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LONG PAPER

Interactive safety education using building anatomy modelling

Hai Chien Pham[1] · Akeem Pedro[1] · Quang Tuan Le[1] · Do-Yeop Lee[1] · Chan-Sik Park[1]

Abstract In order to proactively prevent accidents and injuries in construction, tertiary safety education should equip students with adequate safety knowledge and skills. However, in most construction curricula, safety is considered a low priority, and safety education is delivered in isolation, without sufficient interaction and practical experience to improve safety learning. On the other hand, anatomical theory in medicine has been adopted by and proved advantageous to various scientific disciplines. With this regard, this study presents an interactive construction safety education system using building anatomy modelling (BAM) based on the integration of anatomical theory and state-of-the-art visualization technologies. The BAM system comprises two modules: (1) knowledge acquisition module, which delivers safety knowledge to students; and (2) practical experience module, which enables students to interact with BAM to improve their hazard identification and elimination skills. The building anatomy concept (BAC) and BAM prototype are evaluated through interactive system trials with educators and learners. Findings suggest the BAC has significant pedagogic potential, and the proposed system can effectively provide safety knowledge and interactively support the development of practical safety skills of learners.

Keywords Building anatomy modelling · Visualization · Construction safety education · Interactive learning

✉ Chan-Sik Park
cpark@cau.ac.kr

Hai Chien Pham
phamhaichien@gmail.com

Akeem Pedro
lanrepedro3@gmail.com

Quang Tuan Le
lequangtuan2009@gmail.com

Do-Yeop Lee
wiztim@naver.com

[1] Department of Architectural Engineering, Chung-Ang University, Seoul, South Korea

1 Introduction

Accidents, injuries and fatalities still prevail in the construction industry causing many problems related to cost overruns and time delays. In 2014, 514 people died on construction sites [1] and the accident cost was 8.5% of the tender price in Korea [2]. Over 49% of construction accidents are caused by human errors [3], which can be prevented proactively through effective safety education and training [4]. Furthermore, Le et al. [5] emphasized that safety education at the tertiary level plays a critical role in promoting safety performance. However, in most construction curricula, attention has not been paid to safety subjects. Furthermore, most safety programmes consider safety matters in isolation or do not effectively represent the dynamic sequence of safety procedures [6]. As a result, students who enter construction industry without adequate safety knowledge tend to be more prone to perform unsafe actions. Furthermore, several studies have recognized the current limitations of safety education such as the lack of interaction, motivation and hands-on engagement [5, 6]. Wu [7] also argued that the delivery of safety courses should shift from traditionally didactic methods to more interactive and practical approaches. Therefore, the construction industry needs an effective safety education tool, which can address the aforementioned problems.

As mentioned by Jackson [8], there are close resemblances between the human body and the construction building. For example, the skeletal system of the human

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body resembles the structural frame of building in order to keep them straight and upright. The circulatory system responsible for circulating blood and nutrients in the human body is similar to the plumbing and mechanical system in the building for transporting water, waste, heat and air conditioning. In an effort to solve problems similar to those encountered in construction safety education, the medical field has applied the anatomy approach, which tried to deliver complex medical knowledge (such as nervous system and brain structure) through the detailed analysis and dissection of real cadaver. The anatomy approach allows students to reinforce and elaborate knowledge acquired in lectures and tutorials [9]. Moreover, it offers opportunities for hands-on experience and first-hand perception, which solidify learning. However, despite these advantages, the conventional anatomy approach has several notable shortcomings. In addition to the huge costs and difficulties in acquiring human cadaver, learners also experience anxiety and repulsiveness, which are major barriers to learning [10]. In order to overcome these issues, visualization-based human anatomy has emerged in the medical discipline. Students interactively anatomize 3D visualization models to actively gain a comprehensive and thorough understanding of the human body and its constituent systems. The BioDigital Human is a visualized platform in which users can explore and interact with a 3D human body for medical, surgical and fitness education [11]. With this regard, the visualization-based anatomy approach could be beneficial in construction safety education. However, very few studies have adopted this approach for improving construction education in general and safety education in particular. Construction education lacks a potential powerful tool where students interact with an active learning environment to effectively gain safety knowledge and skills.

As a solution, this study presents a building anatomy concept (BAC), which integrates anatomical theory from the medical discipline with advanced visualization technologies in order to enhance tertiary construction safety education. A BAM system has been developed, taking advantage of interactive learning environments, with the aim of improving student's safety knowledge and safety skills. The BAM system consists of two modules: firstly, a knowledge acquisition module (KAM) in which safety knowledge is delivered by educators through visually enhanced lectures with 3D anatomy models; and secondly, a practical experience module (PEM) where students play the role of a safety manager and actively identify and mitigate construction hazards through interactive BAM system features. In order to assess BAM, system trials were conducted with students, educators and engineers using virtual scenarios derived from real accident cases. An evaluation scheme comprising a concept and usability evaluation (subjective) and a comparison-based effectiveness evaluation (objective) was conducted. Useful insights regarding the potentials of the BAM approach for safety education and construction industry were acquired.

2 Background and related work

2.1 State of construction safety education at tertiary level

Safety education at tertiary institutions is essential in improving the safety performance in the construction industry. By delivering safety knowledge and developing safety skills, safety education prepares students to recognize potential hazards and faces safety challenges of construction jobsites before learners enter construction industry. Academic safety qualification is very important for students to address new safety issues by applying their knowledge and skills to real circumstances at the construction site that they have not previously encountered [12]. Thus, construction safety education at tertiary level should play a crucial role to enhance the construction safety at the jobsites. However, current construction safety education has not been given attention in universities [13]. For example, in countries such as South Korea and Vietnam, no standalone safety courses are offered as part of construction curricula. A possible explanation could be the fact that safety typically assumes a lower priority than cost, schedule and quality in the construction industry. Hence, few universities have established construction management programmes, which include safety courses [14]. Safety in fact is associated with construction methods, materials, equipment and machinery utilized on construction sites. Thus, construction safety matters need to integrate with their corresponding educational subjects.

Several studies also point out that safety education lacks student engagement and motivation due to lessons taking place in hands-off, off-site environments. In most cases, supplementary 2D material such as images and videos is used to illustrate potential hazards and safety issues [15]. Even though these approaches can be effective, learners are often left inactively listening and watching lecture material, without any direct experience or interaction. Didactic approaches that enable student-led investigations are more effective than passive approaches [16]. However, in the case of construction education didactic methods fall short in providing hands-on experience [17]. Hence, students tend to feel bored and disengaged with their passive learning. As a result, knowledge acquired without interaction may be quickly forgotten by learners [5]. Consequently, graduates enter the construction industry with insufficient safety knowledge and cannot fully perceive hazards in the construction sites. By leveraging innovative technologies, these critical shortcomings in construction safety education could be effectively addressed.

2.2 Application of visualization in construction safety education

Visualization technologies such as augmented reality (AR) and virtual reality (VR) have been applied in construction safety education for recent years. Tsai et al. [18] stated that AR affords experiences, which bring new opportunities to teaching–learning processes, especially in disciplines that place emphasis on practical training. Shirazi et al. [19] found that content delivery through augmented reality stimulates learner's interest and increases involvement. Visualization technologies allow construction students to visually generate and update project information; improve the communication among team members; and visualize construction sequences [20] as well as identify safety issues in a safety environment [21]. VR-based safety education and training offer an interactive and immersive environment where users can identify construction hazards and can then develop their safety cognitive abilities and awareness [3]. Lin et al. [4] developed a virtual simulation game that enabled students to assume the roles of safety inspectors and identify potential jobsite hazards. Pedro et al. [15] adopted a similar approach, focusing on integrating safety information into construction methods education through interactive VR in order to improve the safety performance of construction students. Le et al. [6] developed a social VR-based construction safety education system for experiential learning that allowed students to practice construction activities within virtual environment and recognize potential hazards during this process. These studies have emphasized advantages such as improved captivation, engagement and information accessibility through human–computer interaction-enabled pedagogic systems. However, current visualization applications for construction safety education have focused on delivering general safety information without adequately presenting realistic safety procedures as well as accident case analysis on construction sites. Thus far, most studies have focused on technical-push instead of learning strategies in order to achieve the objectives for construction safety education. This raises a problem involving how to effectively adopt visualization technologies for construction safety education.

2.3 Visualization-based anatomy approach for interactive construction safety education

The medical and surgical disciplines have also encountered similar problems as those in construction safety education, especially in aspects of delivering in-depth, context-specific, interactive and engaging contents, which are authentic and effective in educating learners. However, anatomy in medical science, which involves a similar pedagogical objective to construction, effectively dealt with these related issues through real experiences with hands-on cadaver dissection. Despite the longstanding success of the approach [22], the use of cadaver in medical education has declined significantly. Main reasons for this include the high costs for acquiring, storing and maintaining cadaver [10]: ethical and religious resistance to the use of cadaver [23] as well as stress and the burdensome psychological impact of exposure to human cadaver [24, 25]. In response to these disadvantages, a new approach to anatomy for medical and surgical education has emerged, leveraging modern visualization techniques [26, 27]. Various interactive 3D systems have been developed, to enable engaging, cost-effective and intuitive educational systems to deliver context-specific knowledge of human anatomy to medical students. Furthermore, 3D and virtual simulations have been extremely beneficial in training emergency medical technicians to operate in harmful and critical situations [28].

Jackson [8] stated that there are close resemblances between the human body and construction building. The skeletal system of the human body resembles the structural frame of a building and has a similar function in keeping parts straight and upright. The circulatory system, which is responsible for circulating blood and nutrients in the human body, is similar to the plumbing and mechanical system in a building for transporting water, waste, heat and air conditioning. Considering these similarities, this paper applies the visualization-based anatomy approach, which has been effective in medical education, for construction safety education. As highlighted above, several studies utilized VR and other visualization techniques for construction safety education; however, the majority focused on technology aspects, without adequately addressing pedagogic delivery and teaching strategies. Moreover, existing systems do not enable learners to interact with virtual/3D content freely in order to easily access detailed safety information. Furthermore, conventional pedagogic tools in construction education fail to cater to students various learning styles and preferences. This paper introduces the visualization-based anatomy concept for construction safety education as an innovative method for interacting with virtual construction buildings both holistically and anatomically. A visualization-based anatomy system which provides human–computer interaction is necessary to: (1) provide students with highly detailed levels of contextual safety information; (2) aid students in deeply understanding complex construction safety issues and (3) support learners by providing access to learning materials suitable for various learning styles and preferences.

2.4 Building anatomy model for interactive construction safety education

Before detailing the BAM framework, the definition of BAM and other educational terms are specified, for clarity.

Regarding the resemblances between human body and construction building structure, visualization-based human anatomy education has been successfully applied in medicine area for many years and could potentially be an effective method for construction education. In particular, in human anatomy safety and health, medical students practice to diagnose patients' diseases based on the 3D virtual body parts' symptoms. Meanwhile, construction accidents can be prevented proactively by identifying the hazards and understanding safety knowledge. As such, construction safety education borrows the visualization-based anatomy concept from medicine, to develop a visualization-based building anatomy concept (BAC). As illustrated in Fig. 1, the new concept is figured out by shifting "learn symptoms, prevent diseases" and "study diseases, make healthier" to "identify hazards, prevent accidents" and "learn accidents, make safer" through visualization-based building anatomy. BAC represents the same educational strategies from anatomy and applies them for construction safety education specifically.

According to visualization-based anatomy, some educational terms related to anatomy features are explained in more detail as follows:

- *Anatomize* Display or examine the building structure to study safety issues related to construction elements;
- *Attach and Detach* In order to illustrate the safety issues in conjunction with construction process, these terms within this study allow to show an individual element or construction sequences;
- *Dissect* Demonstrate the internal aspects of buildings and the relationships among construction elements to analyse the sequential effects when accidents happen.

With this regard, this study aims to answer the question: "what is BAC and how can construction students use it to learn and gain safety knowledge". BAC is designed to provide an interactive virtual environment in which construction students are motivated to acquire safety knowledge and develop safety skills through case-based learning.

From the perspective of BAC, the study develops a novel approach for interactive construction safety education using building anatomy modelling (BAM), with the goal of effectively delivering safety knowledge and interactively developing the safety skills of learners. As illustrated in Fig. 2, the anatomy approach, which serves as a fundamental basis for the BAC concept established in this study, is integrated with visualization technologies. The BAM approach underpins various learning activities, whereby students interact with 3D building models and access safety information related to specific building elements, acquire safety knowledge and eventually develop safety skills. Key affordances of the BAM approach for safety education include support for interactive 3D environments, whereby students are motivated and engaged through case-based pedagogy; support for highly contextualized safety learning, as related to building elements and specific construction activities; and detailed interactive visualizations, which support learning on both elemental and holistic levels through the predefined anatomization and dissection features.

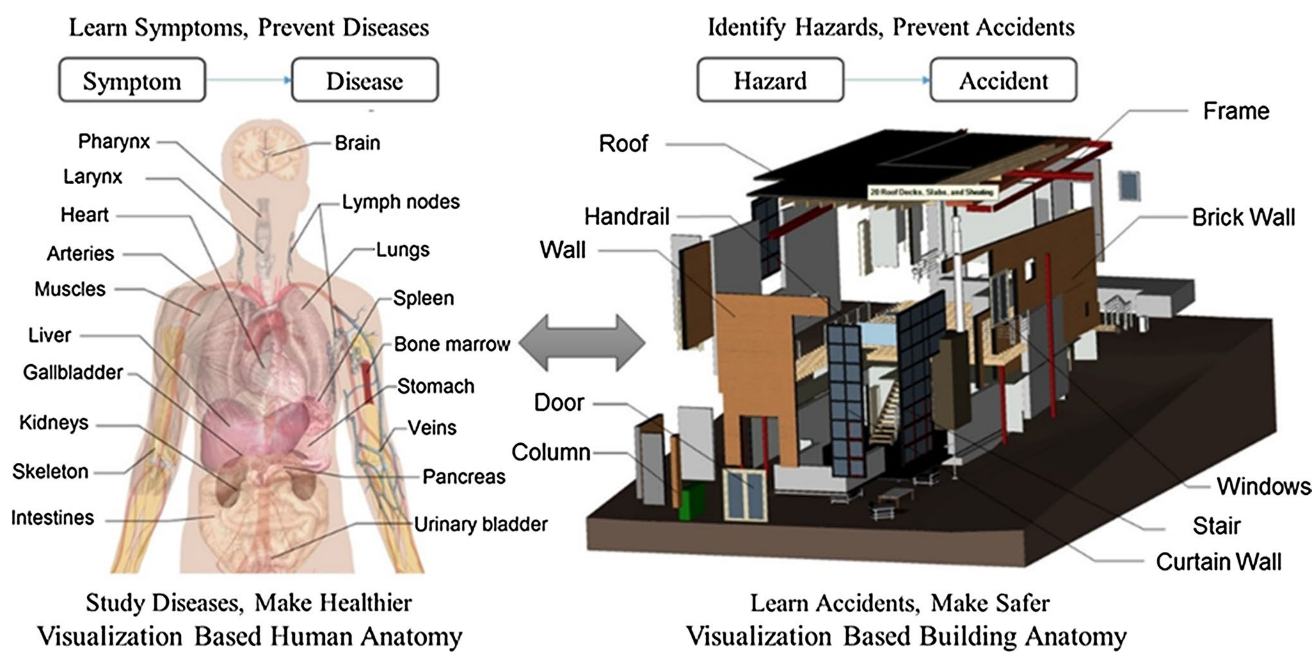


Fig. 1 Building anatomy concept for construction safety education

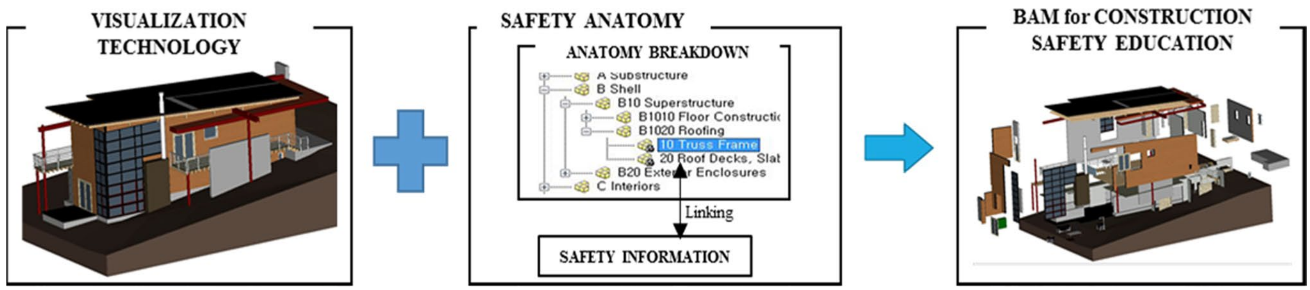


Fig. 2 BAM approach

Table 1 Safety classification for BAM

Elemental classification (uniformat)			Safety information		
Major group elements	Group elements	Individual elements	Accident type	Accident case analysis	Safety reference
B. Shell	B20. exterior enclosure	B2020. exterior windows	Fall with boatswain's chair	Template F01	OSHA standards, multimedia resources, safety course material
			Fall due to scaffold collapse	Template F02	OSHA 1926.450, multimedia resources, safety course materials
			Fall from opening to below	Template F03	OSHA 1926.500, multimedia resources, safety course material
			Struck-by falling objects	Template F04	OSHA 1926.95, multimedia resources, safety course material
			Other	–	–

As presented in Table 1, the anatomy approach for construction safety education integrates an elemental breakdown of building components with hazard and accident information pertinent to specific building elements. In order to facilitate this, 3D building model components are categorized based on the UNIFORMAT classification and broken down into groups, subgroups and individual elements. Thereafter, individual virtual elements are linked with safety contents including common related on-site accidents, an accident case analysis template and safety reference materials. As illustrated in Fig. 7, the purpose of the accident case analysis template is to provide detailed information regarding accident causes, prevention methods and ideal safe practices. Furthermore, safety reference materials, which include safety and health standards, multimedia resources and course materials, are linked to the template, enabling students to conveniently access additional safety information and then develop their safety cognition.

2.5 BAM framework

The BAM framework consists of the knowledge acquisition module (KAM) and the practical experience module (PEM), as shown in Fig. 3. The KAM represents the safety knowledge dissemination process in which educators teach safety lessons to students through accident case-based learning using BAM models. PEM allows learners to apply their safety knowledge and develop safety skills such as hazard identification, elimination and Job Hazard Analysis within the interactive BAM. The instructional method applied in both modules is the case-based learning (CBL), which involves the interactive, student-centred exploration of realistic and specific unsafe situations. Through this, construction students are expected to understand safety issues comprehensively and become familiar with common safety engineers' works and then develop their safety competency prior to entering the construction industry.

The following sections describe each module in detail.

2.6 Knowledge acquisition module

KAM focuses on supporting students to acquire a substantial understanding of construction safety issues through demonstrative cases which depict safe practices, as well as accident cases which depict safety violations and jobsite conditions leading up to safety incidents.

The KAM module is initiated with an introduction to a safety topic relating to a specific building structure based on the safety classification for BAM (Table 1). Using BAM, the educator opens up a virtual project on a big screen, dissects a virtual building and then accesses a specific element

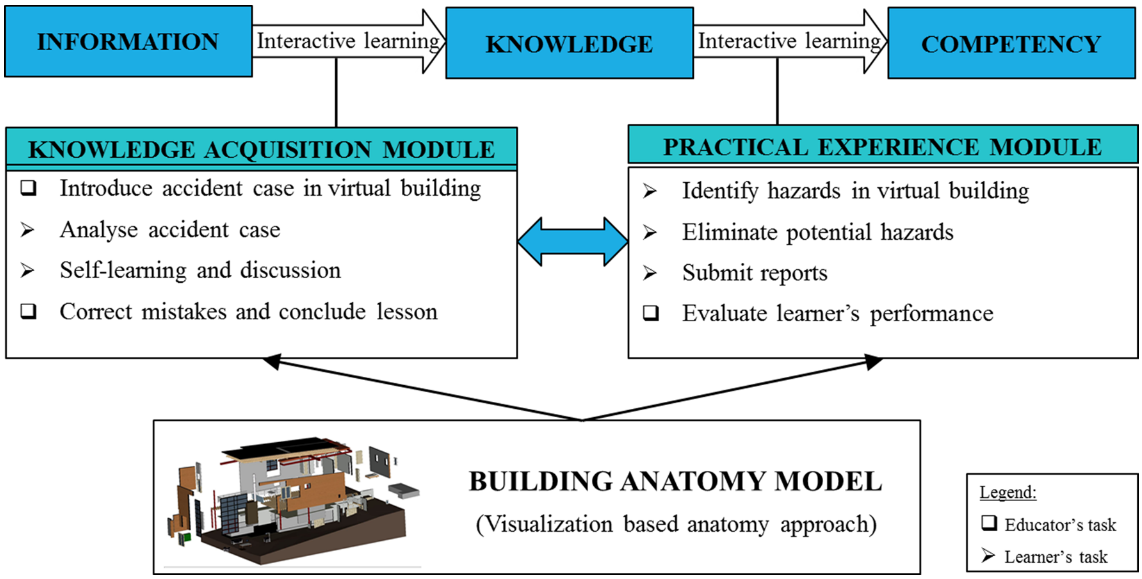


Fig. 3 BAM framework

related to the safety topic of consideration. Selected building elements are automatically highlighted, allowing learners to clearly visualize and easily distinguish building elements. Through the selected building element, the educator loads up embedded animations and videos of an accident case. During this process, the educator explains the root causes of accidents and the severity of their consequences. Following this, the educator presents animations, which demonstrate safe practices and emphasize the importance of complying with safety regulations in order to maintain safety on the jobsite. Through this process, learners can perceive the severe consequences of unsafe actions and acquire safety knowledge.

After receiving the educators' guidance, students can login to the system through their personal accounts and access accident cases, introduced during visually enhanced lectures within BAM. Through this self-directed approach, learners can be actively engaged and develop an understanding of proactive safety precautions and methods related to specific accident cases.

The BAM environment supports real-time human–computer interaction with virtual building elements, allowing learners to clearly visualize and interactively manipulate components to acquire safety knowledge. Similar to human anatomy in the medical area, BAM allows students to use anatomical tools (e.g. cross section, attach/detach, zoom in/zoom out, rotation, explode) designed to dissect (cut through) the virtual building, and access any building element in order to retrieve the necessary safety information embedded in individual elements for interactive learning. Furthermore, individual elements link to accident case analysis templates (Fig. 7), allowing students to conveniently access detailed safety information including accident type, root causes and prevention methods. The template also provides links to Occupational Safety and Health Administration (OSHA) standards, as well as other explanatory multimedia resources, in order to cater to diverse learning preferences and provide students with a holistic understanding of the safety topic.

In addition to the self-learning stages, students also have to partake in a discussion activity and explore safety issues through dissection, attach and detach features in BAM environment. During this process, the educator plays the role of a facilitator, responsible for guiding the process, encouraging discussion and providing additional support as needed.

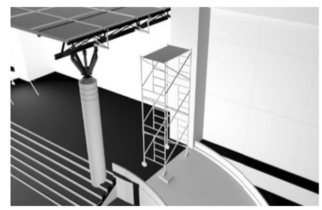
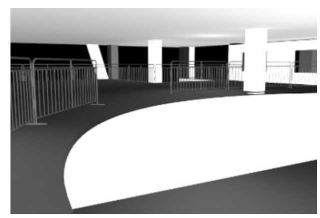
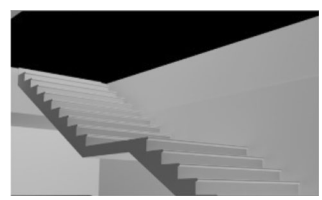
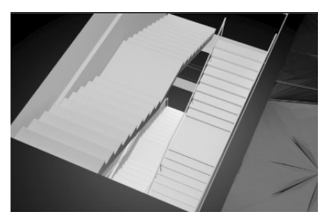
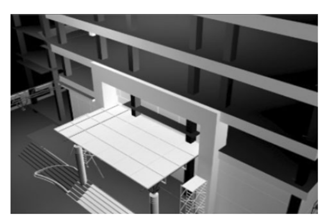
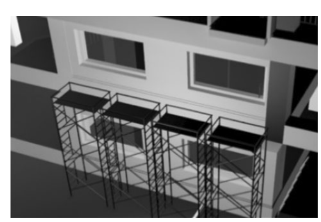
2.7 Practical experience module

PEM focuses on enhancing safety skills for construction students through identifying and eliminating hazard cases embedded virtual construction site in BAM, while educators play a supervisory role. Educators' main duties include notifying students of serious mistakes during hazard identification, assessing recorded hazard responses in BAM, evaluating students' safety performance and providing feedback. Students are required to role-play as construction supervisors and inspect the BAM site, recognize dangerous conditions and fix them. Prior to investigation, a list of under-construction activities within the virtual BAM environment is available to assist students to understand the general site information. After acquiring general understanding, learners interactively anatomize and dissect the BAM model in order to navigate the site. They explore the virtual site and examine the construction structure as well as analyse elements in

BAM environment in order to identify site risks and hazards (Table 2). The hazard types reflect the safety knowledge, which students learned from previous module. Then, step by step, they would interactively investigate construction elements or areas where hazards are embedded. Moreover, additional information about construction elements such as material, function and structure would be provided by double-clicking the elements. With the support of this feature, learners are expected to not only easily recognize hazards but also comprehensively understand about safety issues as well as construction process operation.

After identifying hazards, learners interactively eliminate them by detaching wrong and/or attaching right/appropriate safety facilitates. During the hazard correction process, the educator alarms students for any serious mistakes that could cause severe accidents. This would help learners remember the safety scenarios easily and improve safety attitudes. Students would receive complete mission notification for right

Table 2 Construction hazard investigation

IDs	Potential hazards	Description of case	Screenshot
1	Fall from mobile scaffold	Workers erected a mobile scaffold to install a truss frame in front of building. Two wheels of the scaffold are on the inclined ramp. Workers put a steel plate beneath the scaffold to prevent movement and keep it level. However, during truss frame installation, the scaffold suddenly topples over and a worker falls to his death	
2	Fall from 1st floor to ground floor due to lack of guardrails	While moving materials to the 1st floor, workers remove some parts of guardrail and forget to fit up them again. Later on, due to the neglect, a worker falls to his death from the place, which is lack of guardrail	
3	Fall from stair due to lack of temporary handrails	Due to a tight schedule, workers continued to do work on the 7th floor. However, they overlooked erecting temporary handrails for the staircase connecting the 6th floor to the 7th floor after finishing concrete work	
4	Fall into opening of stair at the 7th floor due to lack of barriers	Workers prepared to pour concrete for a wall next to a staircase's opening. However, they forget to erect temporary barriers or take precautionary measures to prevent fall accidents	
5	Falling from height due to lack of barriers at the edge of building	To execute the finishing works of the façade of a building, workers removed all handrails and barriers from the edge the building on all building floors. During finishing works, one worker slips near the edge and falls down	
6	Struck-by falling objects due to lack of safety nets	During the installation of exterior windows on the second floor, workers on higher floors forgot to assemble safety nets to protect the workers below from falling objects. As a result, after being struck on the head by a falling object, a worker fell off the scaffolding	

hazard identification and replay the case for wrong hazard recognition or correction. Through this, BAM can motivate students to learn and acquire safety knowledge effectively. Afterwards, students would answer questions and make reports relating to the hazard cases, in order to assess their safety knowledge. The report requires students to provide a hazard description and identify the accident type, root causes and prevention methods. This could help learners to retain the safety knowledge for long time through continuous knowledge recalling process.

Furthermore, BAM allows to automatically record the students' hazard identification and correction process that assist educators to evaluate construction students' performance and explain critical points about safety issues for learners. This module aims to develop a comprehensive understanding of construction safety for students and enhance their safety attitudes and behaviours. Through this, they can perform safely when entering the construction industry. Finally, educator corrects student's mistakes and evaluates their performance. By interacting with virtual building in KAM, safety knowledge retention of students may be enhanced due to their motivation and engagement. Moreover, practical experience in PEM is necessary to improve student's skill as a safety manager in real construction site.

3 Case study

3.1 BAM prototype design and setup

As illustrated in Fig. 4, there are two key phases in creating BAM. In the design and modelling phase, 3D models of a building are simulated based on computer-aided drawing (CAD) engine (e.g. Revit Architecture, AutoCAD) in order to create virtual construction sites for interactive learning. Moreover, simulations of safety facilities are designed to assist learners to eliminate potential hazards when interacting with virtual construction environment. All 3D models are classified based on the Uniformat classification according to major group elements, group elements and individual elements so that safety information would be linked to these individual elements. After that, safety material such as accident analysis templates, OSHA standards, animations, digital course material (e.g. e-book, e-lecture) and multimedia resources (e.g. images and videos of real accidents) is integrated with individual elements of 3D models in the application phase to develop BAM for construction safety education. In addition to the BAM interactive learning features, the system also provides supplementary digital materials to accommodate users' learning preferences. For instance, visual (spatial) learners can access animations and videos, while linguistic and logical learners can access safety standards, reports and accident case analysis templates. Through this, BAM enables the effective acquisition of safety knowledge and skills, with techniques suited to students' learning styles.

In order to determine the system advantages and limitations, a prototype BAM model was developed based on real accident cases that may occur during the construction of a high-rise building. The MySQL Server functions as a database, storing digital safety materials, multimedia resources, visualization models and students' profiles. Revit Architecture 2014 was used to simulate 3D models. These models were imported into Okino PolyTrans 64 and then converted to NGrain producer environment according to the anatomy breakdown in order to establish the anatomy prototype. Lastly, the prototype was encoded to support educational activities, which could enhance learner–instructor model interaction, and create an embedded question and answer test for assessing students' knowledge. Figure 5 illustrates the BAM interface comprising: (1) the main window in which users can manipulate and interact with BAM models; (2) the parts window which provides a breakdown of the building or element being viewed; (3)the animation window which provides links to supplementary digital materials (videos or animations) relating to the selected element; and (4) function windows and toolbars which allow users to cross section, zoom out/in, rotate, highlight, anatomize, cut through BAM elements. These anatomy functions support users to acquire safety knowledge and develop safety skills interactively within virtual BAM environments.

3.2 BAM prototype implementation

The prototype was implemented in the CONTIL Laboratory at the department of architectural engineering in Chung-Ang University, South Korea, and Ton Duc Thang University in Vietnam. A pilot BAM trial was carried out by educators and students in order to identify the BAM advantages and limitations.

Firstly, educators delivered a safety lesson pertaining to fall accidents, with a case of a fall from a boatswain's chair during the installation of exterior windows in a high-rise building. A fall from a specific height case was chosen since falls have the highest proportion of "Fatal Four" construction accidents according to OSHA statistics [29].

In order to disseminate the safety information based on this falling accident, educators dissected the virtual high-rise building BAM model to establish the context around the case and then navigated to the exterior window in the 3rd floor façade. Next, they explored an attached link to the falling accident case, with a video demonstrating a worker using a boatswain's chair to carry out finishing work of the exterior window. As demonstrated in Fig. 6, the teacher zoomed in and clicked on the exterior window in the BAM models main

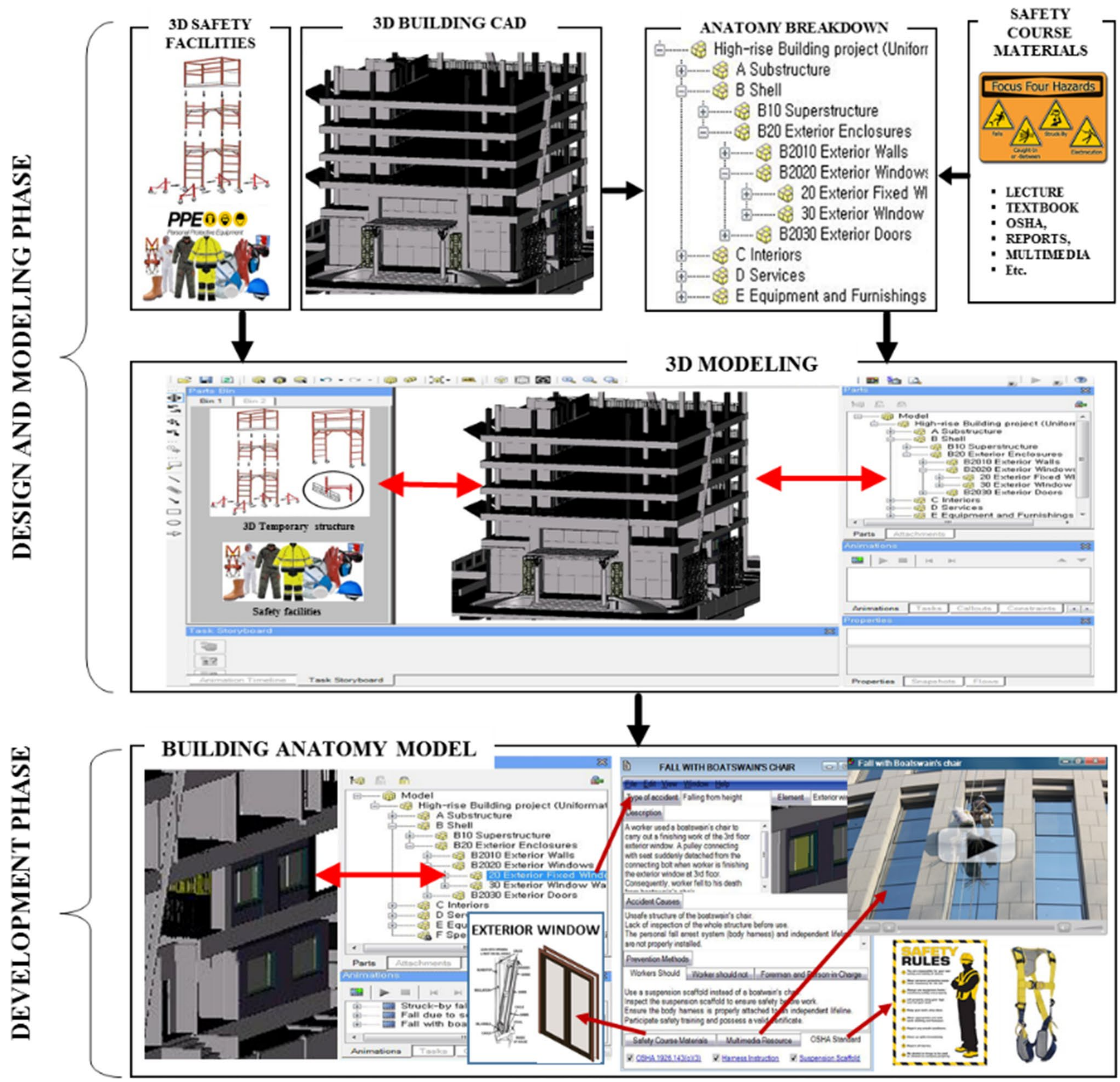


Fig. 4 BAM development process

screen that linked to a couple of related accident videos in the animation windows as well as the element breakdown structure in the parts windows. Then, the educators clicked on the video titled "Fall with boatswains' chair" to deliver safety knowledge to students. In this case, while the video was playing, the educators explained that a pulley connecting with the seat suddenly disconnected from the connecting bolt, and the worker fell to his death. During this process, the instructor used the BAM model to explain the root causes of the accident due to the unsafe structure of the boatswain's chair and lack of an independent lifeline for the personal fall arrest system. The instructor showed an additional animation demonstrating safe work practices with boatswains' chairs and emphasized the importance of complying with safety regulations in order to prevent accidents. Through these processes, learners could perceive the context of the accident case, recognize fatal consequences of falling accidents and acquire safety knowledge.

The instructor used BAM to emphasize that different construction methods have different risks of accidents, by teaching students using various accident scenarios within the BAM environment. For example, the construction

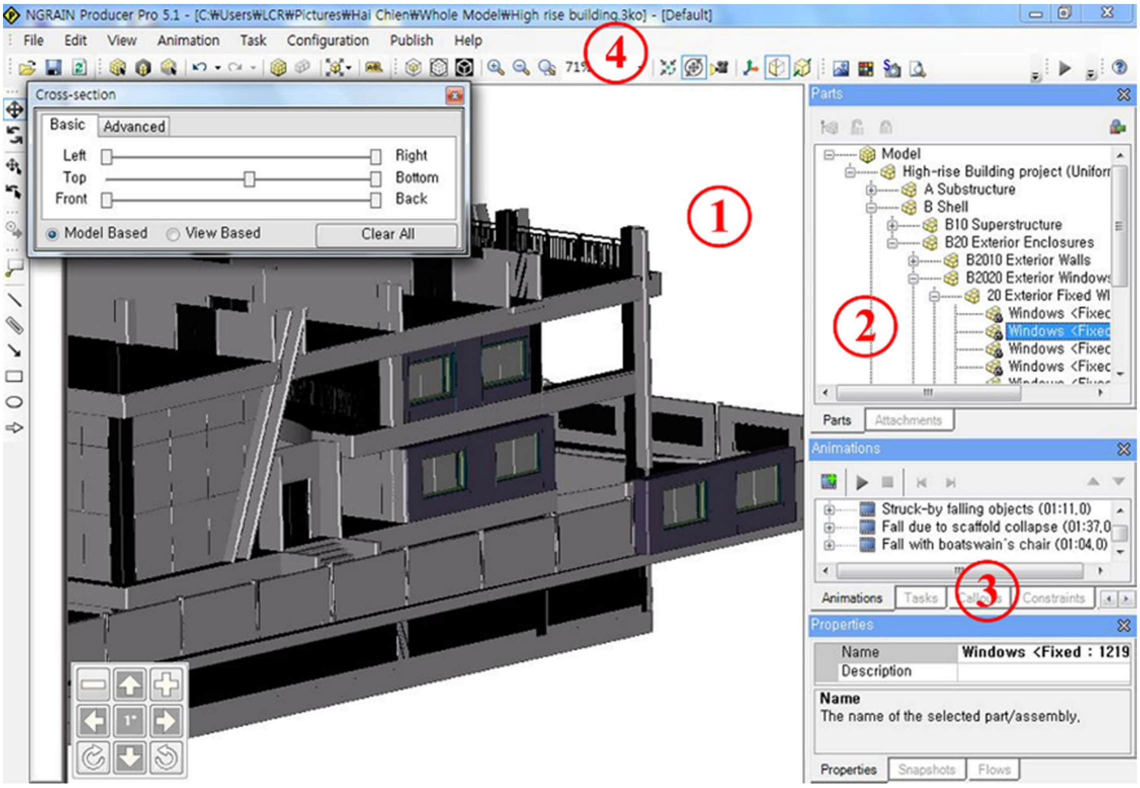


Fig. 5 BAM system interface

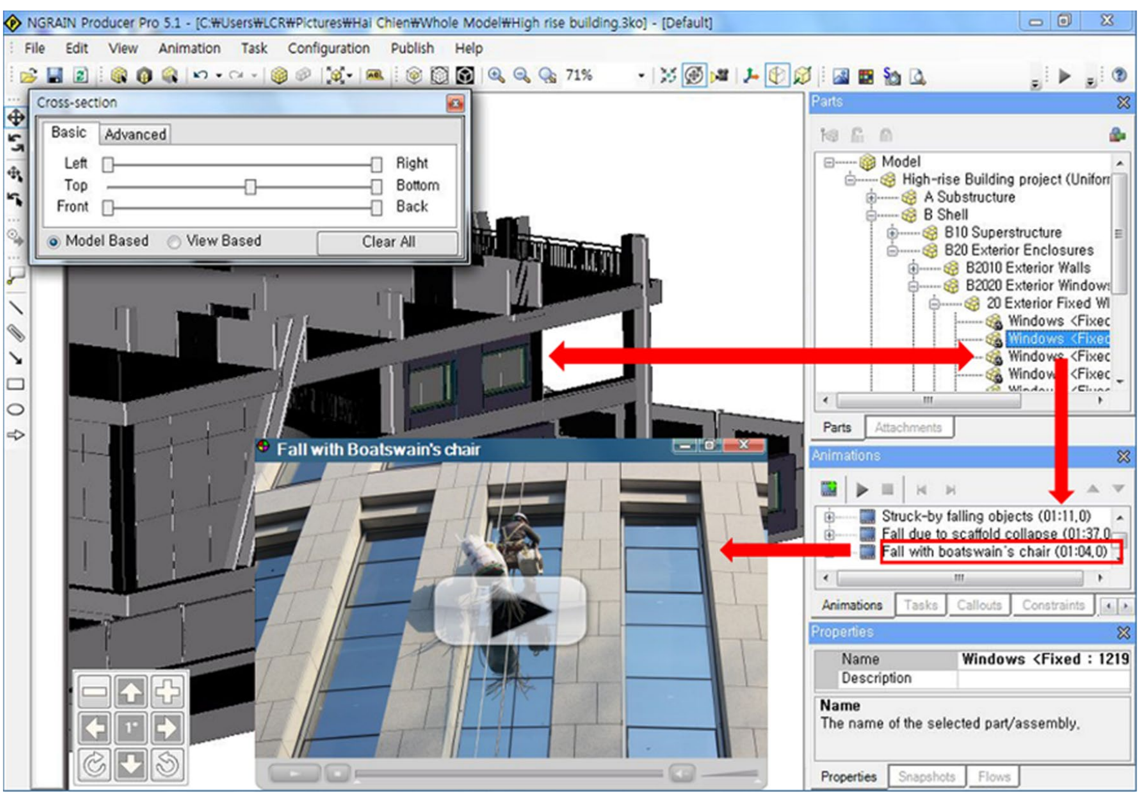


Fig. 6 Interacting with BAM to acquire safety knowledge

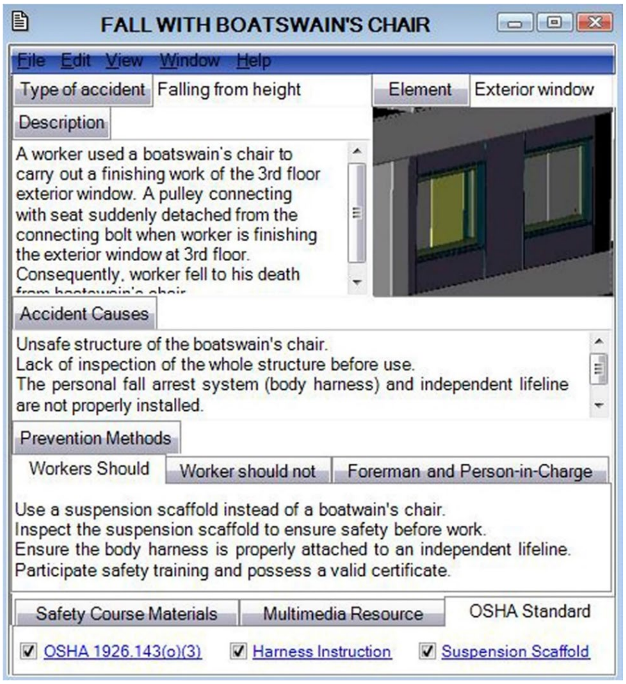


Fig. 7 Accident case analysis template for the case of fall with boatswain's chair

method for exterior windows is different to that for interior windows, and the construction method for third floor exterior windows is different to that for exterior windows at the ground floor of high-rise building too. The instructor used BAM to contextually distinguish between safety rules and precautions for each construction method in order to prevent construction accident and ensure safety practice. In order to illustrate this information, the educators would access the template by right clicking the element related to the accident within BAM after playing fall video. As shown in Fig. 7, the template provides additional detailed information regarding the accident type and description, and root causes. Furthermore, links to digital safety course materials and multimedia resources are available for students. The instructor also accesses the OSHA standard tab and clicks on OSHA 1926.143(o)(3) (Fig. 7) linking to this article in the OSHA website depicting the safety requirements which must be complied with to ensure safety with boatswain's chairs.

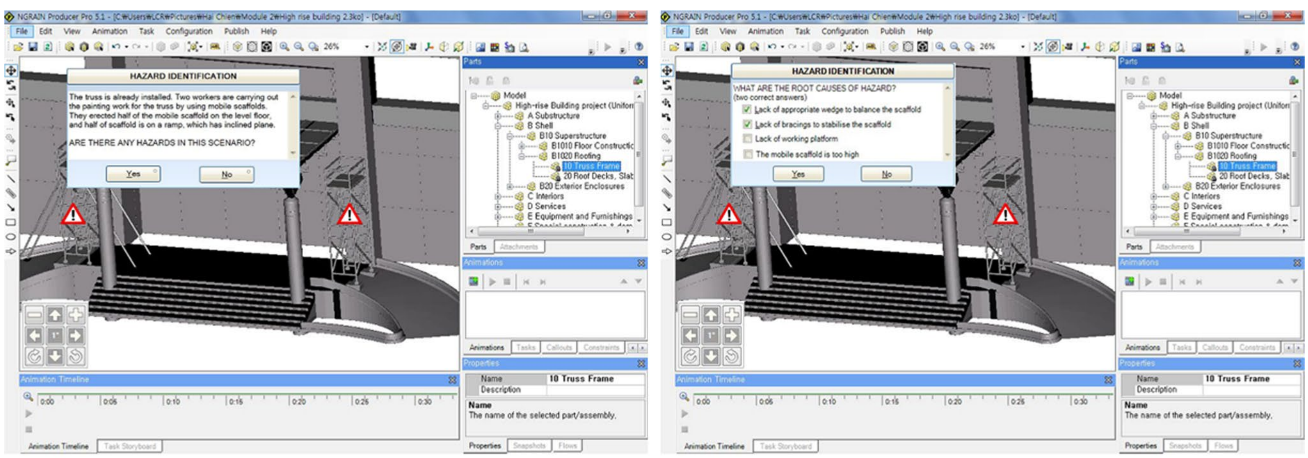
Secondly, in order to consolidate safety knowledge, students are required to partake in a self-learning activity and analyse a falling accident from a scaffold within BAM. Following the instructor's guidance, students login to the system through their own accounts and navigate to the same exterior window and access a video of a fall from scaffold accident. In this case, workers use mobile scaffolds instead of a boatswain's chair while carrying out finishing work. However, a worker falls off the scaffold because of workers not checking the stability of the scaffold. Similar to the visualization-based anatomy approach in the medical field, 3rd floor exterior window is automatically highlighted, allowing learners to clearly visualize and easily distinguish other building elements. Moreover, safety information embedded in this exterior window includes accident type, causes of accidents, sequences of safe practice and prevention methods, in order to help learners clearly understand this accident. For this accident case, these safety contents are aligned with construction method of using scaffold according to the safety standard (OSHA 1926.452 (w)). Students can access the OSHA website to understand OSHA requirements of using mobile scaffold to assure safety. By analysing different construction methods for finish work of the same exterior windows, students thoroughly understand the importance of construction method affecting safety practice, as well as the compliance of safety standard for the given construction method. During the learning process, the instructor's role is to guide learners as to how to interact with BAM, stimulate discussion and correct students' mistakes. Through BAM, students play an active role in acquiring safety knowledge.

Next, students are required to interactively investigate construction hazards by using the anatomy functions in BAM in order to improve their hazard identification and elimination skills. Students play the role of supervisor and identify construction hazards (Table 2) by navigating the exclamation signs within BAM. Before hazard investigation, a pop-up information window including a list of construction activities is available in the virtual BAM environment in order to help learners understand the status of the construction site.

After gaining a general understanding of the virtual construction site, learners close the pop-up window and start to interactively dissect the building in BAM in order to navigate dangerous situations and identify potential hazards.

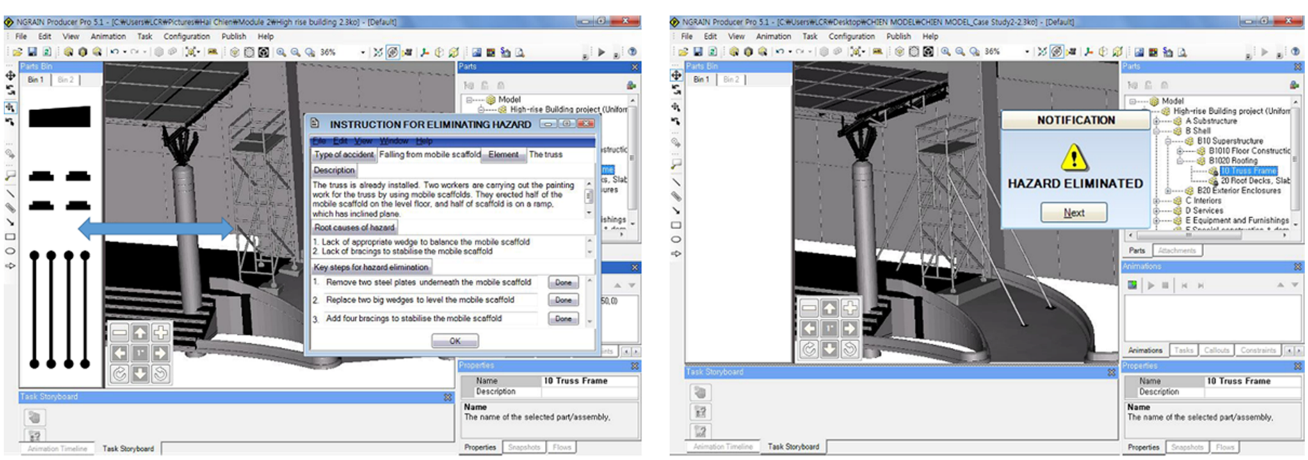
In the virtual building, some workers are preparing to pour concrete on the 7th floor, and another group of workers is installing exterior windows on the third floor of the building, while a third group installs a truss in front of the building. When students navigate the truss frame in front of the building, they can see the mobile scaffold supporting the installation of this truss frame. Students zoom in and see half of the mobile scaffold positioning on the level floor, while remaining half of scaffold is on a ramp, which has inclined plane. After double-clicking on an exclamation sign tagged on this scaffold (Fig. 8a), a new window opens up, showing the detailed description of working situation on the scaffold and the 1st question entitled "are there any hazards in this scenario?" (Fig. 8a). The student is required to answer by selecting Yes or No. If students answer incorrectly, a reply notification pops up announcing "WRONG ANSWER! MINUS SCORE" along with an audio alarm. Students are then required to re-answer the question until they finish this task with the right answer. After that, students move to the second multiple-choice question asking what types of hazards exist (Fig. 8b). Similar to the previous question, students can only move to the next once they have identified the right accident type. Thereafter, students answer the third multiple-choice question related to the root causes of accident and then move to the next step after answering these questions correctly.

All pop-up windows are then closed, and the students start to eliminate the identified hazard by interacting with the BAM. As illustrated in Fig. 9, a library on the left side of the BAM interface shows safety facilities (wedges, bracings) for hazard elimination, while a pop-up instruction window on the right side (Fig. 9a) instructs learners on how to eliminate the hazard. Following the instruction on the right window, students use their mouse to drag and drop the right safe facility to appropriate location in the virtual scaffold displayed in the centre screen of BAM. Firstly, students replace the steel plate underneath with a big wedge to balance the mobile scaffold and then add four bracings to secure it. If students choose the wrong safe facilities and place them in the wrong location in BAM, a notification will alarm learners, and ask them to redo hazard elimination task. Otherwise, a "hazard eliminated" notification (Fig. 9b) along with a congratulatory sound effect will be available to inform students that the hazard has been removed and the inspection task for the first hazard has been completed. To thoroughly understand the hazards as well as the accident prevention methods, students move to the next step of job hazard analysis (JHA). In this step, a pop-up window showing the JHA form is available for learners to fill in information regarding the safety regulation and prevention method



(a) (b)

Fig. 8 Hazard identification. **a** Hazard identification question, **b** hazard type multiple-choice question



(a) (b)

Fig. 9 Hazard elimination. **a** Before hazard elimination, **b** after hazard elimination

(Fig. 10). After completing this form, the right JHA form will pop up to show the right answers in red colour in order to help the learner understand the right OSHA article for compliance and the right prevention methods in order to prevent accident.

After inspecting the first construction hazard, students continue to navigate around the virtual building to investigate other potential hazards. When the six construction hazards assigned by the instructor are checked by the students, a “mission complete” notification informs them about the completion of the hazard investigation job. It is noted that the hazard identification and elimination are automatically recorded in order to help the students review their performance and support the educator in evaluating the students.

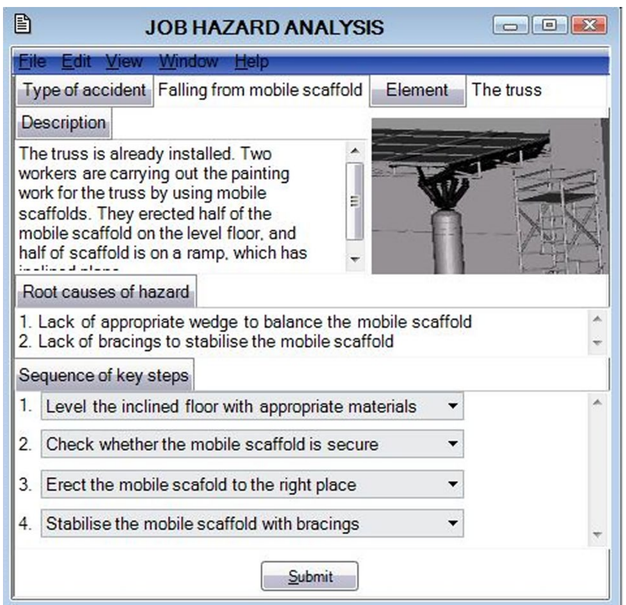


Fig. 10 JHA

4 Evaluation

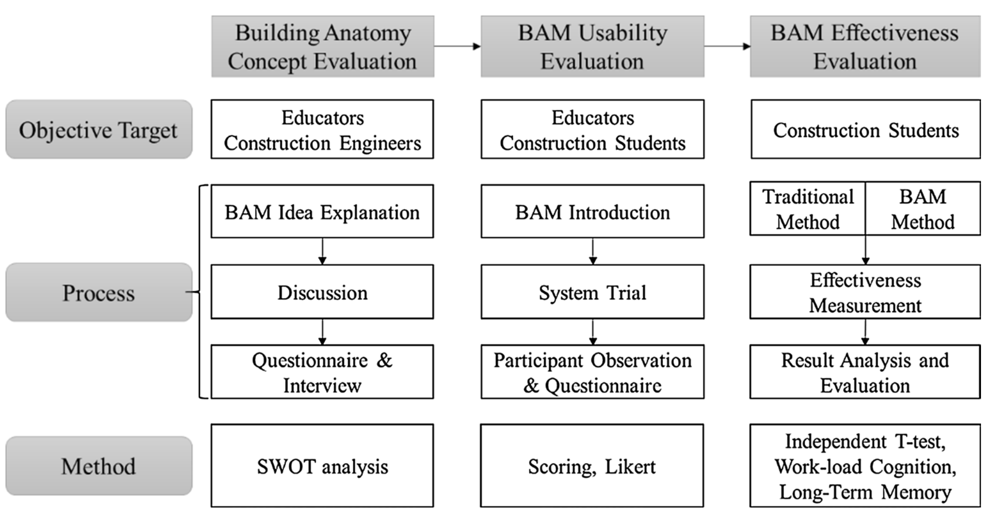
4.1 Evaluation process

In order to address the pedagogic effectiveness and limitations of the new education concept and the BAM system, an evaluation scheme was designed, comprising the following three phases: building anatomy concept evaluation, BAM usability evaluation and BAM effectiveness evaluation (Fig. 11).

Phase 1, BAC evaluation, focused on evaluating whether the new anatomy concept for construction safety education is innovative and whether it has pedagogic potential for construction safety education. Educators and construction engineers played a central role in identifying the applicability of the new concept through the strengths, weaknesses, opportunities and threats (SWOT) analysis method. Initially, the anatomy idea and the application method for construction safety education were explained in detail. Then, discussion sessions were held with educators and construction engineers in order to ensure the participants understood BAC. Subsequently, interviews with construction engineers and educators were conducted to identify the advantages and limitations of BAC for construction safety education.

Phase 2, BAM usability evaluation, was based on a system trial focused on accounting for educators’ and learners’ experiences in interacting with the BAM system. Phase 2 was concerned with the impact of the system; its constituent tools and functions; the Graphic User Interface (GUI); the system workflow; and overall user satisfaction. The usability evaluation was conducted with educators and students who directly experienced using the system prototype. The educator delivered a visually enhanced lesson on falling accidents based on accident scenarios through BAM and then explained how students can individually recognize and eliminate hazards within the interactive BAM environment.

Fig. 11 Evaluation framework



Students were then required to reflect on their safety knowledge and interactively identify and mitigate hazards, which could lead to accidents in BAM.

After a short break, the educator and the students answered questions about BAM usability according to the following criteria [5, 6, 15, 30]: (1) ease of use, i.e. focusing on learners comfort and how simple it is to execute tasks within BAM; (2) ease of navigation, i.e. considering how easily learners can navigate through system interfaces, tasks and functions; (3) intuitiveness of design, focusing on how well the workflow of the BAM system follows user's intended actions; (4) interactivity, considering how interactive the system features are; (5) capability in handling high detail and complexity of models; and (6) effectiveness in visualizing safety contents.

Phase 3, BAM effectiveness evaluation focused on objectively comparing the safety knowledge and skills of learners taught with traditional methods and the proposed BAM method. This approach involved assessing the baseline knowledge and skills level of learners in two groups and then assessing their safety performance following learning and instruction with the traditional and BAM approaches. Through this, the immediate and short-term impact of BAM on the acquisition of safety knowledge and skills can be evaluated. Furthermore, the workload cognition impacts of both approaches would be assessed, and 6 months after, long-term safety knowledge retention would be assessed.

4.2 Evaluation results

Table 3 presents a participant summary including gender and experience of all participants for the evaluation scheme of the proposed BAM system. As shown in Fig. 11, educators and engineers participated in BAM concept evaluation with a SWOT analysis, while educators and thirty-one construction students experienced the BAM system and evaluated its usability in terms of the aforementioned criteria. For the objective evaluation of BAM effectiveness, a paper-based test was carried out in a real class to measure the learning outcomes of 4th year construction students by randomly dividing the class into a BAM group of thirty-one students using the proposed BAM system for their learning and a group of thirty-one students following the traditional method (whiteboard lectures).

Table 3 Participant data

	Educator	Engineer	Construction student
Number of participants	8	7	31
Gender (male/female)	(7;1)	(6;1)	(26:5)
Experience			4th year undergraduate student
> 10 years	2	3	
5–10 years	4	3	
< 5 years	2	1	

In order to evaluate the BAC and BAM systems for construction safety education, interviews and discussions were conducted with eight educators (from Chung-Ang University in Korea and Ton Duc Thang University in Vietnam) and seven Vietnamese construction engineers. Face-to-face interviews, Skype interviews and web-based surveys were used to acquire feedback regarding the proposed concept. These interviews focused on the applicability of the anatomy concept for construction safety education. Interviewees stated that using BAC is innovative, and it greatly enhances current pedagogic processes for construction safety education. Educators also emphasized that the interactive anatomy features of BAM could actively engage learners, facilitate hands-on learning and drive them towards safety competency. In addition, the interviewees also emphasized that the variety of digital learning materials available would cater to diverse learning preferences and also make construction safety education more interesting and effective in delivering safety knowledge. A few quotes regarding the potential of BAM were provided as follows:

> I believe that BAC would bring a new way of learning for construction education as a whole, not only for construction safety. It could be effective for construction quality and structural engineering courses as well (Educator No.1);

> BAM seems to be a powerful tool with great potential to transform construction safety education. I think it can help to make complex construction safety content clearer, and easier to visualize. Not only at universities, but also in industry training and practice as well (Educator No.4);

> To date, the construction industry has not adopted any educational tool or system as interactive as BAM. I feel the BAM features could captivate and motivate students to learn about safety issues (Engineer No.1);

> This is definitely an innovative idea for construction education and training (Engineer No.3);

> I think the main benefit of this approach is the ability to easily integrate different types of safety resources. Students can access the type of learning materials they are most comfortable through this (Educator No.7).

Eight educators and thirty-one students participated in a hazard identification and elimination tasks and then evaluated the usability of the BAM system in terms of the aforementioned criteria. The subjects rated the usability criteria based on the statements provided, using a Likert scale with responses ranging from 1 (strongly disagree) to 5 (strongly agree). Preliminary results show that participants agreed that the BAM model is a powerful tool for construction safety education. As shown in Fig. 12, educators stated that the BAM model is very easy to use and has a high level of interactivity. They also considered the attaching and anatomizing features very detailed, and more interactive than any traditional pedagogic tool. Moreover, students emphasized that visualizations in BAM were significantly more engaging than the traditional material and tools currently used in universities. They agreed that the BAM approach is learner-centred; hence, it would actively hold learners attention during safety education. However, both learners and educators found navigation within the BAM environment a bit complicated; hence, the low score is shown in Fig. 12. In order to address this, educators recommended more instruction and guidance to assist students during learning activities within BAM. Participants considered the workflow within BAM environments intuitive and easy to follow. BAM visualizations ran smoothly, providing clear visualizations of components without glitches. However, the full-scale system with many models and scenarios would require the use of computers with high-speed central processing units (CPUs) and at least 2 GB of random access memory (RAM). Educators and engineers also raised concerns about the time required for model development and the immense storage capacity necessary for BAM contents.

In order to evaluate BAM effectiveness, an objective evaluation was conducted in real class settings with sixty-two undergraduate students to measure learning outcomes. Firstly, these 4th year construction students were randomly split into two groups—BAM group and traditional group. The proposed BAM method and traditional education were utilized to deliver construction safety knowledge to BAM and traditional groups, respectively. Afterwards, a paper-based examination (comprising 20 multiple-choice questions, with a total score of 100) related to safety lessons was carried out for all sixty-two construction students. Subsequently, an independent *T* test model was developed in order to determine whether there was a statistically significant difference between the score means in the two groups. The null hypothesis was that the score means from both educational methods are same, while the alternate hypothesis was that the score means from the two educational methods are significantly different. The 5% significance level was set to analyse the learning score of construction students by using SPSS20 statistics software. Table 5 represents statistical results of the Levene's test and the independent *T* test for the two educational approaches. As given in Table 5, the *p* value (0.223) of Levene's test for equality of variances is greater than the significance level of 0.05. It can thus be concluded that there is no difference in the variances between two groups. Therefore, the independent *T* test for equality of means is tested based on the homogeneity of variance. As given in Table 4, the mean value and standard deviation are (84.68 and 6.44) for BAM and (76.13 and 7.61) for the traditional approach, respectively. The *p* value of 0.001 is smaller than the significance level of 0.05 to reject the null hypothesis. Furthermore, the mean score of the BAM group is higher than the mean of the traditional group; therefore, it can be concluded that the proposed BAM system is more effective than the traditional method. In other words, learners studying in the class using BAM system had a higher score than those learning the traditional class based on whiteboard lectures. This objective evaluation partially proves that the proposed BAM system can improve construction safety education and help learners to effectively acquire construction safety knowledge.

Table 4 Group statistics

Paper-based test				
Education method	Number of students	Mean	Std. deviation	*p* value
BAM group	31	84.68	6.44	0.001
Traditional group	31	76.13	7.61	

5 Discussion and conclusion

Construction projects are consistently becoming more complex, requiring knowledgeable, highly skilled and competent professionals for their safe and timely execution. Tertiary safety education can play a vital role in promoting safety performance; however, current construction management curricula do not pay attention to safety aspects and conventional pedagogic teaching strategies and tools fail to actively engage students to acquire knowledge.

This study presents an innovative education system for construction safety, which integrates virtual reality and BAC to interactively deliver construction safety education. BAC was found to have major potential not only for safety, but also for construction education as a whole. A BAM prototype was developed and evaluated through system usability trials, user observations followed by discussions, and questionnaire interviews. A comparison between traditional pedagogy and BAM was carried out through learner tests in order to objectively evaluate the effectiveness of the proposed system. Thus far, results suggest that the proposed model can be an effective pedagogical tool to enhance teaching processes and students' knowledge acquisition on construction safety issues. The results of the study have shown that BAM for construction safety education is feasible and has significant benefits in terms of interactivity for learners over conventional methods. Despite the comparison between

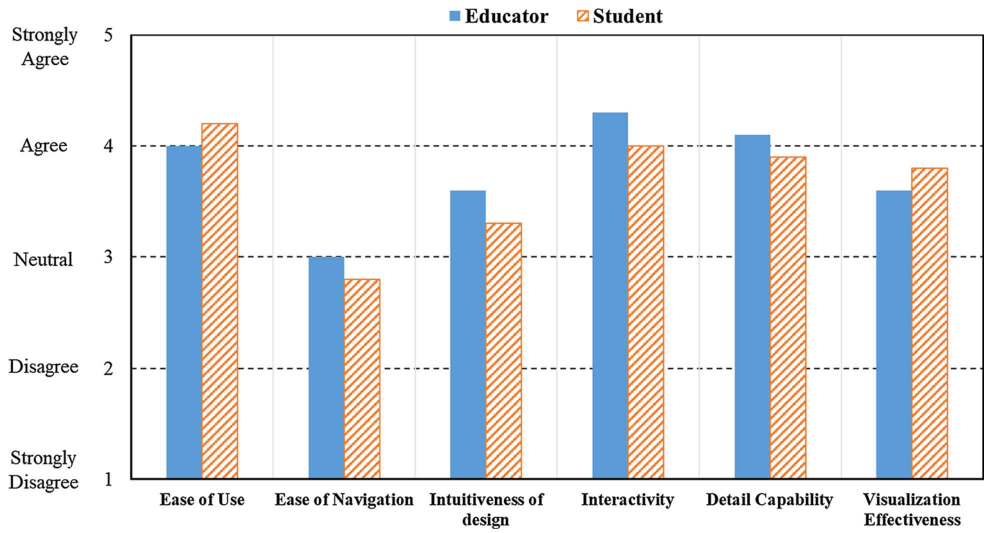


Fig. 12 Results of BAM usability evaluation

Table 5 Statistical results of Levene's test and independent *T* test

Independent samples test						
	Levene's test for equality of variances		*T* test for equality of means			
	F	*p* value	*t*	d*f*	*p* value (2-tailed)	Mean difference
BAM group						
Equal variances assumed	1.519	0.223	4.774	60	0.001	8.55
Equal variances not assumed			4.774	58.431	0.001	8.55

two educational approaches to objectively evaluate the BAM effectiveness, learners' knowledge needs to be assessed before and after their experience with BAM, in order to further validate and ascertain the impact of BAM on learning outcomes. Moreover, in order to comprehensively evaluate BAM effectiveness, future work will assess the long-term safety knowledge retention and workload cognition impacts of both educational methods with the full-scale system after 6 months. In addition, future developments will include intuitive features and a self-reported evaluation form, which will allow students to input their learning preferences and automatically receive learning resources based on their personal learning styles.

In order to reduce the complexity and time consumed in BAM content creation, it is possible to use the existing building information models (BIM) from past construction projects. In the current implementation, the process of linking related safety videos, documents and accident cases required the efforts of educators and content developers. However, given the recent advances in linked data, and the possibilities created by the industry foundation classes (IFC) data model, it is gradually becoming easier to automate the process of managing and delivering construction-related contents. Future research will consider implementing BIM, ontologies and linked data technologies with BAM in order to reduce complexities and automate certain aspects of the BAM content creation process. This could also address concerns regarding the modelling and programming costs for the full-scale BAM system. Considering the pervasive nature of mobile devices, the BAM system has the potential to provide any learner access to safety contents anywhere and at any time. In addition, the proposed system is extensible for use in the information-intensive construction industry; the BAM approach combined with ubiquitous computing and online technologies could support digital access to safety information anywhere and anytime. Future work will also consider the anatomy model in conjunction with augmented reality (AR) and cloud computing for enhancing communication and information accessibility in the construction industry.

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