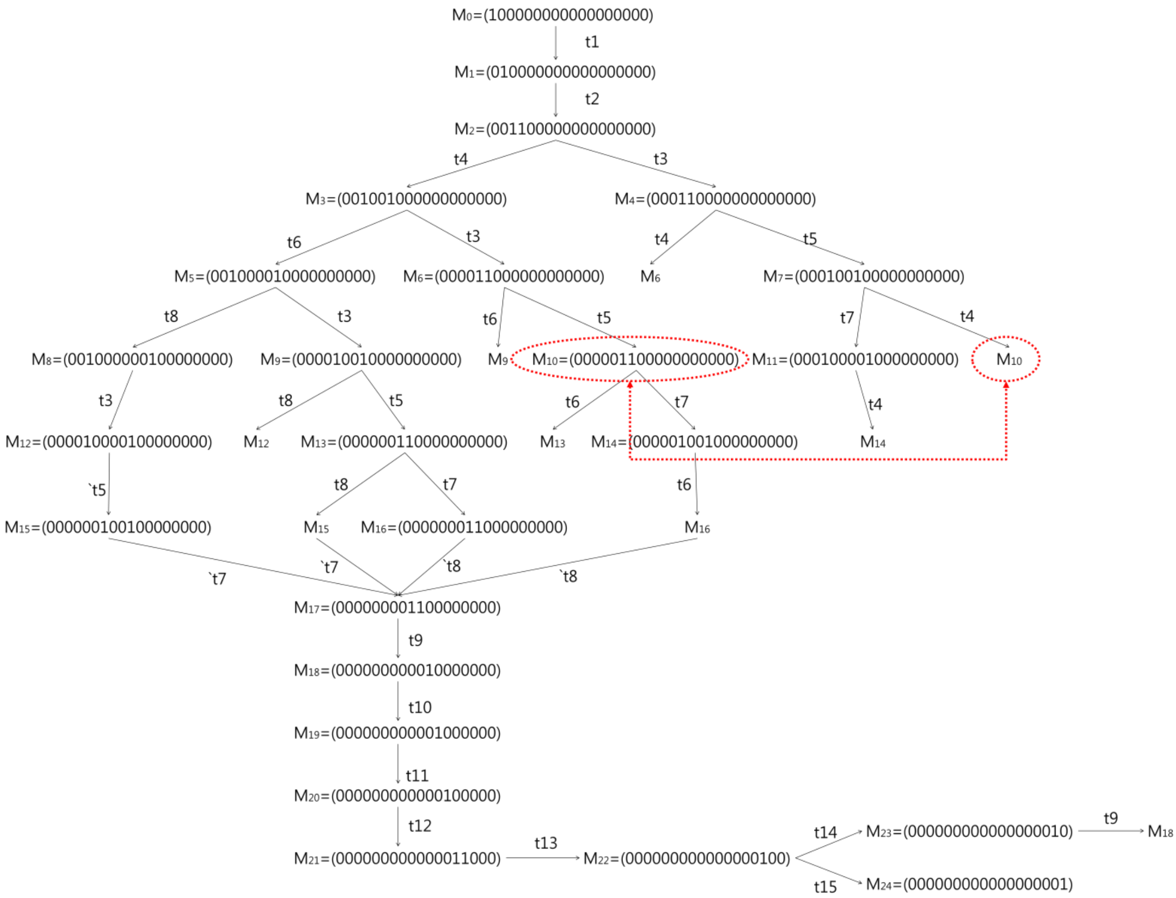


Figure 12. The reachability tree of the Petri-Nets model.

As mentioned earlier, work-oriented BIM models are very diverse in form, and it is difficult to specify the LOD. Additionally, because the subjects participating in the work may all be different, it is inefficient to model and manage each process. It is difficult to make decisions about projects quickly and continuously based on these models. From this perspective, Figure 12 is the result of verifying the effectiveness of the process using the exCPM model proposed in this study. The flow of continuous, repetitive collaboration was conceptually expressed through the Scrum framework, and a specific process model for this was built through exCPM. This study modeled and verified a BIM-based collaboration process that must be performed continuously and repeatedly for construction coordination progress. The results of this study can be generalized and applied to actual BIM-based construction projects.

6. Conclusions

This paper proposed a framework for collaborative BIM work processes, focusing on construction coordination tasks among participants in the construction phase of a construction project, and modeled and validated BIM-based construction coordination progress based on this framework. This process can be summarized as follows. First, the limitations of traditional construction project management methodologies were analyzed through an analysis of prior research, and the Agile project management methodology, which is similar to the lean approach, was reviewed. The Scrum framework was used as a framework for this study, as it produced valuable features in each short time-boxed iteration rather than local optimization. In addition, through the analysis of a case study of a BIM-based construction project for an apartment house, a gap was identified in the level and method of construction project management compared with advanced construction companies that are introducing lean techniques. In this study, a Scrum framework for BIM-based construction coordination progress was proposed as a concrete action plan to overcome the gaps identified through the analysis of previous studies and actual project cases. This practice was modeled with exCPM, and the exCPM model was transformed into a verifiable Petri-Nets model using MGBBs and transformation rules that were modified and supplemented for model validation. The converted Petri-Nets model utilized reachability tree analysis, a powerful regularized methodology for analyzing systems that are simultaneously occurring and distributed over an infinite number of states. An analysis of some process sections showed that the same iterations with the same state variations occurred during the construction of the reachability tree. This indicates that no deadlock occurs in any state of the converted Petri-Nets model, and the Petri-Nets model converted based on the exCPM model has been analyzed to be reversible. This result indirectly validates the exCPM model.

The academic value of this study is as follows. First, a management methodology for BIM-based construction projects based on an empirical process control approach was proposed. The management methodology provided specific practices based on the Scrum framework, and the model was built and validated through exCPM. This could be extended to other types of construction projects, not just apartment buildings. Second, the exCPM methodology, which can model collaborative processes between multiple performers and different organizations, was applied to the construction sector. In particular, the exCPM model was built for the iterative, continuous process of BIM-based construction coordination, which could contribute to the achievement of project goals. The need for new research approaches to LOD and MVD was also argued. Academically, LOD is often misunderstood to mean that the higher the level of detail of information or geometry, the better it supports decision-making. It also conveys the insight that the model view required to achieve a particular purpose could have different levels of detail, formats, and ways of conveying information.

Despite the academic value of this study, it has the following limitations. The exCPM model was built through a single-case analysis of the construction process of an apartment house. This can later be addressed by building and validating exCPM by deriving common construction coordination progress across different types of construction projects. Furthermore, the reliability of the exCPM model built through this study is expected to be improved by using multiple project cases rather than a single project when targeting multifamily housing. Lastly, the results of this study can be used as a reference to simply model and verify complex collaboration processes for the advancement of construction projects such as lean construction, DfMA, and OSC.

Author Contributions: Conceptualization, J.-H.S. and N.-H.H.; Formal analysis, J.-H.S. and N.-H.H.; Investigation, J.-H.S. and N.-H.H.; Methodology, J.-H.S. and N.-H.H.; Resources, J.-H.S. and N.-H.H.; Supervision, J.-J.K. and N.-H.H.; Visualization, J.-H.S. and N.-H.H.; Writing—original draft, J.-H.S. and N.-H.H.; Writing—review and editing, J.-J.K. and N.-H.H. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2021R1F1A1052050).

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Chan, A.P.; Scott, D.; Chan, A.P. Factors affecting the success of a construction project. *J. Constr. Eng. Manag.* **2004**, *130*, 153–155. [CrossRef]
2. Ham, N.; Moon, S.; Kim, J.H.; Kim, J.J. Economic analysis of design errors in BIM-based high-rise construction projects: Case study of Haeundae L project. *J. Constr. Eng. Manag.* **2018**, *144*, 05018006. [CrossRef]
3. Abourizk, S.; Halpin, D.; Mohamed, Y.; Hermann, U. Research in modeling and simulation for improving construction engineering operations. *J. Constr. Eng. Manag.* **2011**, *137*, 843–852. [CrossRef]
4. Preidel, C.; Borrmann, A.; Oberender, C.; Tretheway, M. Seamless integration of common data environment access into BIM authoring applications: The BIM integration framework. In *eWork and eBusiness in Architecture, Engineering and Construction*; CRC Press: Boca Raton, FL, USA, 2017; pp. 119–128, ISBN 9781315386904.
5. Singh, M.M.; Geyer, P. Information requirements for multi-level-of-development BIM using sensitivity analysis for energy performance. *Adv. Eng. Inform.* **2020**, *43*, 101026. [CrossRef]
6. Eastman, C.; Sacks, R. Introducing a new methodology to develop the information delivery manual for AEC projects. In Proceedings of the CIB W78 2010: 27th International Conference, Cairo, Egypt, 16–18 November 2010.
7. Beetz, J.; Borrmann, A.; Weise, M. Process-based definition of model content. In *Building Information Modeling: Technology Foundations and Industry Practice*; Springer: Berlin/Heidelberg, Germany, 2018; pp. 127–138. [CrossRef]
8. Sacks, R.; Eastman, C.; Lee, G.; Teicholz, P. *BIM Handbook: A Guide to Building Information Modeling for Owners, Designers, Engineers, Contractors, and Facility Managers*; John Wiley & Sons: Hoboken, NJ, USA, 2018; ISBN 978-1-119-28753-7.
9. Charef, R.; Alaka, H.; Emmitt, S. Beyond the third dimension of BIM: A systematic review of literature and assessment of professional views. *J. Build. Eng.* **2018**, *19*, 242–257. [CrossRef]
10. Jupp, J. 4D BIM for environmental planning and management. *Procedia Eng.* **2017**, *180*, 190–201. [CrossRef]
11. Smith, P. Project cost management with 5D BIM. *Procedia-Soc. Behav. Sci.* **2016**, *226*, 193–200. [CrossRef]
12. Kaewunruen, S.; Sresakoolchai, J.; Zhou, Z. Sustainability-based lifecycle management for bridge infrastructure using 6D BIM. *Sustainability* **2020**, *12*, 2436. [CrossRef]
13. Marta, A.; Stefano, B.; Carlo, B.; Filippo, M. 7D BIM for sustainability assessment in design processes: A case study of design of alternatives in severe climate and heavy use conditions. *Archit. Eng.* **2019**, *4*, 3–12. [CrossRef]
14. Sampaio, A.Z.; Constantino, G.B.; Almeida, N.M. 8D BIM model in urban rehabilitation projects: Enhanced occupational safety for temporary construction works. *Appl. Sci.* **2022**, *12*, 10577. [CrossRef]
15. Olanrewaju, O.I.; Kineber, A.F.; Chileshe, N.; Edwards, D.J. Modelling the relationship between Building Information Modelling (BIM) implementation barriers, usage and awareness on building project lifecycle. *Build. Environ.* **2022**, *207*, 108556. [CrossRef]
16. Mesa, H.A.; Molenaar, K.R.; Alarcón, L.F. Comparative analysis between integrated project delivery and lean project delivery. *Int. J. Proj. Manag.* **2019**, *37*, 395–409. [CrossRef]
17. Kunz, J.; Fischer, M. Virtual design and construction. *Constr. Manag. Econ.* **2020**, *38*, 355–363. [CrossRef]
18. Wasim, M.; Vaz Serra, P.; Ngo, T.D. Design for manufacturing and assembly for sustainable, quick and cost-effective prefabricated construction—A review. *Int. J. Constr. Manag.* **2022**, *22*, 3014–3022. [CrossRef]
19. Hosseini, M.R.; Martek, I.; Zavadskas, E.K.; Aibinu, A.A.; Arashpour, M.; Chileshe, N. Critical evaluation of off-site construction research: A Scientometric analysis. *Autom. Constr.* **2018**, *87*, 235–247. [CrossRef]
20. Ogunnaike, B.A.; Ray, W.H. *Process Dynamics, Modeling, and Control*; Oxford University Press: Oxford, UK, 1994; p. 364, ISBN 0-19-509119-1.
21. Schwaber, K. *Agile Project Management with Scrum*; Microsoft Press: Redmond, WA, USA, 2004; ISBN 9780735619937.
22. Sacks, R.; Korb, S.; Barak, R. *Building Lean, Building BIM: Improving Construction the Tidhar Way*; Routledge: London, UK, 2017; ISBN 9781138237230.
23. Maestas, A.; Parrish, K. Exploring the roots of lean culture at DPR Constuction: A case study in lean culture. In Proceedings of the 22nd Annual Conference of the International Group for Lean Construction: Understanding and Improving Project Based Production, IGLC 2014, Oslo, Norway, 25 June 2014; pp. 1413–1424.

24. Zhang, B.; Dong, N.; Rischmoller, L. Design Thinking in action: A DPR case study to develop a sustainable digital solution for labor resource management. In Proceedings of the 28th Annual Conference of the International Group for Lean Construction, Berkeley, CA, USA, 6–10 July 2020; pp. 6–12. [CrossRef]
25. Paulk, M.; Davis, N.; Maccherone, L. *On Empirical Research into Scrum*; Institute for Software Research, Carnegie Mellon University: Pittsburgh, Pennsylvania, 2011.
26. Fernandes, J.M.; Almeida, M. Classification and comparison of agile methods. In Proceedings of the 7th International Conference on the Quality of Information and Communications Technology, Porto, Portugal, 29 September–2 October 2010; pp. 391–396. [CrossRef]
27. Dingsøyr, T.; Dybå, T.; Moe, N.B. Agile software development: An introduction and overview. In *Agile Software Development: Current Research and Future Directions*; Springer: Berlin/Heidelberg, Germany, 2010; pp. 1–13. [CrossRef]
28. Hamed, A.M.M.; Abushama, H. Popular agile approaches in software development: Review and analysis. In Proceedings of the International Conference on Computing, Electrical and Electronic Engineering (ICCEEE), Khartoum, Sudan, 26–28 August 2013; 2013; pp. 160–166. [CrossRef]
29. Larman, C.; Vodde, B. Scaling Lean & Agile Development. *Organization* **2009**, *230*.
30. Han, S.; Lee, S.; Pena-Mora, F. Identification and quantification of non-value-adding effort from errors and changes in design and construction projects. *J. Constr. Eng. Manag.* **2012**, *138*, 98–109. [CrossRef]
31. Liao, L.; Teo EA, L.; Chang, R.; Li, L. Investigating critical non-value adding activities and their resulting wastes in BIM-based project delivery. *Sustainability* **2020**, *12*, 355. [CrossRef]
32. Jasti, N.V.K.; Kodali, R. Lean production: Literature review and trends. *Int. J. Prod. Res.* **2015**, *53*, 867–885. [CrossRef]
33. Rashidian, S.; Drogemuller, R.; Omrani, S. Building information modelling, integrated project delivery, and lean construction maturity attributes: A Delphi study. *Buildings* **2023**, *13*, 281. [CrossRef]
34. Salem, O.; Solomon, J.; Genaidy, A.; Minkarah, I. Lean construction: From theory to implementation. *J. Manag. Eng.* **2006**, *22*, 168–175. [CrossRef]
35. Schimanski, C.P.; Pradhan, N.L.; Chaltsev, D.; Monizza, G.P.; Matt, D.T. Integrating BIM with Lean Construction approach: Functional requirements and production management software. *Autom. Constr.* **2021**, *132*, 103969. [CrossRef]
36. Michalski, A.; Głodziński, E.; Böde, K. Lean construction management techniques and BIM technology–systematic literature review. *Procedia Comput. Sci.* **2022**, *196*, 1036–1043. [CrossRef]
37. Tezel, A.; Taggart, M.; Koskela, L.; Tzortzopoulos, P.; Hanahoe, J.; Kelly, M. Lean construction and BIM in small and medium-sized enterprises (SMEs) in construction: A systematic literature review. *Can. J. Civ. Eng.* **2020**, *47*, 186–201. [CrossRef]
38. Kim, J. Why Perform Low When You can Perform High? BIM/Lean/IPD in DPR Construction, The BIM_ The Building Information Modeling. *Summer* **2013**, *9*, 36–39.
39. De Saram, D.D.; Ahmed, S.M.; Anson, M. Suitability of the critical incident technique to measure quality of construction coordination. *J. Manag. Eng.* **2004**, *20*, 97–109. [CrossRef]
40. Shen, F.Y.; Chang, A.S. Exploring coordination goals of construction projects. *J. Manag. Eng.* **2011**, *27*, 90–96. [CrossRef]
41. Mehrbod, S.; Staub-French, S.; Mahyar, N.; Tory, M. Beyond the clash: Investigating BIM-based building design coordination issue representation and resolution. *ITcon* **2019**, *24*, 33–57. Available online: https://www.itcon.org/2019/3 (accessed on 1 December 2023).
42. Won, J.; Cheng, J.C.; Lee, G. Quantification of construction waste prevented by BIM-based design validation: Case studies in South Korea. *Waste Manag.* **2016**, *49*, 170–180. [CrossRef]
43. Messner, J.; Anumba, C.; Dubler, C.; Goodman, S.; Kasprzak, C.; Kreider, R.; Leicht, R.; Saluja, C.; Zikic, N. *BIM Project Execution Planning Guide*, 3rd ed.; Computer Integrated Construction Research Program, The Pennsylvania State University: University Park, PA, USA, 2021. Available online: http://bim.psu.edu (accessed on 1 December 2023).
44. Won, J.; Lee, G. How to tell if a BIM project is successful: A goal-driven approach. *Autom. Constr.* **2016**, *69*, 34–43. [CrossRef]
45. Lee, G.; Park, H.K.; Won, J. D3 City project—Economic impact of BIM-assisted design validation. *Autom. Constr.* **2012**, *22*, 577–586. [CrossRef]
46. Ham, N.; Moon, S.; Kim, J.H.; Kim, J.J. Optimal BIM staffing in construction projects using a queueing model. *Autom. Constr.* **2020**, *113*, 103123. [CrossRef]
47. Ham, N.H.; Yuh, O.K. Performance Analysis and Assessment of BIM-Based Construction Support with Priority Queuing Policy. *Buildings* **2023**, *13*, 153. [CrossRef]
48. Huh, S.H.; Ham, N.; Kim, J.H.; Kim, J.J. Quantitative impact analysis of priority policy applied to BIM-based design validation. *Autom. Constr.* **2023**, *154*, 105031. [CrossRef]
49. Luo, W.; Alex, T.Y. A framework for selecting business process modeling methods. *Ind. Manag. Data Syst.* **1999**, *99*, 312–319. [CrossRef]
50. Wang, W.; Ding, H.; Dong, J.; Ren, C. A comparison of business process modeling methods. In Proceedings of the IEEE International Conference on Service Operations and Logistics, and Informatics, Shanghai, China, 21–23 June 2006; pp. 1136–1141. [CrossRef]
51. Alizadehsalehi, S.; Hadavi, A.; Huang, J.C. From BIM to extended reality in AEC industry. *Autom. Constr.* **2020**, *116*, 103254. [CrossRef]

52. Alreshidi, E.; Mourshed, M.; Rezgui, Y. Cloud-based BIM governance platform requirements and specifications: Software engineering approach using BPMN and UML. *J. Comput. Civ. Eng.* **2016**, *30*, 04015063. [CrossRef]
53. Al Hattab, F.M. Hamzeh, Information Flow Comparison Between Traditional and BIM-Based Projects in the Design Phase. In Proceedings of the 21st Annual Conference of the International Group for Lean Construction, IGLC, Fortaleza, Brazil, 29 July–2 August 2013; pp. 761–770, Retrieved on 3 May 2017.
54. Salimifard, K.; Wright, M. Petri net-based modelling of workflow systems: An overview. *Eur. J. Oper. Res.* **2001**, *134*, 664–676. [CrossRef]
55. Ryu, K.; Yücesan, E. CPM: A collaborative process modeling for cooperative manufacturers. *Adv. Eng. Inform.* **2007**, *21*, 231–239. [CrossRef]
56. Lee, S.; Ryu, K.; Lee, S.; Shin, J.; Kim, B. Extended collaboration process modeling method enabling model validation. In Proceedings of the 40th International Conference on Computers & Indutrial Engineering, Awaji City, Japan, 25–28 July 2010; 2010; pp. 1–6. [CrossRef]
57. Park, G.B.; Ham, N.H.; Kim, K.H.; Kim, J.J. Application of extended collaborative process modeling (exCPM) for multi-disciplinary collaboration and coordination in planning phase. *J. Archit. Inst. Korea Plan. Des.* **2014**, *30*, 21–30. [CrossRef]
58. Eastman, C.M. Information exchange architectures for building models. *Durab. Build. Mater. Compon.* **1999**, *8*, 2139–2156. Available online: https://itc.scix.net/pdfs/w78-1999-2139.content.pdf (accessed on 9 December 2023).
59. Yoo, T.; Jeong, B.; Cho, H. A Petri Nets based functional validation for services composition. *Expert Syst. Appl.* **2010**, *37*, 3768–3776. [CrossRef]