Integrating 4D Simulation and Automation Features of BIM toward Construction Safety Management

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***Abstract*—Despite the benefits that the construction industry contributes to the global economy, the impacts that it causes on occupational safety remain a significant concern. Moreover, specific systems are necessary to account for the factors influencing the implementation of construction safety. Proportionately, integrating advanced technologies such as Building Information Modelling/Management (BIM) manifests as one of the strategies for mitigating construction safety programs. Thus, this research aims to expand previous research and fill the gaps in current measures taken for adopting and implementing BIM, focusing on improving construction safety management and implementation. This study presents a framework that incorporates 4D Simulation and automation features of BIM. The framework aims to overcome challenges related to regulating construction schedules, taking into account weather conditions, and adhering to standard safety codes in the construction safety planning process. The ultimate goal is to promote sustainable construction safety management. This research conducts a case study on a large-scale incineration project in Japan, considering the Japanese construction working environment and Japan Industrial Safety and Health Association (JISHA) and JICA Safety Standard Specifications (JSSS).**

***Keywords*—construction safety, Building Information Modelling (BIM), Application Program Interface (API), construction management, automation**

I. Introduction

According to studies, the construction industry accounts for a high impact on most countries' Gross Domestic Product (GPD) [1]. However, despite the economic contribution of the construction industry to the global market, it is denounced as one of the riskiest occupations. According to the International Labor Organization (ILO), construction is associated with a proportionately high number of job-related accidents and diseases, as one-sixth of all fatal occupational accidents globally occur on a construction site [2].

For decades, the construction industry has been one of the riskiest occupations in Japan. According to the Japan Industrial of Safety and Health Association (JISHA), the construction industry takes a 33.2% rate of fatal accidents in Japan [3], as shown in Fig. 1. The number of accidents has continually decreased from 1999–2021.

However, the share of construction accidents in the total number remains around 30%–40%, excluding the year 2011. Data for 2011 include industrial accidents caused by the Great East Japan Earthquake.

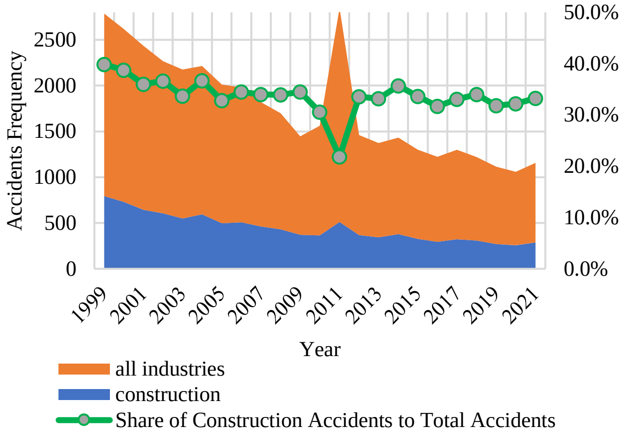

Figure 1. Trends of number of accidents 1999-2021.
Source: JISHA

It is a pressing concern as accidents significantly impact the construction project's progress and finance. Accidents cause work delays interrupting the construction schedule and resulting in additional costs from the construction budget. It causes incremental expenses for hospitalization and disability benefits for the affected individuals in the incident.

In view that the construction industry is one of the economic drivers of society, the government, stakeholders, contractors, and all involved in construction, including the workforce, are responsible for strengthening the promotion of construction safety [4]. Thus, since construction safety is a managerial and technical concern, adopting digital strategies such as BIM is considered a significant aid in decision-making, planning, and management. Consequently, the construction sector needs to catch up with technological innovation as existing

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construction technology grows very slowly [5]. It needs more enhancements in its existing policies toward innovation and sustainability to address concerns, particularly in occupational safety.

Furthermore, automating the workflows within BIM could support the challenges in its implementation; accordingly, it decreases time spent on engineering tasks and increases focus on achieving building performance during the design process [6]. In this concern, this research proposes a framework utilizing the automation feature of BIM, in combination with the 4D simulation. Previous research papers have proposed frameworks for integrating BIM into construction safety mitigation, however, discuss limitations in the focused construction safety elements, and to the US working environment and safety standard code, Occupational Safety and Health Administration (OSHA). This research extends the previous research papers by considering the Japanese construction sites condition and safety regulations such as Japan Industrial Safety and Health Association (JISHA) and JICA Safety Standard Specifications (JSSS).

Relative to human aspects as factors influencing construction safety, the proposed framework in this research aims to produce an intuitive construction layout and hazard report that is straightforward to disseminate across teams and personnel involved in the construction project. Concerning construction site conditions, this research considers the weather conditions in addition to the site layout/space, construction schedule, safety standard, and safety elements as explored in previous studies in improving construction safety management. The safety elements focused on in this research include ladders, railings, scaffoldings, cranes, equipment, travel path, vehicle route, and temporary structures such as toilets for workers, site offices, and storage which are identified as a few of the large causal agents of Japanese industrial fatal accidents in construction in 1999–2021 [7]. These safety elements support major hazard causes in the Japanese construction industry, identified as falling from a height, being struck by a falling object, being caught in between, collapsing, and crashing [8].

II. The Link of BIM to Construction Safety Management

A. Factors Influencing Construction Safety

The research of F. Muñoz-La Rivera *et al.*, with results shown in Fig. 2, conveys that human aspects and the construction site condition, take the highest percentage distribution influencing construction safety [9].

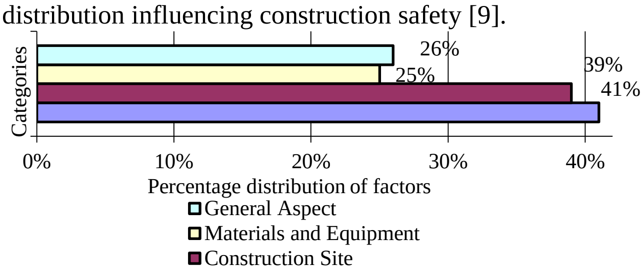

Figure 2. Percentage distribution of factors [9].

The human aspects-work and team include communication, worker actions/behavior, work pressure, competency, and motivation. On the other hand, the construction site condition comprises local hazards, site layout/space, work environment, housekeeping, work schedule, and site constraints.

B. Impact of BIM on Contractors and Stakeholders

Correspondingly, the impacts of BIM favor the aspects influencing construction safety, explicitly on the communication, site layout, and work environment. Fig. 3 shows a report from National Building Specification (NBS), U.K., showing the top five benefits of BIM to contractors and stakeholders who agreed to adopt BIM [10]. This report substantiates that BIM is one of the corresponding solutions to improving construction site accident prevention.

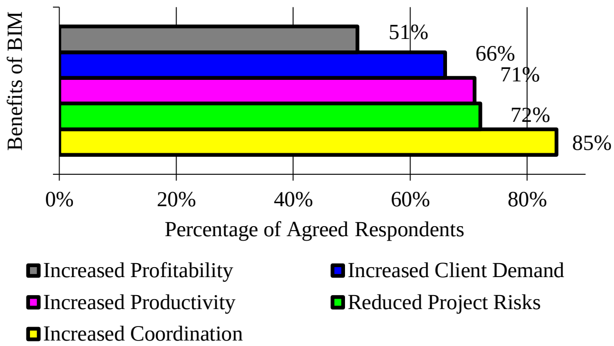

Figure 3. Impacts of BIM on contractors and stakeholders [10].

C. Previous Studies About the Integration of BIM into Construction Safety

BIM has been expanding its application, improving design quality output, and collaboration through project teams, and is gradually extending its capability to construction safety planning and implementation.

Earlier research focused on risks due to falls, which Sulankivi *et al* (2010), and Zhang *et al.* (2015) had developed automation to model temporary handrails [11, 12] while Kim *et al.* (2016) developed automation for modeling scaffoldings [13]. Cheng *et al.* (2014) contributed to improving safety by a developed tool to automate construction facility layout and consider adjustments due to frequent changes in design and construction plans [14]. Shen *et al.* (2015) identified and reported near-miss to prevent accidents during construction by developing automation to visualize near-misses [15]. Shwabe *et al.* (2016), proposed a framework of a rule-based checking of placement of safety equipment when modeling for construction site layout [16]. Years later, Khan *et al.* (2019) made a difference in their proposal of a framework for optimizing construction safety plans by focusing on excavation works [17]. In the year 2020, a research by Pham *et al.* (2020) explored Information and Communication Technology (ICT) capabilities to develop automation of construction site layouts and provide safety measures. The research achieved optimized safety based on the Occupational Safety and Health Administration’s (OSHA’s) top four causes of construction hazard-based:

falls, struck by, electrocutions, and caught-in between [18]. In reference to previous literature about the safety protocol of hazards, Akram *et al.* (2022) proposed a framework using Autodesk Revit to generate hazard reports based on the 3D model inputs [19]. Table I shows previous research and the corresponding approach in investigating potential construction hazards using BIM applications.

TABLE I. PREVIOUS RESEARCH AND APPROACH TO INVESTIGATING HAZARD THROUGH BIM FEATURES

Author (et al)	Year	Specified safety regulation standard	Focused Safety Element
K. Sulankivi	2010	not specified	safety railings
J.C.P Cheng	2014	not specified	travel path
X. Shen	2015	OSHA	(not specified)
S.Zhang	2015	OSHA	railings
K. Schwabe	2016	not specified	safety equipment
K. Kim	2016	OSHA	scaffoldings
N. Khan	2019	OSHA	earthwork safety elements
K-T. Pham	2020	OSHA, Bureau of Labor and Statistics (BLS), and the National Institute for Occupational Safety and Health (NIOSH)	temporary safety facilities and workspace
R. Akram	2022	OSHA	safety equipment

Moreover, studies show that BIM significantly impacts efficiency and productivity from design to construction. BIM, as a process, is depicted by previous studies to improve construction safety by handling and collaborating textual, calculation, and visual data.

III. BARRIERS TO BIM ADOPTATION

As BIM emerged two decades ago, it is taking time to train users and explain and forward knowledge. According to National Building Statistics (NBS) in the UK, the barriers to adopting BIM include the unavailability of standards, expertise, and analysis on the application and benefits [10]. In most companies, the knowledge of its application still needs to be improved; thus, combining computer literacy and a specialty or profound experience in the project-related engineering fields is essential in developing expertise. It reflects similarities to the study results on the barriers to BIM adoption in the building construction industry in China. As the relevant skills and knowledge are critical, adopting BIM depends on finances and organizational support [20]. In Japan, the awareness of project clients on the BIM applications and the collaboration system between the clients-to-general contractor and general contractor-to-sub contractors influence the adoption [21].

Nonetheless, the work and organizational strategies vary in different companies according to culture and regional background, thus, having various difficulties in adopting the applications. Hence, unfamiliarity with BIM applications is a common problem [22]. Therefore, it is mere to expand research to unlock breakthroughs for its further development and give stakeholders and the government more awareness about its benefits and applications.

IV. RESEARCH METHODOLOGY

Simultaneously, considering the issues in the construction industry, such as slow innovation and accidents, as well as the challenges in adopting BIM, this paper proposes to enhance construction safety management by identifying construction hazards by considering the factors influencing construction safety, project parameters and through BIM 4D-Simulation and automation features.

A. *Factors Influencing Construction Safety*

Fig. 4 shows that the layout of temporary buildings and establishments, machines, tools, materials, and the natural environment are the most common causal agent of fatal and non-fatal construction accidents. In this research, the natural environment is considered and limited only to weather conditions.

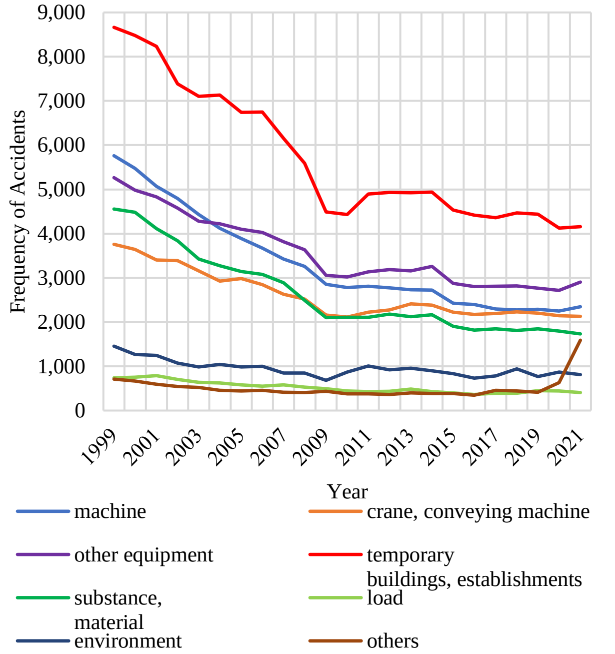

Figure 4. Frequency of fatal and non-fatal accidents due to large causal agents in construction in 1999-2021[7].

Concurrently, the types of accident sources were collected and filtered according to the frequency of occurrence of non-fatal and fatal accidents in construction in Japan, as shown by the statistics from the Ministry of Health, Labor, and Welfare of Japan in Fig. 5.

The statistics show that accidents in construction due to falls from height have the highest number of occurrences, followed by accidents due to falling to the same height, being caught in between, being struck by a falling object, reaction to motion/improper motion, crashing by, collapsing, cut, and others [8]. Furthermore, safety codes were collected and classified according to the associated type of accident source.

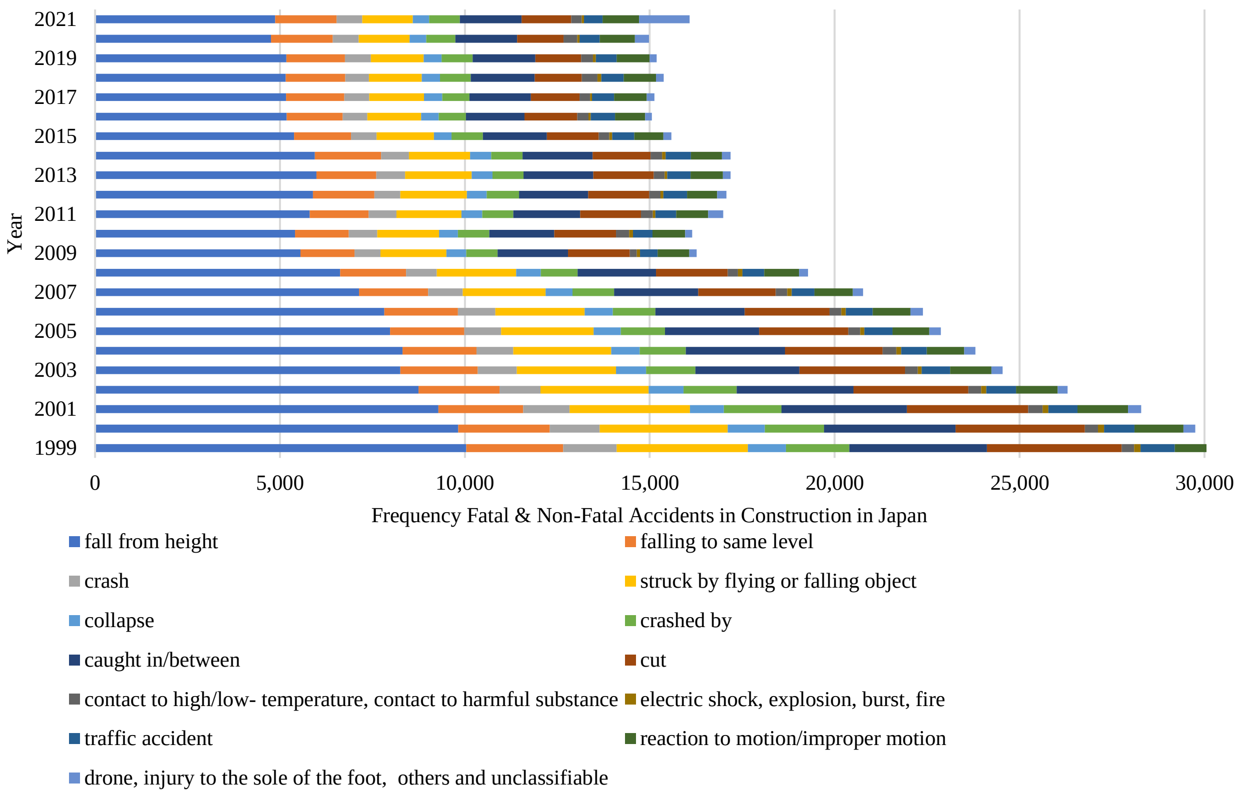

Figure 5. Fatal & non-fatal accidents in construction in Japan in 1999-2021 [8].

B. Selection of Project Model

This research selects an incineration plant located in Japan as a project model. The project model, generated in Revit, was contributed by a Japanese company venturing into infrastructure and renewable energy projects. The project model already contains structural model elements, including element parameters. A large-scale project is considered in this study as this involves multiple subcontractors and can have a long duration, requiring a high level of safety and project management. It can be expensive and have a higher risk of occupational accidents.

C. Investigating Hazards through BIM

Previous research has implied methods of optimizing construction safety. This research aims to go further from these studies by proposing a framework for ways to inspect hazards in BIM. One is through visual inspection by 4D-Simulation. 4D-Simulation refers to the simulation of planned construction activities to the 3D model in BIM, which contains data about the project's site, design, and logistics. The concept of this method is to utilize 4D-Simulation to visually inspect conflicts in activities concerning changes in the construction layout and the sequences in the construction schedule.

However, there can be many drawbacks to visual inspection. As manual checking can be prone to human error, this research uses Navisworks. NET API (Application Program Interface) to create a plug-in tool to automate hazard identification tasks in the Navisworks GUI (Graphical User Interface). The automation attributes to the listed safety standards, types of hazard sources, and most common causal agents of fatal construction accidents. Table II shows the classification of approach to investigating these hazards according to the source. In general, the automation tool investigates hazards in three ways; check the existence of safety elements according to the elevation of model elements, clash check, and weather conditions. A weather API called WeatherAPI is integrated into the Navisworks .NET API to check weather conditions.

TABLE II. APPROACH TO INVESTIGATING HAZARD

Cause	Approach for hazard investigation
Fall Hazard	check the existence of safety elements according to the elevation of structural model elements
Struck by a falling object, Caught in between, Collapse, Crash	Clash check: a. Safety model elements vs. structural model elements b. Safety model elements in the current date of investigation vs. future Safety model elements to be installed at the same location
Check weather	Check weather conditions and task descriptions on given dates using a weather API

V. INVESTIGATING CONSTRUCTION HAZARDS

Fig. 6 shows the framework for investigating hazards from the construction schedule, consisting of three modules; Safety Planning and Modelling, Hazard Identification, and Integrated Hazard Report. Each module consists of succeeding works to systematically prepare a 3D model with safety model elements to simulate actual construction set-up, investigate hazards and then produce a hazard report.

A. *Safety Planning and Modelling*

In this research, the first thing to have for safety planning and modeling is to prepare a construction schedule in a CSV file. It is necessary to input a task code, task type, task description, and the start-end date of erection in each task in the construction schedule.

Consequently, preparing the 4D-Simulation model requires adding safety elements to the existing project model. After modeling the safety elements, the subsequent work assigns the task code and type to the model elements. The task type is either "construct," which refers to structural, or "temporary," which refers to safety elements. Moreover, a programmed tool aids the tedious work of assigning task codes and task types in each element in the model in Revit.

After preparing the CSV file of the construction schedule and 3D model in REVIT, transferring these data to the Navisworks graphical user interface is necessary to perform 4D-Simulation and automated hazard investigation. Subsequently, the next step is creating mapping rules to assign the project timeline task code to each model element accordingly. The assigned task code to the 3D model elements attributes the project timeline tasks for the 4D-Simulation, appertaining to the imported construction schedule data.

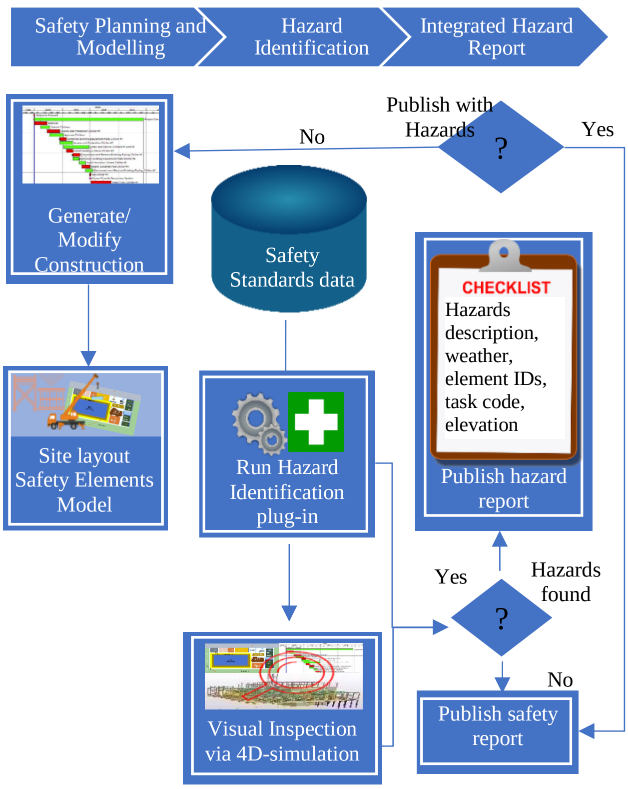

Figure 6. Proposed hazard identification approach.

B. *Case Study: Hazard Identification*

1) *4D-Simulation*

After mapping the timeline tasks to each of the 3D model elements, the following work is to configure the appearance definitions of model elements according to the start and finish date of the task and the task type of the simulation. It is necessary to define the appearance definition according to the task type, as safety elements tagged as "temporary" must disappear after the utilization period (end-date). On the other hand, the structural elements or "construct" task type must remain visible in the GUI even after the end date of installation. Fig. 7 shows an example of the imported model to Navisworks with already mapped task codes and types.

4D-Simulation shows the changes in the location and existence of temporary facilities, equipment, and other safety model elements at a particular date in the construction schedule. This helps managers visualize future construction sequences and potential problems.

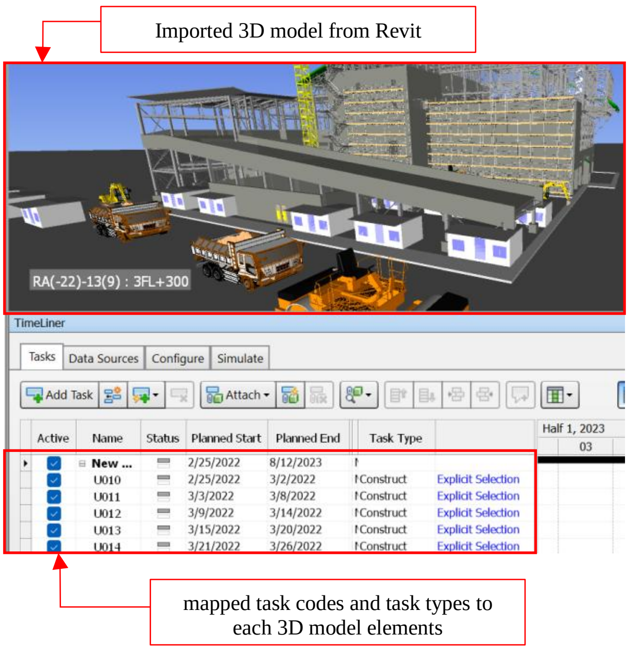

Figure 7. The imported 3D model from Revit to Navisworks with mapped task codes and task types.

2) *Automation*

The plug-in tool developed in this study allows users to select which hazard causes and safety causal elements the program will investigate. Moreover, the user specifies to consider the weather condition in the hazard identification by inputting the construction project's location in the plug-in tool panel. Fig. 8 shows the output of the plug-in when the user prompts to check the daily and 5-day weather forecast and the task IDs or task codes that are scheduled to accomplish.

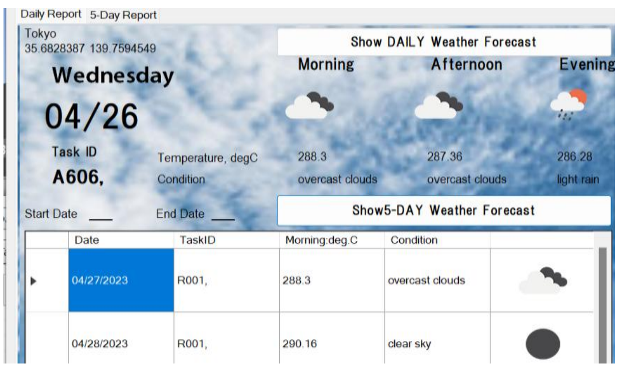

Figure 8. Plug-in display on checking weather forecast and scheduled task ID.

Fig. 9 shows the algorithm for investigating hazards for each task in the construction schedule. The program collects the task code, task type, annotated element IDs, and task dates from the construction sequence data in the Navisworks GUI. The program also gets the element IDs of all safety elements in the model.

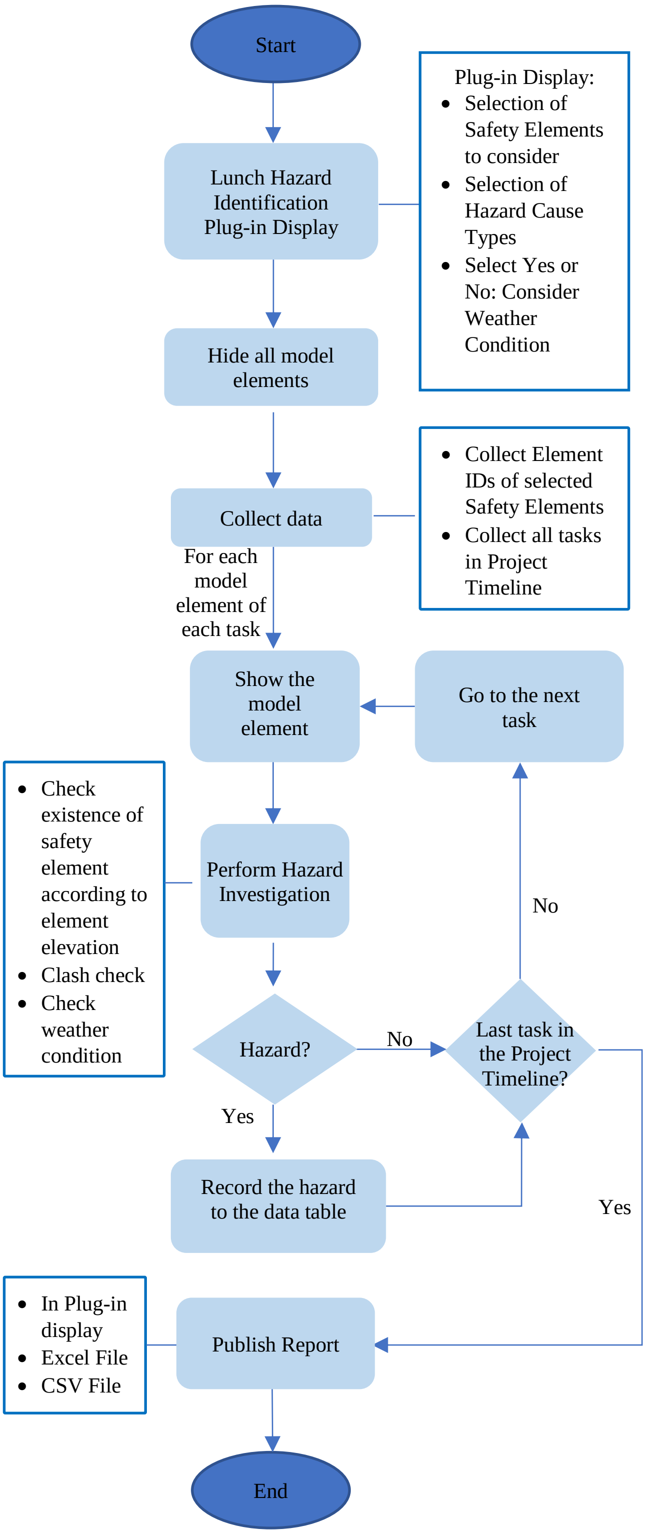

Figure 9. The algorithm in investigating hazards for each task in construction schedule data.

After collecting the task codes with annotated model elements, task type, and task sequence schedule, the program loops through each task and performs hazard identification on each task's member element. Then, the program gets the elevation for each member element on each task code and finds safety elements such as a ladder, scaffolding, and crane at the same height; consequently, it determines if the model element is accessible for construction. The program identifies the task type of the model element and checks if it clashes with safety elements. In addition, the program examines safety model elements such as travel paths, vehicle routes, cranes, equipment, offices, toilets, and others if they do not clash. The automation tool writes in the database if it finds no access to the model element and has found clashes with safety elements. If the model element is a safety element, it will indicate that it clashes with other safety elements. Fig. 10 displays the plug-in output when the programming tool identifies a potential hazard of the current task. The display includes the elevation, task ID or Task Code, Task Type, and GUID of the Safety Element.

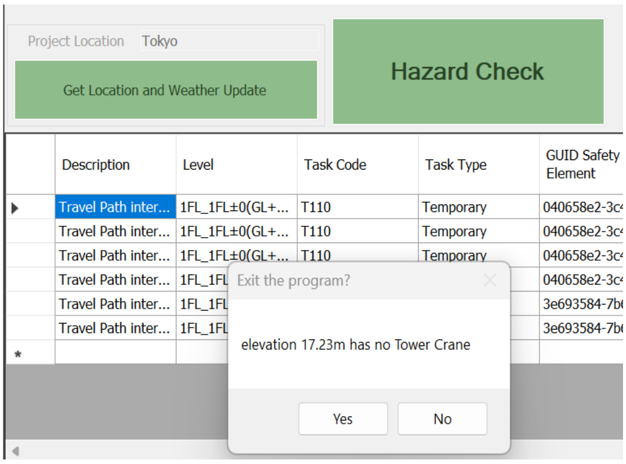

Figure 10. Plug-in display of identified hazard for each task ID.

Before the program loops to the following task code, it investigates the weather condition according to the start and end date of the task. Integrating a weather API into the automation algorithms supports forecasting weather conditions on the day of the task and tasks five days before the erection schedule. With the limitation of the weather API used in this research, the process limits only to a daily and 5-day basis of weather forecasting. The program adds an input of weather conditions in the database accordingly.

Subsequent to checking the weather, the program moves to the succeeding task code and performs the same process until the last task in the Project Timeline. The program loops throughout the collection of task codes, store the hazard in the database, and ends on the last day of the construction schedule. The tool will output a hazard report that can be displayed on the tool panel, giving options to output to an Excel file or a CSV file.

Furthermore, as it is inevitable that the 3D model data and construction schedule changes over time, the hazard report may vary according to the time basis of investigation. This paper suggests hazard investigation before the construction period. Nevertheless, during the construction period, this paper also recommends an investigation a few days ahead and on the day of each task to ensure the safety of work considering weather forecasts. This research suggests presenting the output of the investigation on a daily and 5-day basis to guide the workers and the managers during morning or toolbox meetings. Finally, managers and engineers can decide to modify the construction schedule and layout of the hazards list if found unacceptable.

VI. Conclusion

Construction site safety is of utmost importance and cannot be compromised. Identifying construction hazards before construction is critical to developing robust construction safety layouts that prioritize safety measures and minimize the risk of accidents. There can be no compromises made when it comes to ensuring the safety of workers and visitors on construction sites. Respectively, this research suggests a framework and automation tool that utilizes the 4D simulation and automation features of BIM in detecting potential construction hazards, considering the factors that could impact safety, such as weather conditions, site layout, construction schedule, safety standard regulations, and placement of safety elements. According to the case study, the framework and automation tools successfully generate construction hazard reports that align with the construction schedule, project 4D simulation model, safety standards, and weather conditions. Hence, engineers and managers can mitigate construction hazards before construction by considering human aspects and construction site conditions influencing construction safety.

In addition, this paper aimed to contribute to the improvement of technological innovations in construction and propose frameworks for reducing on-site construction accidents. Countermeasures and strategies will be carried out by fortifying digital twins (BIM) as a realistic simulator for actual construction, improving construction safety management and sustainability. As with the developed framework and automation tool, this research contributes to expanding research and innovation by providing a piece of evidence and guidelines on applying BIM as a powerful tool to eliminate construction accidents, secure adequate time to overview the entire project, acquire reliance from a client, and advance to asset management.

In order to maximize the effectiveness of the tools and framework created through this research, the authors recommend implementing them across a range of construction projects of different scales. Expanding the hazard database will help identify further challenges and gather a more diverse range of knowledge and experience-based causal agents of hazards. Thus, to ensure a comprehensive hazard identification process, it is recommended to include other factors that could cause hazards, such as traffic, pollution, the number of workers for each workspace, and workers' age and work period in the hazard identification process. This process will involve simulating the most recent 4D-simulation model and construction schedule. Anticipating potential problems around and within the construction site will help prevent accidents and delays that could pose risks to the project.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Ellen Ngaseo Piniano and Mitsuyasu Iwanami conceived the presented idea. Ellen Ngaseo Piniano developed the framework and automation tools and wrote the manuscript. Mitsuyasu Iwanami verified the methods and supervised the findings of this work. All authors discussed the results and contributed to the final manuscript.

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