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4D BIM FOR SITE LAYOUT AND ON-SITE LOGISTICS (SLOL) PLANNING: A CASE STUDY OF MODULAR CONSTRUCTION

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Abstract: Construction site layout and on-site logistics planning (SLOL) is an important task in the pre-construction phase of projects due to its impact on project time, cost, productivity, health and safety. This planning task is challenging using traditional approaches such as 2D drawings or Gantt charts. For example, modular construction requires the handling and installation of large modules on site, which can be complicated on congested sites due to safety and productivity concerns. 4D BIM can address this complexity by simulating the main construction activities, their impact on site layout and their interactions over time to identify issues, bottlenecks and potential room for improvement. This paper presents a case study of adopting 4D BIM for site layout planning and on-site logistics of a modular construction project. In addition, a proposed method is developed from a conceptual framework outlining the process for adopting this approach. Using the widely adopted 4D BIM software packages in the construction industry, Autodesk Navisworks and Synchro 4D Pro, the proposed method was validated, and 4D BIM analysis identified and mitigated different critical issues in this case study, which can improve site layout and logistics management in off-site construction projects. Furthermore, the capabilities of both 4D software packages were compared, and it was found that Navisworks is useful for quick 4D review, clash detection and coordination, while Synchro 4D Pro provides stronger 4D planning, resource management, identification of workspace clashes and task sequencing. This study contributes to the body of knowledge and practice by providing insight into how to adopt 4D BIM for site layout and on-site logistics planning in modular construction through developing a proposed method and analysing it in a case study.

Keywords: Site layout and logistics planning; Off-site construction; 4D BIM simulation; Workspace clashes; Illogical task sequences; Timeline clashes; Resource allocation.

1 INTRODUCTION

Site layout and on-site logistics (SLOL) planning are critical pre-construction tasks because they directly influence project time, cost, productivity, health, and safety. Site layout planning focuses on the efficient spatial arrangement of physical elements within the construction site, such as material storage areas, workspaces, and access routes, while on-site logistics deals with the movement, coordination, and management of resources (Sadeghpour and Andayesh 2015, Voigtmann and Bargstädt 2010). Appropriate site layout and logistics planning play a significant role in the successful delivery of a construction project (Salah et al. 2023).

Modular construction is an advanced form of construction in which modules are manufactured in controlled environments at off-site construction facilities and then transported and safely installed on site (Alvanchi et al. 2012, Salah et al. 2023). Compared with traditional on-site construction, this approach can increase project speed, improve quality because the modules are developed in controlled facilities, enhance site safety due to reduced construction activities on site, and lower the environmental impact (Thai et al. 2020). On the other hand, during the transportation and installation stages, these large modules require careful planning for storage and lifting, especially on congested sites where space limitations can create safety and productivity challenges. SLOL planning also plays a significant role in coordinating module movements, positioning equipment, sequencing installation activities, and managing temporary site facilities (Zhang and Pan 2020, Zolfagharian and Irizarry 2014).

The dynamic nature of construction operations requires practitioners to account for complex, time-varying scenarios on construction sites. SLOL planning for on-site construction is challenging when traditional approaches, such as 2D drawings or Gantt charts, are used. In contrast, integrating 3D models with time-based information linked to resources provides a 4D BIM (Building Information Modelling) environment that can address this complexity. It allows the simulation of major construction activities, their impact on the site layout, and their interactions over time. This helps identify issues, bottlenecks, and potential areas for improvement before site execution, which can improve construction project efficiency (Kumar and Cheng 2015, Jin et al. 2019).

4D BIM can improve decision-making through effective visualization, allowing stakeholders to review the same construction activities under different scenarios before their implementation on site. This can lead to more efficient SLOL planning by integrating spatial, resources, and temporal information into a single visual environment (Caldart and Scheer 2022). Hence, 4D BIM-based construction SLOL planning can be outlined as a process that involves managing, connecting, and using information to provide different viewpoints of the same plan. Such planning uses spatial information about objects, physical spaces, equipment, and material characteristics to support efficient layout simulations and logistics decision-making (Caldart and Scheer 2022, Sulankivi et al. 2009).

Although previous research has shown that 4D BIM can support construction planning, workspace and logistics coordination, and improvements in the safety and productivity of construction projects, its role in the SLOL planning of modular construction must be studied in detail because there is still room for improvement. Modular projects face several challenges because large modules must be transported, stored, lifted, and installed, sometimes on congested sites. These operations require cranes, trucks, lifters, and other heavy machinery to operate within the same time intervals and limited spaces. Traditional 2D drawings and basic schedules are limited in showing how these activities and resources interact over time. Therefore, a practical 4D BIM-based method is needed to identify workspace clashes, hard clashes, unsuitable resource allocation, and illogical task sequencing before site execution (Zavari et al. 2022).

Accordingly, the aim of this paper is to investigate how 4D BIM can support site layout and on-site logistics planning in modular construction through a case study approach. The objectives are: (1) to develop a conceptual framework and proposed method for applying 4D BIM to site layout and on-site logistics planning; (2) to implement the proposed method in a modular construction case study using Autodesk Navisworks and Synchro 4D Pro; (3) to evaluate how 4D BIM supports the identification and mitigation of workspace and hard clashes, resource conflicts, illogical task sequencing; and (4) to compare the practical capabilities of Navisworks and Synchro 4D Pro for 4D-based site layout planning and logistics coordination.

2 LITERATURE REVIEW

Planning construction site layouts for temporary facilities is fundamental to improving safety and on-site logistics management (Salah et al. 2024, Whitlock et al. 2018). A BIM-based conceptual framework showed a 13.5% reduction in on-site travel distance compared with traditional methods (Kumar and Cheng 2015). The efficiency of a construction project is directly linked to an effective site plan. A case study was conducted to test a dynamic BIM-based site layout plan, which showed that it not only reduced site transportation costs by 43.45% but also significantly decreased on-site noise pollution and improved project sustainability (Tao et al. 2022). Information used for conventional site layout planning is mainly gathered from contractors and subcontractors. However, a new database was developed using information collected from the BIM model, schedules, and available logistics and resources. This improved the visualization and understanding of planners and enabled them to better identify the required resources and adjust workspaces into different shapes according to project requirements (Zavari et al. 2022).

The integration of a timeline with a 3D model is known as 4D BIM. The visualization of this additional dimension not only improves the understanding of different activities but also helps predict obstacles and clashes so that they can be mitigated efficiently (Jin et al. 2019, Kim et al. 2018). 4D BIM also helps planners and managers identify workspace and hard constraint clashes, where the spaces required for different tasks, resources, or objects intersect with each other. In addition, the timeline provides information about how much time and space are required for each activity (Hosny et al. 2022, Mirzaei et al. 2018). This visualization reduces the likelihood of mistakes, misunderstandings, human errors caused by complexity, and the transfer of incorrect information during the project planning stage by allowing issues to be identified at an early stage (Martins et al. 2022, Sheikhkhoshkar et al. 2019). 4D BIM shows stakeholders how the project will develop over time, which activities must be completed before the next activities can begin, and provides a platform for comparing and tracking the performance of planned activities against actual progress. This not only supports successful planning but also improves overall project efficiency (Crowther and Ajayi 2021, Nafe Assafi et al. 2023, Singh et al. 2021).

In off-site construction projects, modules are manufactured away from the site and then transported to the project location, where heavy lifting operations are required to position and install them. However, many workspace-related issues and serious safety concerns may arise during these operations (Zhang and Pan 2020). 4D simulations can support the management of logistics and crane lifting operations, even in complex construction projects. A study conducted on a real project in Canada showed that these simulations can identify clashes and improve the understanding of how a crane will move during lifting operations (Tak et al. 2021). Allocating workspaces and equipment to activities is a critical task in SLOL planning. However, 4D BIM can predict workspace clashes, and different simulations can be created using different resources. After comparing these simulations, the most suitable scenario, with fewer clashes and more efficient equipment, can be selected (Fang et al. 2016, Mirzaei et al. 2018).

Logistics management is highly important in off-site construction projects, as a delay in the delivery of any material can disrupt the entire project. A proposed 4D framework implemented in a case study showed that hazards could be predicted through look-ahead scheduling and visualized using a 4D BIM tool. This information could then be shared with stakeholders to support effective decision-making (Zeng et al. 2023). Task sequencing also plays a significant role in construction project planning and scheduling. In one case study, a construction sequence was generated by carefully visualizing each activity in 4D and comparing different scenarios to determine the most effective option. This reduced the time required for scheduling and sequencing by 97% compared with traditional methods (Singh et al. 2021). Overall, the literature indicates that 4D BIM has the potential to improve SLOL planning through effective visualization, leading to informed decision-making, appropriate activity sequencing, clash identification, and resource management.

Recent research has demonstrated the effective use of 4D BIM in off-site construction. Lee and Kim (2017) developed a 4D simulation framework capable of managing factory-based module production, including material quality and quantity. Bortolini et al. (2019) proposed a lean-based 4D simulation model for planning and controlling the delivery, storage, unloading, and on-site assembly of prefabricated steel systems. Kolarić et al. (2022) focused on 4D scheduling, logistics, and the temporary facilities required for BIM-based site planning. Mayouf et al. (2024) developed a lean-integrated 4D BIM model for construction projects that can improve project health and safety, operations, and time performance.

Although these studies provide a strong foundation for the use of 4D BIM in off-site construction and logistics, each mainly focuses on a specific area, such as factory production, logistics control, information requirements, or scheduling. The contribution of this study lies in combining dynamic clash testing, crane and module movement, access-route coordination, workspace analysis, and installation sequence checking within a single case study workflow, covering activities from groundwork to module installation rather than focusing on an individual function. Furthermore, Navisworks and Synchro 4D Pro were used to identify problems that were then addressed through changes to the module design, equipment selection, site layout, and schedule before the revised scenarios were retested.

3 METHODOLOGY

The main purpose of this research is to demonstrate the benefits of 4D BIM for site layout and on-site logistics (SLOL) planning in a prefabricated modular construction project. A detailed conceptual framework is developed from an extensive literature review, and a proposed method is then generated to examine its practicality and validity through a case study. Autodesk Revit is used for 3D BIM modelling, and the developed model is transferred into 4D BIM tools, namely Autodesk Navisworks and Synchro 4D Pro, where the construction timeline is attached. These 4D tools are utilised for task sequencing, resource assignment, timeline integration, and the identification of hard constraint clashes and spatial workspace conflicts. Furthermore, simulations and animations are tested and analysed using timeline visualisation to improve the understanding of different activities and to identify improperly allocated resources or activities arranged in an illogical sequence.

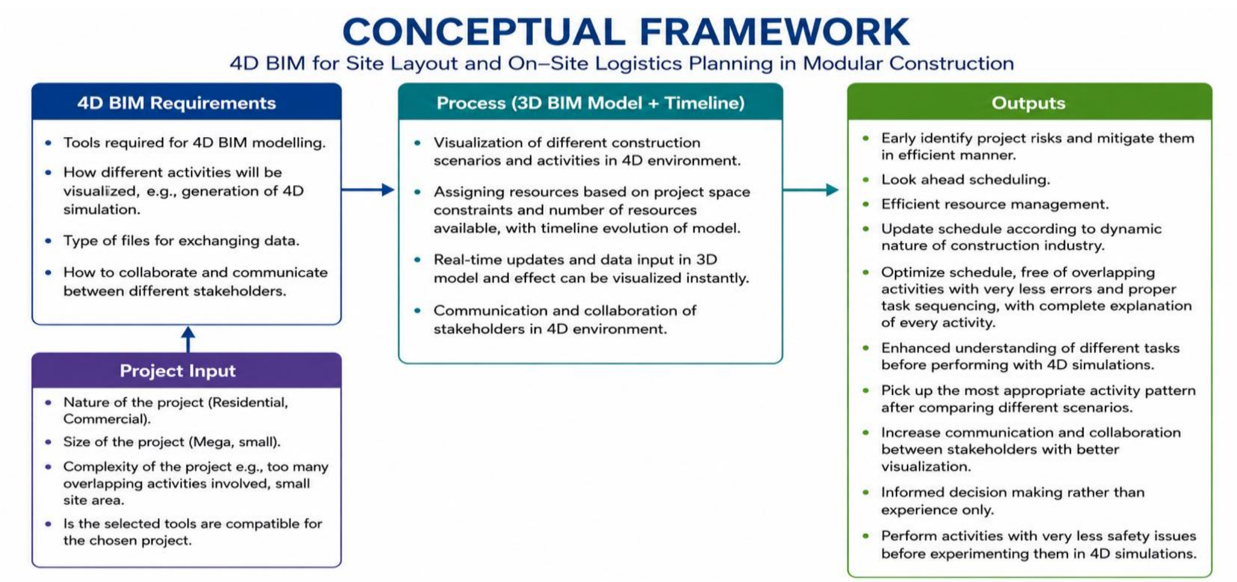

Figure 1: Conceptual framework for 4D BIM-based SLOL planning.

The conceptual framework in Figure 1 shows how 4D BIM implementation supports site layout and on-site logistics planning by linking the 3D BIM model with the construction timeline. This helps project teams visualise construction activities, assign resources according to site constraints, update the model when changes occur and improve coordination between stakeholders. The framework also shows that project size, complexity, activity sequence, site constraints and selected tools can affect how effectively 4D BIM is applied. Outputs include early identification and mitigation of risks, visualization of activities before the execution, generate schedule free of illogical task sequences and overlapping activities, effective communication and collaboration and informed decision making, enhance health and safety (Caldart and Scheer 2022, Kim et al. 2018, Mirzaei et al. 2018, Zeng et al. 2023).

The proposed method in Figure 2 converts this framework into a practical workflow for the case study. It starts with defining the project goals, site layout requirements, required data and BIM tools. The 3D model is then developed in Autodesk Revit, including the site layout, modules, temporary facilities, access routes, equipment and resources. The model is transferred into Autodesk Navisworks and Synchro 4D Pro, where construction activities are linked with the schedule and resources are assigned to tasks.

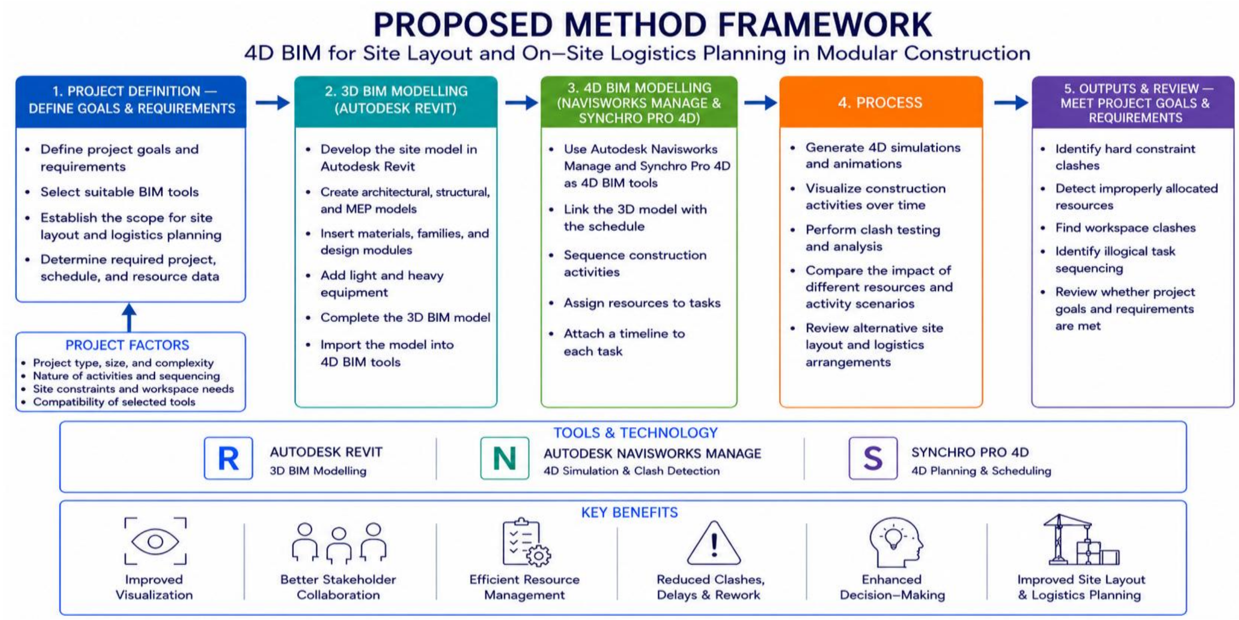

Figure 2: Proposed method for 4D BIM-based SLOL planning.

Final stage involves generating 4D simulations, testing hard and workspace clashes, reviewing resource allocation, identifying illogical sequences and comparing alternative arrangements before site execution.

Table 1 explains the main stages followed in this research, from selecting the case study to developing the 3D and 4D models, assigning resources, identifying clashes and retesting the revised model. It also shows the input data, software tools and expected outputs at each stage.

Table 1: Methodological structure for implementing the proposed 4D BIM-based SLOL method.

Stage	**Input data**	**Tool used**	**Analysis/output**
Case study selection	Modular project with limited site space, access routes, temporary facilities, module delivery and crane lifting operations	N/A	Smith Docks selected as a suitable case for SLOL analysis
3D model preparation	Site layout, modules, roads, cranes, trucks, excavators, compactors and temporary facilities	Autodesk Revit	3D site layout and construction resources developed and revised
4D model development	3D model, activity sequence and construction timeline	Navisworks and Synchro 4D Pro	Model elements linked with construction activities to generate 4D simulations
Workspace and resource assignment	Equipment, modules, activity zones and working spaces	Synchro 4D Pro	Resources and workspaces assigned to tasks for spatial clash analysis

Stage	Input data	Tool used	Analysis/output
Clash and sequence analysis	Moving modules, cranes, trucks, access routes and task links	Navisworks and Synchro 4D Pro	Hard and workspace clashes, resource conflicts and illogical task sequences
Revision and re-testing	Revised module arrangement, crane size, road position and task sequence	Revit, Navisworks and Synchro 4D Pro	Updated simulations tested to confirm whether conflicts were removed

3.1 Case Study

Smith Docks, a prefabricated residential development located in North Shields, Tyne and Wear, UK, was selected through purposive case selection because it contained the main conditions required to test the proposed 4D BIM-based SLOL method. These conditions included prefabricated module delivery and installation, crane-dependent lifting operations, a congested site area, temporary facilities, managed access routes, heavy vehicle movements and overlapping groundwork and installation activities. The project also provided sufficient geometric, scheduling and resource information to develop the 3D and 4D models and test alternative planning scenarios. Therefore, the case was considered information-rich and suitable for analysing spatial, temporal, resource and logistics interactions in modular construction. Navisworks was used in this case study to link the timeline and detect dynamic hard clashes, while Synchro 4D Pro was used to identify workspace clashes, inappropriate resource assignments and illogical task sequences.

3.1.1 Case Study in Navisworks

For this case study, site layout planning was divided into two main phases: excavation and module installation. Figure 3 illustrates the sequential development of the Smith Docks site layout through 4D simulation. Figure 3(a) presents the initial site boundary with outer fencing, Figure 3(b) shows internal access roads and temporary facilities, Figure 3(c) represents excavation activities, Figure 3(d) and 3(e) show compaction and concreting using rolling compactors and concrete trucks.

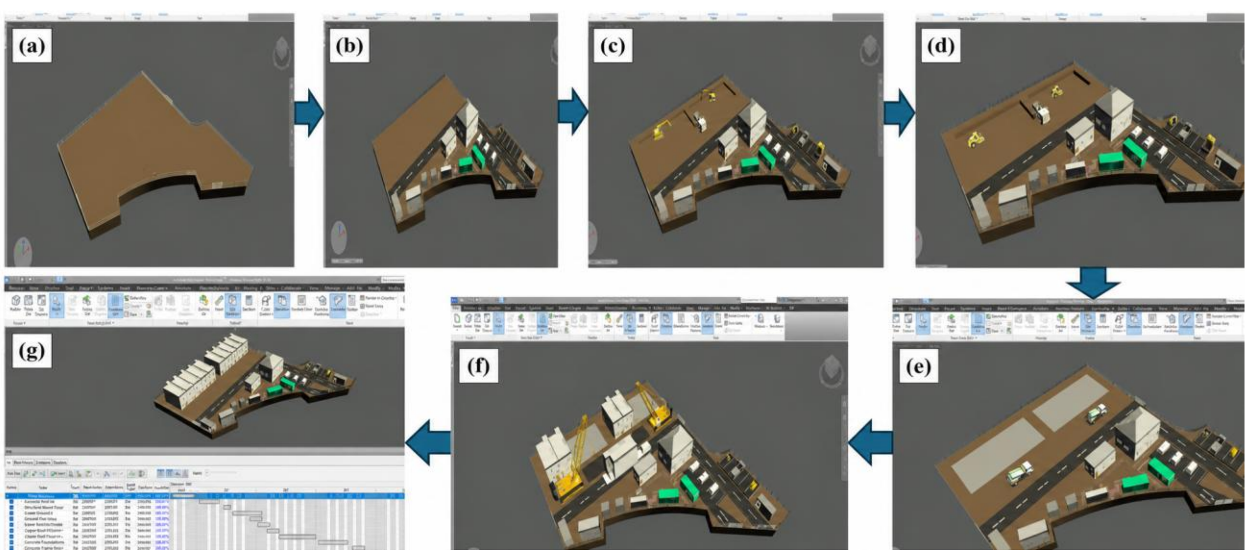

Figure 3: Initial 4D site layout development in Autodesk Navisworks.

Figure 3(f) shows the transition from groundwork to module installation, while Figure 3(g) presents the completed installation with the construction timeline linked to the model in Navisworks. By linking construction activities, resources and timeline data, the 4D model provided a clear visual representation of how the site layout changed at different project stages. The layout was reviewed activity by activity, and the preferred arrangement was selected after visualisation, analysis and clash testing.

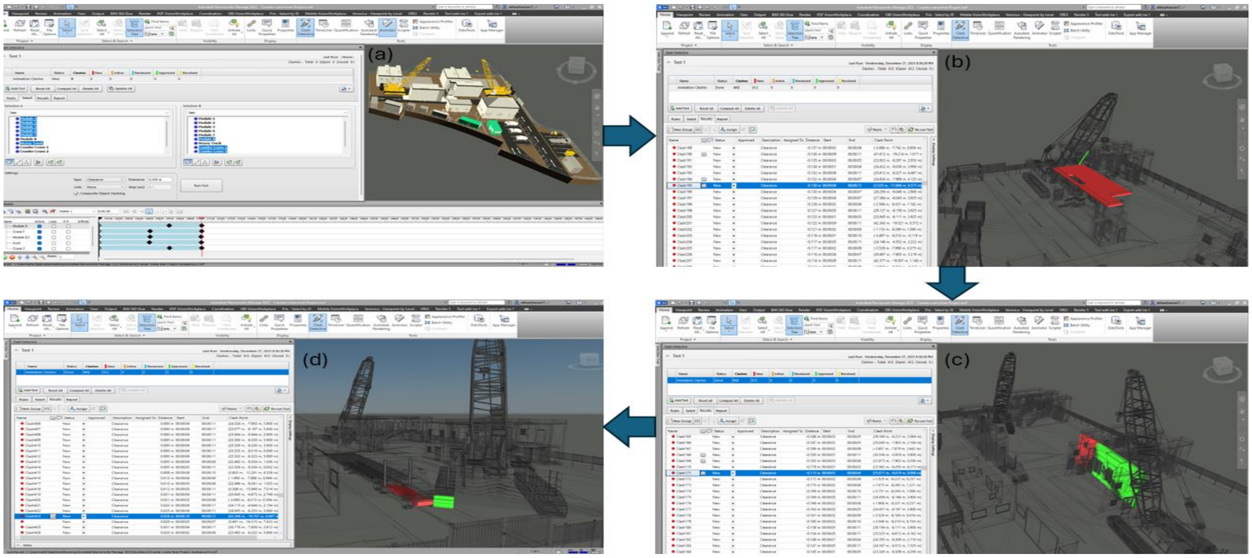

Figure 4: Simulation/animation clash detection test in Navisworks.

To assess whether the selected resources were suitable for the planned construction sequence, 4D animations were generated in Autodesk Navisworks. Figure 4(a) shows the selection sets and linked construction activities used for the clash test. The simulated scenario involved a heavy truck delivering a module while one crane lifted the module for installation and another crane handled an already placed module. The test identified several conflicts during the animation. In Figure 4(b), the roof of the lifted module intersects with the crane boom. Figure 4(c) shows a clash between the moving module and an adjacent installed module. Figure 4(d) shows the crane crawler extending into the access route and conflicting with the approaching truck. These results show that the original module arrangement and crane selection required further review before construction.

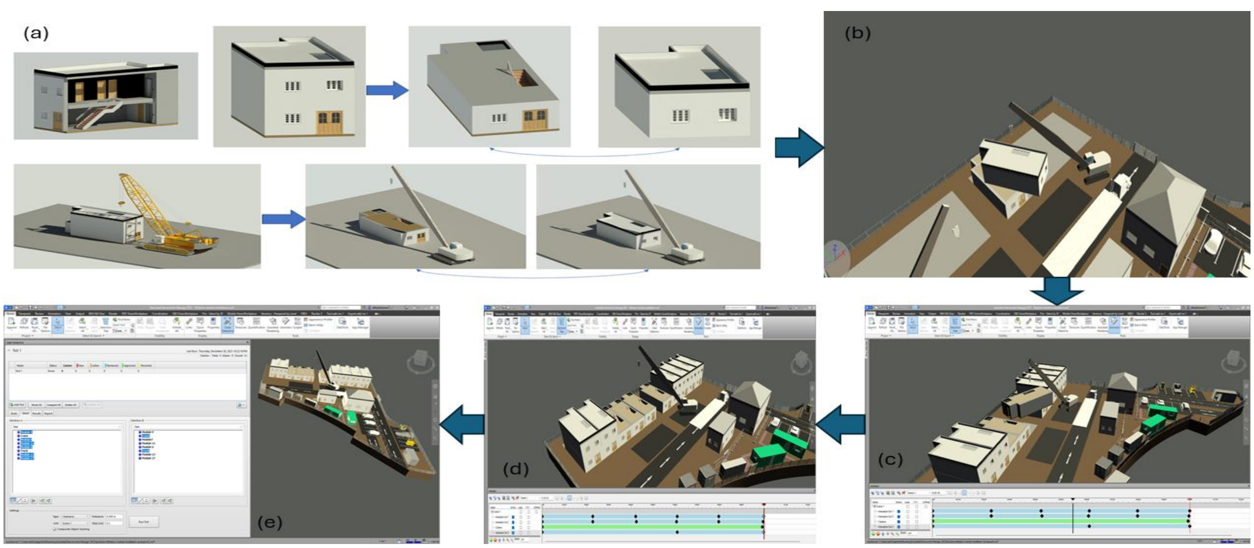

Figure 5: Revised module design, crane selection and site layout after clash analysis.

Figure 5(a) shows the design revision made after the animation-based clash test. The original module height caused conflicts with the crane boom and adjacent modules. To retain the overall building dimensions while reducing the lifting height, the module was divided into separate ground floor and first floor units. The original crane also conflicted with the access route, so it was replaced with a smaller crane suitable for the available site space. In addition, the road location was adjusted slightly away from the crane working zone to provide safer separation between crane operation and ongoing site traffic.

Figure 5(c) shows the revised animation, where a truck delivers the first-floor unit after the ground-floor unit has been placed and the crane positions it on top. In Figure 5(e), the revised animation showed no collisions between modules, cranes or site traffic. A Navisworks test using two selection sets confirmed that no clashes remained. Although no direct physical clash was identified between the cranes, the 4D visualisation indicated that operating two cranes at the same time on a congested site could create potential safety risks (Jin et al. 2019). This demonstrates how 4D BIM can support logistics decisions by testing alternative module arrangements, crane selections and road positions before site execution.

3.1.2 Case Study in Synchro 4D Pro

For 4D site layout planning, workspaces were assigned to individual construction activities to identify spatial overlaps among tasks, equipment and site resources at different stages of the project. Figure 6 illustrates the workspace clash detection process carried out through the 4D model.

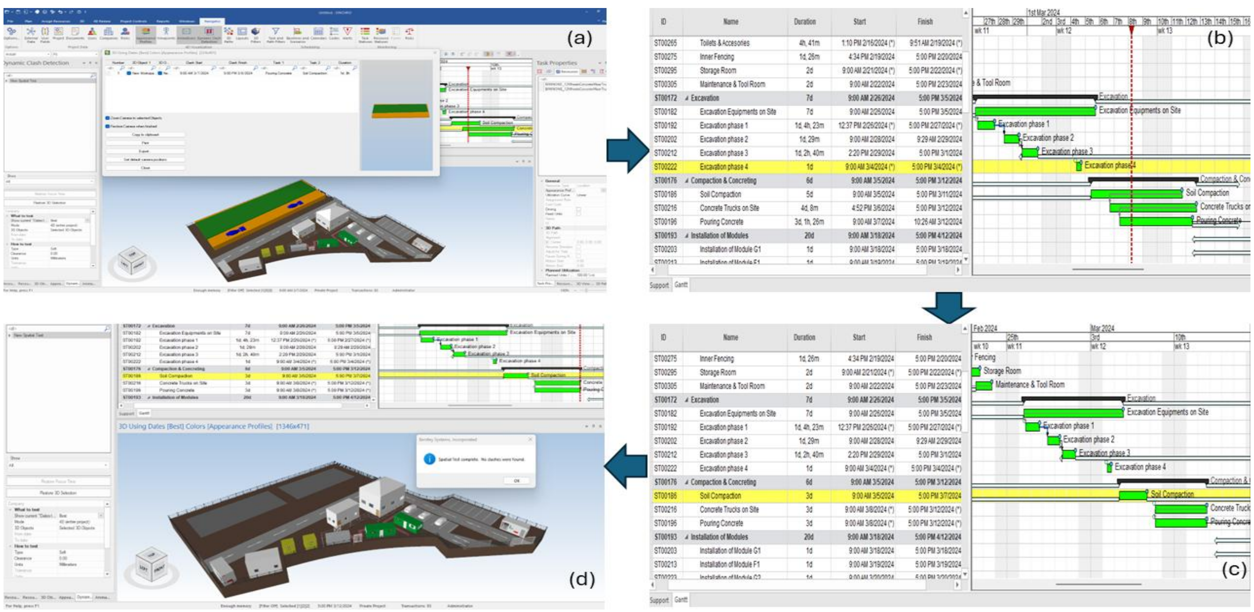

Figure 6: Workspace clash detection between soil compaction and concrete pouring in Synchro 4D Pro.

The analysis identified an overlap between the soil compaction and concrete pouring activities. As shown in Figure 6(a), the dynamic clash test revealed that both activities were taking place within the same workspace. A clash lasting 1 day and 8 hours was identified between rolling compaction and concrete pouring, indicating that concrete pouring had started before the compaction work was completed.

The task timelines were then adjusted, as shown in Figure 6(c), so that the concrete truck arrival and concrete pouring activities started only after the compaction work was completed. The dynamic clash test was performed again, and the results confirmed that the revised schedule was free from workspace clashes. This demonstrates how 4D site layout planning can improve activity coordination, support logical sequencing, and reduce spatial conflicts during site operations.

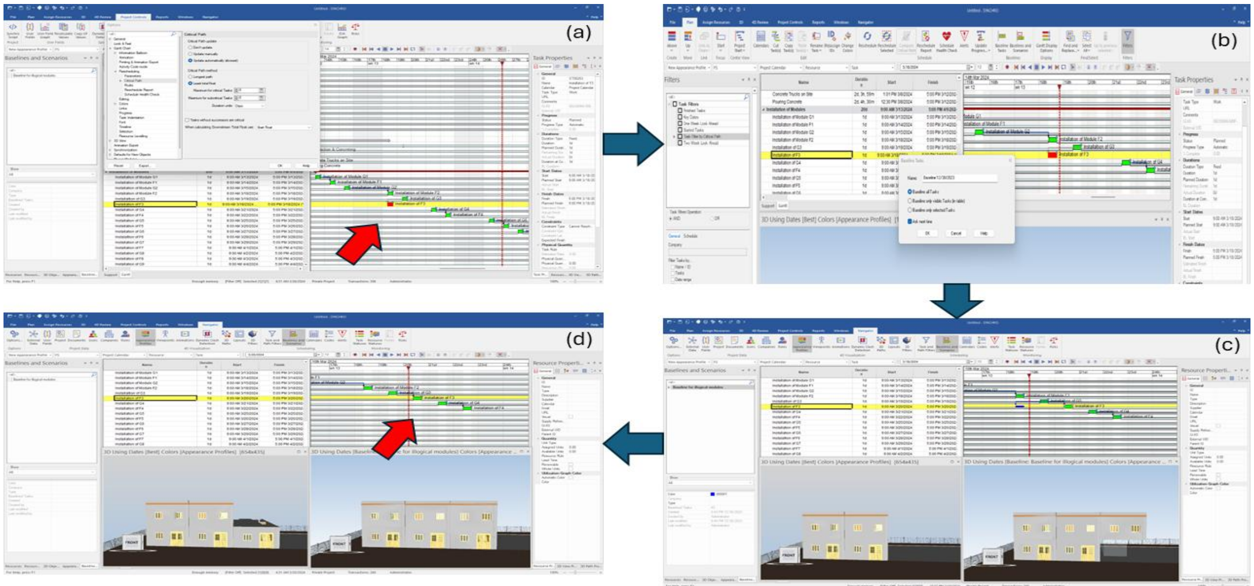

Figure 7: Identification and correction of illogical task and resource sequencing in Synchro 4D Pro.

Task links were created in Synchro 4D Pro to examine whether the planned construction sequence could affect site logistics and project performance. Figure 7(a) highlights an activity marked in red that did not follow the intended sequence. When this activity was reviewed in the 4D model, the installation of the first-floor module (F3) was scheduled before the ground-floor module (G3). As a result, the first-floor module appeared hanging in the air without structural support, which indicated an illogical task sequence.

The 4D schedule was then adjusted by setting the installation of G3 before F3, as shown in Figure 7(d). From a site layout and logistics management perspective, the revised sequence helps coordinate module delivery, crane operations and installation areas. It reduces the risk of delivering upper-floor modules before the required ground-floor units are ready for installation, which helps minimise unnecessary on-site storage, rehandling and delays caused by unsuitable delivery or resource arrangements.

4 RESULTS AND DISCUSSION

After implementing the proposed method in the case study, the results showed that 4D BIM supported both the identification and mitigation of site layout and logistics issues in modular construction. The analysis focused on workspace clashes, hard and dynamic clashes, resource conflicts and task sequencing errors. Table 2 summarises the main issues identified in the case study, the tool used for analysis, the mitigation action and the result after revision.

Table 2: Summary of 4D BIM findings and mitigation actions from the case study.

Issue identified	Tool/analysis	Mitigation action	Result after revision
Lifted module clashed with crane boom during animation testing	Navisworks hard/dynamic clash test	Module divided into ground-floor and first-floor units while maintaining overall building dimensions	No collision between module and crane boom in revised animation
Moving module clashed with adjacent installed module	Navisworks animation review	Lifting sequence and module arrangement revised	No clash observed in revised simulation

Issue identified	Tool/analysis	Mitigation action	Result after revision
Crane crawler extended into access route and conflicted with truck movement	Navisworks logistics/resource review	Oversized crane replaced with smaller crane and road shifted away from crane working zone	Improved separation between crane operation and site traffic
Soil compaction and concrete pouring were planned in the same work area during overlapping activity periods	Synchro 4D Pro workspace clash test	Activity timeline adjusted so concrete pouring started after soil compaction in the affected area	Workspace clash removed after re-testing
First-floor module was scheduled before ground-floor module	Synchro 4D Pro task sequencing review	Ground-floor module installation linked before first-floor module installation	Logical sequence achieved with reduced delivery, storage and installation conflicts

The findings show that the proposed method was effective because the same 4D environment was used to identify problems and then test revised scenarios after mitigation. For example, the workspace clash between soil compaction and concrete pouring lasted 1 day and 8 hours in the initial sequence, but it was removed by adjusting the timeline and repeating the spatial clash test. Similarly, clashes between the module and the crane, between modules, and between the crane and the truck were identified during animation testing and mitigated through revisions to the module design, crane selection and road position, supported by effective visualisation and decision-making. The proposed method also helped identify inappropriate resource assignments and arrange them in a logical manner, thereby reducing the risk of unsuitable resources arriving on a congested site and preventing delays and incidents.

Based on the observations made while applying both tools to the case study. Navisworks was effective for quick model review, visual coordination and clash testing, while Synchro 4D Pro provided stronger support for detailed 4D planning, workspace assignment, task dependencies, resource analysis and identification of illogical sequences. Therefore, Navisworks is more suitable for rapid coordination and visual checking, while Synchro 4D Pro is more suitable for detailed planning and logistics decision making in complex modular construction projects.

5 CONCLUSION

This paper investigated how 4D BIM can support site layout and on-site logistics planning in a prefabricated modular construction project. A conceptual framework was developed from the literature review and converted into a proposed method, which was implemented in the Smith Docks case study using Autodesk Navisworks and Synchro 4D Pro for simulation and analysis. The findings confirm that 4D BIM can improve SLOL planning by visualising changes in temporary facilities, access routes, equipment zones, workspaces and module installation areas over time. Workspace clashes between soil compaction and concrete pouring were detected and removed by adjusting the activity timeline. Simulation clash test also identify the issues related to excessive module height according to congested site of Smith Docks, improper selection of crane and the access route for traffic which was later modified by splitting the module into two parts which also enable us to choose the small crane instead of bigger one because dimensions and weight of module is almost reduced to half and also site access road is little moved away from the crane operation area.

The study also showed that 4D BIM can support effective decision-making by identifying illogical task sequences that may be difficult to detect in 2D drawings or basic schedules. This study contributes to knowledge and practice by presenting a practical 4D BIM-based method for site layout and on-site logistics planning in modular construction. The contribution is focused on integrating 3D modelling, 4D simulation, workspace clash and dynamic clash testing, resource review and task sequencing within a case study workflow. The comparison also showed that Navisworks is useful for clash detection, quick coordination and visual checking, while Synchro 4D Pro is more effective for detailed 4D planning, workspace control, resource management and logistics decision-making.

The study is limited to one modular construction case study and is mainly based on simulation-based analysis, literature review and modelling assumptions. Therefore, the findings show the practical value of the proposed method in this case study, but they should not be treated as a general result for all modular construction projects. Future research should focus on developing AI-supported digital twins for ongoing construction projects, rather than relying only on manual review and simulation testing. This approach could shift visual 4D SLOL planning towards a more intelligent system capable of generating multiple possible solutions. For example, if a module delivery route conflicts with equipment movement, crane operation, overlapping activities or workspace clashes, the AI-supported system could highlight the critical areas and suggest the most suitable solutions based on the identified problem. These solutions could also be integrated with VR and AR platforms, such as Unity 3D and Fuzor 4D VR, allowing project teams to visualise them in an immersive environment before implementation on site.

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