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Energy-Efficient Learning System Using Web-Based Panoramic Virtual Photoreality for Interactive Construction Safety Education

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Abstract: Construction safety education plays a crucial role in improving the safety performance in the construction industry. Many research works have successfully adopted computerized three-dimensional model-based virtual reality (3D-VR) to provide students with adequate safety knowledge and skills before they enter construction sites. Despite the advantages of improving learning outcomes, 3D-VR has limitations not only in reflecting real-world visibility but also in consuming significant energy and requiring strict user–device compatibility. Therefore, this research methodology was initiated with a thorough investigation of VR application in construction safety education. On the basis of a literature review, the study subsequently analyzes the energy-consumption problems of conventional VR systems. Initial findings motivate the development of an energy-efficient learning system (the interactive constructive safety education (eCSE)) using Web-based panoramic virtual photoreality technology for interactive construction safety education. The eCSE system provides three key interactive modules, namely, lesson delivery (LD), practical experience (PE), and knowledge assessment (KA), for use in mobile devices. The trial system has been developed and validated through scenarios derived from real construction sites. The preliminary evaluation reveals that the eCSE system not only overcomes the 3D-VR limitations in terms of energy efficiency, user device adaptability, and easy implementation, but also improves learning usability.

Keywords: energy efficiency; construction safety education; virtual reality; virtual photoreality

1. Introduction

Construction safety education is of significant importance to improve safety performance in the construction industry. Safety education at the tertiary level plays a crucial role in providing concrete knowledge and safety skills for students [1] before they enter a jobsite, so that they can safely perform construction work. However, safety curricula have not been given much attention in universities. In fact, some programs entirely exclude safety education in their courses (in South Korea and Vietnam, for instance, where there are no standalone safety courses), while some programs offer short safety courses that tend to be taught in isolation [2]. This could be explained as a result of the fact that safety issues are often considered to be of lower priority [3] than quality, cost, and scheduling aspects in the construction industry [4]. Similarly to construction education at the tertiary level, learners are taught by focusing on various construction methods, theories, and techniques for effectively managing quality, cost, and scheduling [5], while safety topics are often overlooked. Consequently, construction graduates lack the adequate knowledge and ability to address dangerous situations and inspect hazards in order to avoid accidents [6]. To overcome these issues, many researches have focused on applying virtual reality (VR) technology for improving construction safety education. VR provides an interactive platform for learners to experience virtual construction sites [7]. In a VR environment, students play an active role in recognizing and inspecting potential hazards [8,9]. Through this, they can acquire safety knowledge and develop skills [10]. Furthermore, learning using VR motivates and engages construction students in their learning.

VR has proved to be advantageous in improving the learning outcomes for construction safety. However, there is a lack of research on the energy-efficiency aspect of VR application. Most conventional VR systems run on standalone platforms, which require high-performance device configuration because of the utilization of three-dimensional (3D) modeling (i.e., 3D model-based VR (3D-VR)). For instance, the power analysis performed by Mochocki et al. [11] revealed that 3D rendering and geometry operations consume energy in linear and exponential proportions with the display resolution and model complexity, respectively. In comparison, Miettinen and Nurminen [12] showed that mobile graphic applications (e.g., games and 3D models) have, on average, 6–8-fold higher computational complexity than presentation applications (e.g., Web browsers), resulting in 7–10-fold higher energy consumption. In addition, Web-based applications that work on a Web browser have showed more efficient performance compared to native applications in terms of many aspects, such as platform independence, low complexity, energy efficiency, and easy maintenance [13]. Therefore, a Web-based VR platform has been considered as a potential candidate to improve not only the construction safety learning usability, but also the energy-efficiency aspect.

In response to this status quo, this paper proposes an energy-efficient learning system for interactive construction safety education, referred to as eCSE. This system utilizes Web-based panoramic virtual photoreality technology that consists of three key learning modules, namely, lesson delivery (LD), practical experience (PE), and knowledge assessment (KA) modules. It provides an interactive learning environment for students to acquire concrete knowledge and develop safety skills. Because it is a Web-based platform, eCSE consumes less energy than conventional VR systems, for which the mobile user devices have to handle all the workload. To validate the advantages and limitations of the proposed system, a prototype was developed using virtual scenarios derived from real construction accidents. An evaluation scheme is proposed to prove the energy-efficiency aspects of eCSE in comparison with the conventional 3D-VR system, as well as to improve learning usability. The preliminary results indicate that eCSE is a powerful and energy-efficient learning tool that can improve construction safety education.

2. Research Methodology

As illustrated in Figure 1, the study was initiated with a thorough investigation of VR application in construction safety education. The literature review (Section 3) points out safety education problems and the state-of-the-art VR systems for improving construction learning. Subsequently, Section 4 analyzes the energy-consumption problems of conventional VR systems. The initial findings motivated the development of an energy-efficient learning system (eCSE) for interactive construction safety education (Section 5). To implement the pilot system, two virtual prototypes (eCSE and 3D-VR) were developed, portraying falling hazards that had the highest rate of occurrence in the construction industry. After this, both system trials were carried out with educators, safety engineers, and construction students in order to evaluate the learning-function and resource-consumption aspects of the proposed system. Finally, discussions and conclusions are provided to point out the advantages and limitations of the proposed system, as well as future work recommendations.

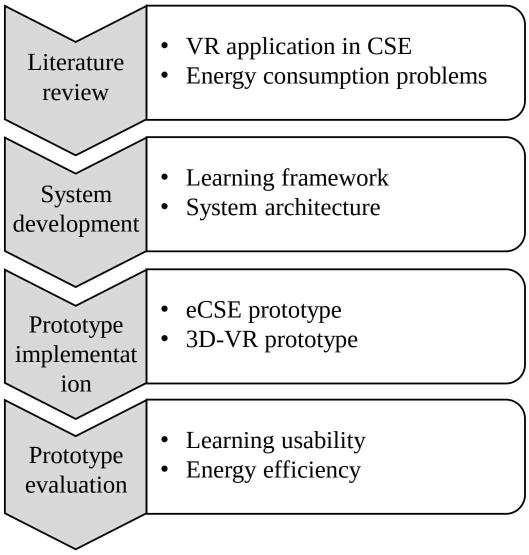


Figure 1. Research methodology.

3. Virtual Reality Application in Construction Safety Education

With the emergence of visualization technology, VR is considered a powerful tool for improving construction safety education. VR refers to computer-generated 3D models that simulate realistic construction scenarios for interactive and experiential learning. Through the VR platform, students can visualize construction jobsites and easily learn about safety issues in a safe environment. Scholars have investigated the potential and applicability of 3D modeling and VR for construction education [14]. For example, Pham et al. [1] adopted the VR-based building anatomy concept, which is borrowed from the medical discipline, to improve construction safety education at the university level. Teizer et al. [15] presented a novel approach for integrating location-tracking and data-visualization technology to advance construction ironworkers' education and training in terms of safety. Furthermore, many interactive 3D-VR game-based platforms [8,16,17] have been developed, in which learners play an active role as a safety manager to inspect potential hazards and acquire safety knowledge. Scholars have proven the effectiveness of 3D-VR application for improving safety learning and training outcomes [18,19].

In addition, the advantages of 3D-VR application are learners' motivation and engagement. With regard to traditional safety education, many studies have pointed out that the current construction safety pedagogy follows a lecture-based method, which takes place in hands-off off-site environments, leading to a lack of motivation and engagement of students [2]. Students often inactively listen and watch safety lectures delivered by the educator, without any interaction or experience [9]. Failing to provide hands-on experience negatively impacts construction safety learning [20]. To overcome the limitations of the conventional passive safety pedagogy, 3D-VR systems provide an interactive learning platform in which students can interact with and experience a virtual construction site to acquire knowledge. By providing hands-on experience, 3D-VR methods motivate and engage learners in their learning [5]. The innovative 3D-VR adopts a learner-centered educational approach, which is proven to be more effective than a passive approach [21]. However, literature studies reveal that energy-efficiency aspects have not been considered as the main constraint in developing the VR-based systems.

4. Energy Consumption Problem Statement

From a technical perspective, the drawbacks of 3D-VR technology are mainly related to the energy consumption and intensive computation, as described in Section 1. These issues are severe, particularly on mobile device applications, where the equipped battery has capacity constraints [22]. As described in [23], the operation of an application results in the generation of multiple workloads. We let $\mathcal{A}$ denote the workload set of the application. The ith workload is characterized by its identification vector $\vec{l}_i$, which is given by

$$\vec{l}_i \triangleq \langle d_i, c_i \rangle \,, \tag{1}$$

where d_i and c_i are the size (in bits) and complexity (in computing cycles per bit) of the ith workload, respectively. In addition, the weight of the ith workload (i.e., λ_i) is given by

$$\lambda_i = d_i \times c_i. \tag{2}$$

Accordingly, the energy consumption $\mathcal{E}$ for application execution is determined by

$$\mathcal{E} = \kappa f^2 \sum_{\forall i \in \mathcal{A}} \lambda_i, \tag{3}$$

where f and κ are the operational central processing unit (CPU) frequency and coefficient factor of the mobile user device, respectively. The mathematical energy-consumption expression demonstrates a proportional dependence of $\mathcal{E}$ on the total weight of application workloads. Moreover, many studies, such as [12,24], have concluded that 3D-VR applications possess huge weights as a result of their computational complexities, resulting in considerable energy consumption.

On the contrary, our literature review revealed that Web-based applications achieve low energy consumption as a result of their on-demand and low-complexity features. The rationale behind this is that almost all of their heavy workloads are offloaded and performed remotely in the central server side [25,26]. In addition, the recent emergence of mobile edge/cloud computing technologies has provided effective cloudized computation infrastructure to promote the Web-based application approaches [27–29]. Therefore, Web-based applications are highly considered as an appropriate approach towards an energy-efficient solution for construction safety education.

5. Energy-Efficient Construction Safety Education System

5.1. Learning Framework

Figure 2 depicts the eCSE framework for construction safety education, which shifts from the traditional learning approach to a new interactive educational approach. The eCSE framework includes three modules, namely, LD, PE, and KA modules. The eCSE system applies an innovative Web-based panoramic virtual photoreality, with the aim to develop an energy-efficient learning platform.

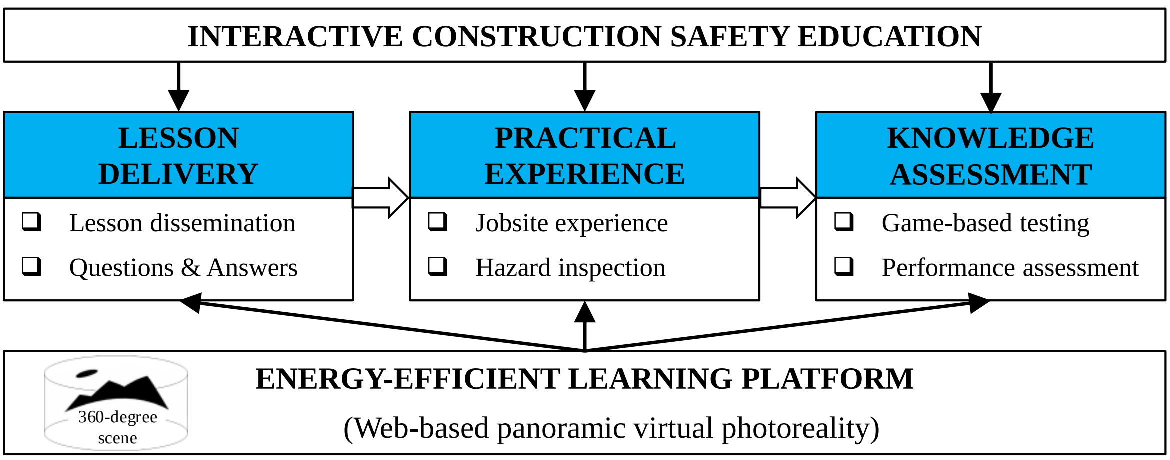


Figure 2. Interactive constructive safety education (eCSE) learning framework.

The LD module aims to deliver safety information and lessons to learners. LD represents the entire LD process, whereby educators disseminate safety lectures to students through an interactive platform. Firstly, the users log into the system and then click on the LD function to initiate learning. After this, with the educator's guidance, the students open the safety lecture slide that introduces safety information and issues, which closely relates to a virtual construction jobsite that they will experience in the next PE module. The educator can connect their own device with a projector to show the lesson on a large screen for teaching in a classroom. Furthermore, for those who cannot attend the class, the slide will include the teaching audio from the educator in order to help learners follow the safety lesson. During the lesson, students can partake in "question and answer" activities with the educator and their classmates through an online chatroom. Besides chat-text, the chatroom permits users to upload other safety e-materials (links to images, videos, animation, and documents) to provide comprehensive information of the safety issues raised during the lessons. This open discussion ensures that learners thoroughly understand the safety lesson and issues taught by the educator before moving to the next step.

The PE module focuses on providing practical experience to the students by enabling them to investigate virtual construction jobsites. Following the educator's instruction, the students click on the PE function and then choose a virtual high-rise building for jobsite experience. To navigate a virtual jobsite, the students follow the building menu, which is classified according to the floors (level 1) and functional rooms (level 2) of the building. The students play the role of a safety manager to identify dangerous situations, which are represented by hotspots in the virtual building. A hotspot includes safety information and e-materials related to hazardous scenarios in order to assist learners in recognizing potential hazards. For example, when clicking on the video function of a hotspot, a video demonstrates the construction process, providing the students with a brief understanding of the dangerous situation. After this, they are required to click on the construction hazard investigation function of this hotspot to open templates, which represent potential hazards in the dangerous case being investigated. As shown in Figure 3, a construction-hazard investigation template describes the type of accident, the context, root causes, and a prevention method to avoid accidents. Furthermore, links to the safety-course e-materials, multimedia resources, and the Occupational Safety and Health Administration (OSHA) standards are embedded in this template in order to assist learners in clearly understanding the hazard that is being investigated. During hazard identification, the learner can discuss with the educator and other online learners through the chatroom until they thoroughly understand all the potential hazards of the dangerous case. The students are required to investigate other hazardous scenarios in the virtual high-rise building by themselves in order to consolidate their safety knowledge.

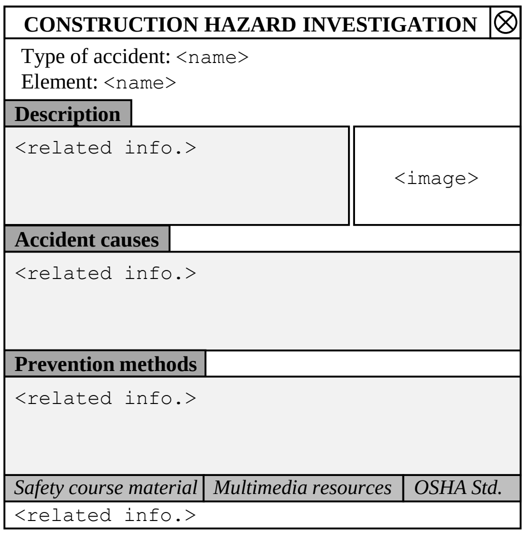


Figure 3. Construction-hazard investigation template.

The KA module is designed to assess the safety knowledge students have obtained from the previous modules. Through game-based testing, KA requires students to apply their safety knowledge and skills for inspecting potential hazards. The students initiate the test by clicking on the KA function of the eCSE system and choose a testing simulation game for investigating a virtual construction jobsite. They can easily navigate the building jobsite by using zoom-in, zoom-out, and rotate functions in the KA module. After identifying a potential hazard, the students are required to answer questions to finish the job hazard analysis (JHA) report. These JHA questions include questions related to accident type, context description, root causes, and prevention methods to avoid accidents. After correctly identifying the hazard and finishing the JHA report, the students continue to investigate other potential hazards. Because of the significant importance of hazard identification skills for preventing accidents in the construction industry, the students cannot move to the next step if they have not accurately identified all the hazards in the current step. The eCSE system automatically records the game-based testing performance for assessing the safety knowledge and skills of learners.

5.2. System Architecture

Because the eCSE system was developed by adopting a Web-based application approach, an advanced three-tier architecture [30] was utilized for the central server, so that multiple mobile user devices can access eCSE services through a communication network by using their built-in Web browsers; see Figure 4. The three tiers of the central server architecture are as follows:

- *Tier I (Web server):* Performs Web layout and format services by adapting to various display resolutions of the mobile user devices. This tier uses the standard Hypertext Transfer Protocol (HTTP) to ensure reliable communication with various built-in Web browsers in the user devices for user interface adaptation and interaction services.
- *Tier II (Application server):* Provides core services, including photoreality integration and plugins such as multimedia, hyperlinks, interactive popups, and materials, in a unified framework. The services in this tier exploit information in the database, process the data, and return it to the Web server.
- *Tier III (Database server):* Supports data access and management services that are scalabilized on the basis of the number of user associations and the level of data usage. The stored data includes jobsite images, plugins' content, user information, and system logs.

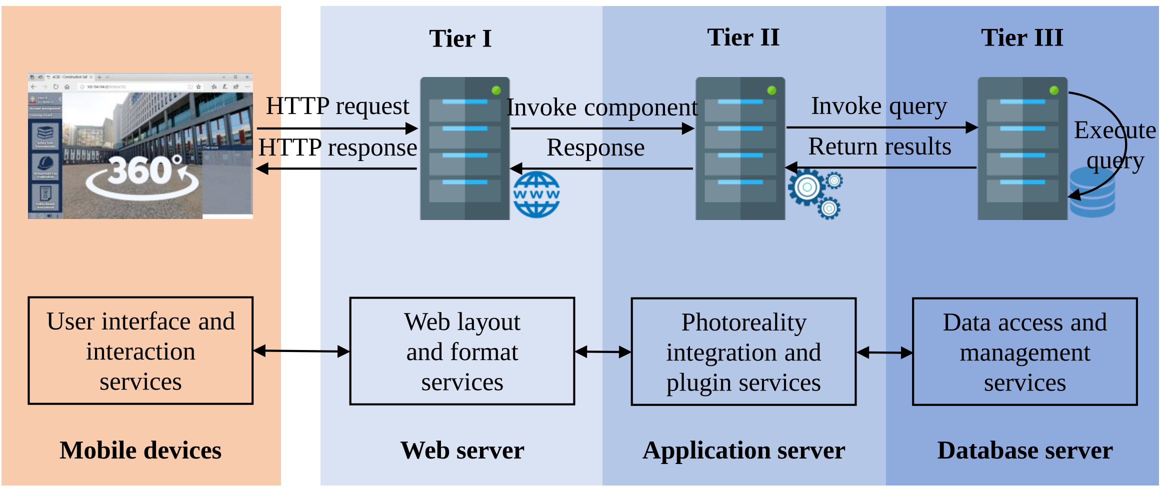


Figure 4. System architecture development.

The system workflow is as follows. First, when either the Web browser initially starts to access the eCSE services or the users interact with the eCSE Web application, corresponding HTTP requests are sent to the Web server in tier I. The Web server handles all the Web layout and content presentation requirements by itself (e.g., layout and font-size adaptations depending on whether the device has a mobile, tablet, or laptop display). For other requests, which require the remaining eCSE functions, the Web server invokes the respective components from the application server in tier II. For instance, jobsite projection and scene-linking hotspot cooperation must be processed by their specific algorithms in order to obtain proper results. The required information is loaded from the database server in tier III by appropriate data query actions.

6. Trial System Implementation

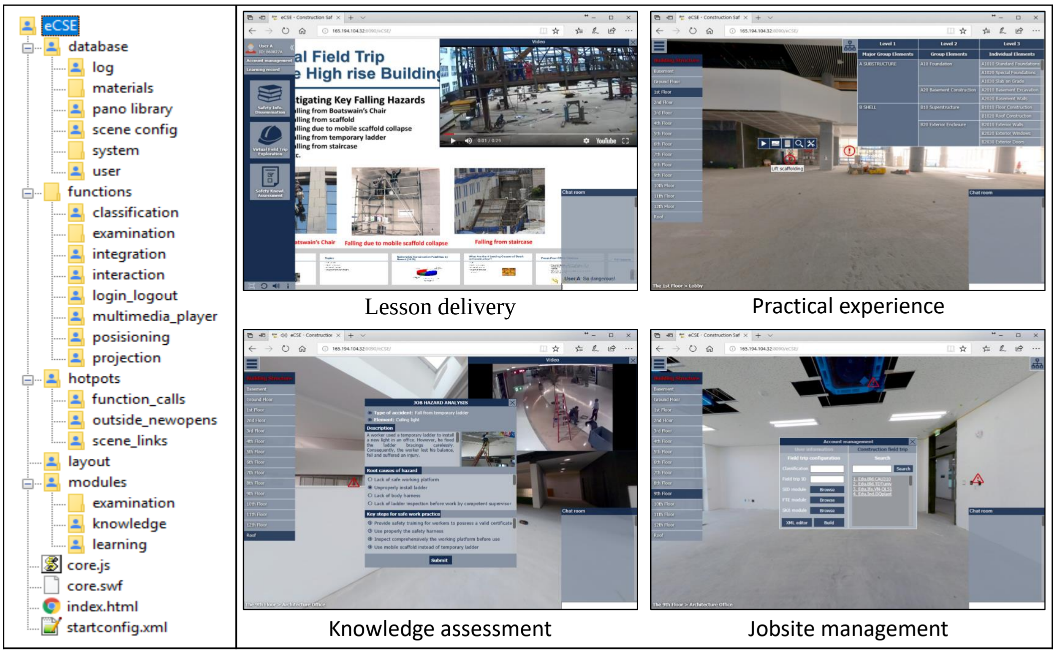
6.1. eCSE System Setups

In order to examine the advanced features of the eCSE framework, a trial system was developed, where krpano [31] was utilized as the integration engine because of its openness, stability, and adaptability in supporting a mobile environment. Although krpano supports both the Adobe Flash and Hypertext Markup Language version 5 (HTML5) Web programming languages for a broad application in not only new devices but also old devices, HTML5 is prioritized by default to provide the best features and performance [32]. To be considered as a component of the HTML5 language family, Cascading Style Sheets version 3 (CSS3) beautifies the user interface and content presentation in the eCSE Web application to generate a friendly workspace (e.g., automatic layout adaptation). Moreover, JavaScript standardizes the subroutines to handle the input/output to/from main functions of the integration engine as well as the extended plugins (e.g., to obtain the system time and assign it to the examination timer plugin). In addition, Extensible Markup Language (XML) is used for variable modification to customize the effects of these functions (e.g., to change auto-rotation speed).

As specified by krpano, two 360° panoramic formats, namely, *cube* and *equirectangular* formats, are used by the image slider droplet to generate a 512 × 512 pixel image piece library. These supported formats are rendered through two steps: (sub)scene capturing and 360° panorama adjustment (stitching and tuning). Because these are beyond the scope of this paper, descriptions of these steps are omitted; detailed information can be found in [33,34]. For the study, professional equipment (Samsung Gear 360 [35]) was used, which automated the 360° panorama rendering processes to obtain jobsite scene photos.

The software structure of the trial system is depicted in Figure 5. Briefly, the trial system includes the following main features:

- A *360° jobsite scene projection* reproduces the captured jobsite environment in a 360° view on the mobile displays.
- *Hotspot positioning* locates dynamic points in every scene to open functions or links to the specified scenes.
- *Multimedia integration* provides additional information sources directly in the workspace.
- *Construction object classification* provides a systematic view and comparison of the construction objects in the jobsite.
- *Interactive exploration* supports multi-level object exploration to obtain information step-by-step.
- The *chat room* displays rich-content conversations among educators and learners.
- *Examination* creates and manages exams for learners on the basis of the virtual photoreality environment.
- Other functions include the system monitor, user management, and database access control.



(a) (b)

Figure 5. Interactive constructive safety education (eCSE) pilot system: (**a**) software structure; (**b**) screenshots.

6.2. 3D-VR System Setups

In order to compare the advantages and limitations of eCSE and 3D-VR systems, a 3D-VR prototype was developed, derived from real accident cases during the construction of a high-rise building as the eCSE prototype models. Firstly, Revit Architecture 2014 software was used to create 3D-VR high-rise building models. After that, the Okino PolyTrans 64 tool was utilized to import the 3D-VR models, and then these models were converted to the NGRAIN Producer Pro 5.1 environment [36] in order to establish the 3D-VR prototype. Moreover, MySQL functions play a supporting role of the database to store digital safety materials, standards, multimedia resources, visualization models, and students' profiles. Lastly, the 3D-VR prototype was encoded to support learning activities, focusing on enhancing learner–instructor–model interaction and engagement, as well as creating game-based tests to assess learners' safety knowledge.

The hardware configuration for the trial system implementation is described in Table 1. To ensure fairness between the 3D-VR and eCSE frameworks, one user device (i.e., a consistent hardware configuration) was used for all evaluations. It is worth noting that the 3D-VR framework is a standalone model, while the eCSE framework is a client–server model. Hence, without specification, all the evaluation results of the eCSE framework combined both client and server performances.

Table 1. Trial system configuration.

	eCSE	**3D-VR**
CPU	Intel Core i7-870 @ 2.93 GHz	Intel Core i7-870 @ 2.93 GHz
RAM	8 GB	8 GB
OS	Windows 7 Home Premium x64	Windows 7 Home Premium x64
Web server	krpano testing server [31]	MySQL
Client software	Internet Explorer 11	NGRAIN Producer Pro 5.1 [36]

6.3. Use Cases

After the system setup stage, the trial system was used by educators and fourth-year students in a building construction class. A virtual high-rise education building consisting of 14 floors and 3 basements was chosen for construction jobsite investigation and safety learning. The OSHA reveals that falling from heights has the highest rate of occurrence among the "fatal four" accidents related to construction [37]; therefore, the falling-from-heights topic was chosen for the trial system.

Firstly, the educators and students log into the trial system and then click on the LD function to start the safety lesson. The educators deliver the slide, which introduces building safety information and key falling hazards that often occur in the type of building construction studied. After understanding the safety issues related to the virtual building, the students begin to navigate and experience a virtual construction site by clicking on the PE function. With the educator's guidance, the students investigate cases of falling from heights in a high-rise education building to acquire safety knowledge. Finally, the students are required to play a testing simulation game using the KA function in order to assess their safety knowledge and skills.

7. Experimental Comparisons

In order to determine the effectiveness of the pedagogy and energy-efficiency aspects of the proposed eCSE system, an evaluation scheme was devised, which comprises functional evaluation and technical evaluation, as depicted in Figure 6.

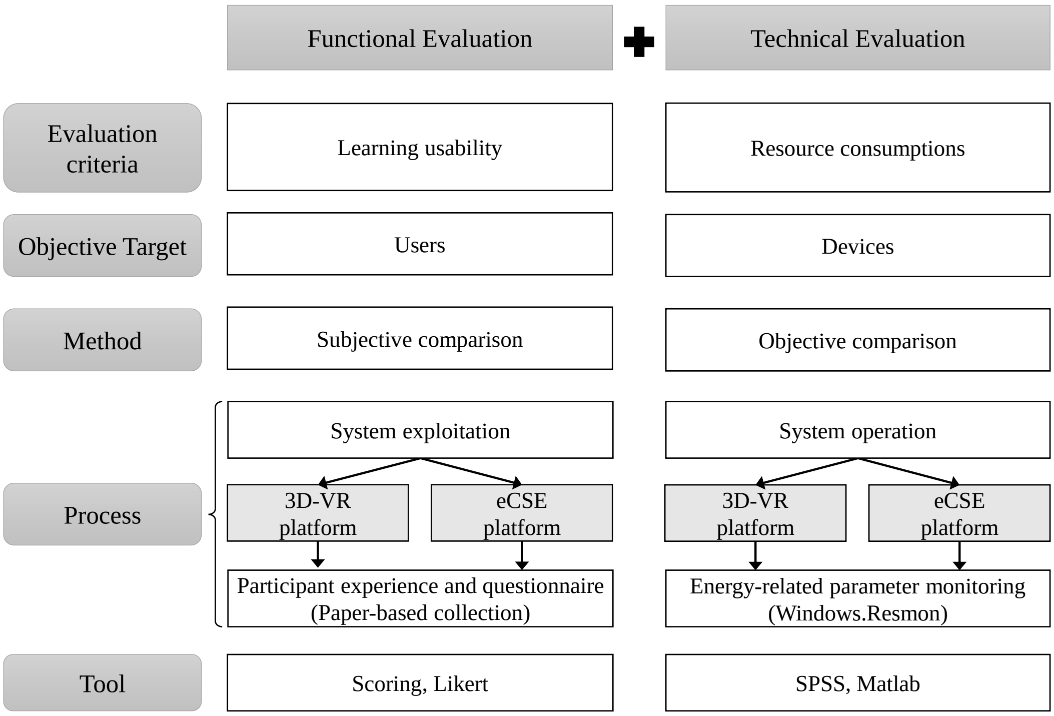


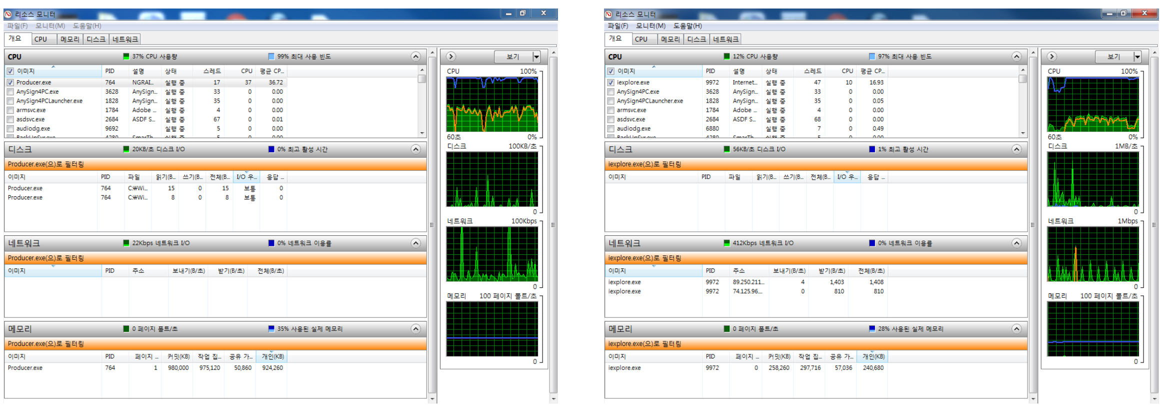
Figure 6. Evaluation scheme.

From a functional perspective, learning usability is evaluated subjectively after users experience two different safety learning platforms, such as 3D-VR and eCSE. The building construction class is divided into two groups of students. The first 30 students are required to learn using the 3D-VR NGRAIN platform [36], while the remaining 30 students are required to learn by using the eCSE platform. Both groups of students investigate similar virtual high-rise building jobsites to identify potential hazards of falling from heights. After learning, the users are interviewed, and a learning usability evaluation is performed according to the following criteria [1,2,9,38]:

1. *Ease of use*: Focuses on how easily users can navigate the virtual construction jobsite through the proposed system.
2. *Comfort of jobsite experience*: Considers the users' comfort during practical experience with the learning platform.
3. *Effectiveness of visualization*: Considers how well the system visualizes safety aspects.
4. *Interactivity with the virtual environment*: Focuses on how interactive the system functions are.
5. *Motivation and engagement* of users in learning construction safety.

In addition, 10 educators (from Chung-Ang University in Korea and Ho Chi Minh City University in Vietnam) and 10 Vietnamese construction engineers were interviewed after they used these systems. Discussions were conducted with all the participants, and they were required to provide a learning usability score based on a Likert scale, with scores ranging from 1 point for "strongly disagree" to 5 points for "strongly agree". A subjective comparison between 3D-VR and the proposed eCSE platform was conducted to evaluate the pedagogy effectiveness of the proposed system.

From a technical perspective, resource consumption was evaluated by monitoring the cumulative energy consumption (unit: joule), power usage (unit: watts per sample), memory usage (unit: byte), and CPU usage (unit: percent) metrics that the 3D-VR and eCSE systems utilized. In order to ensure fairness between these competing systems, the evaluation was performed by conducting 30 min system operations on the same user device configurations (as shown in Table 1) with each evaluated system. The monitoring data was collected by using the built-in Resource Monitor utility (namely, Resmon.exe) in the Windows 7 OS; see screenshots of Resmon monitoring results in Figure 7. An objective comparison was done on the monitoring data by using SPSS statistic [39] and Matlab visualization [40] tools.



(**a**) (**b**)

Figure 7. Screen captures of Resmon monitoring. (**a**) Three-dimensional model-based virtual reality (3D-VR) framework evaluation; (**b**) interactive constructive safety education (eCSE) framework evaluation.

7.1. Functional Evaluation

Figure 8 shows functional evaluation results for the 3D-VR and eCSE systems. Preliminary results proved that eCSE is a powerful pedagogy tool for improving construction safety education. Some quotes regarding the proposed eCSE system are provided below.

- "*I believe that eCSE would be [an] effective learning tool not only for construction safety education, but also for construction education as a whole. I think this innovative learning method can support construction quality and structural engineering courses as well.*" —Educator No. 2

- *"The eCSE seems to be a powerful tool to transform construction safety education. I think it can assist users easily to visualize and navigate virtual construction jobsites. The eCSE can adapt not only at universities, but also in industry training."* —Educator No. 5
- *"I think the main benefit of [the] eCSE system is the ability to easily integrate and access different types of safety resources. Students are most comfortable through this."* —Educator No. 9
- *"The construction industry has not adopted any learning system as interactive as eCSE. I believe the eCSE features could captivate and motivate learners to learn about safety topics."* —Engineer No. 1
- *"It is definitely an innovative idea for construction education and training. I believe eCSE would bring new way of construction learning at anytime and anywhere."* —Engineer No. 6

The participants agreed that both the learning systems were easy to use and the system features were designed for convenient interaction with the virtual environment. Furthermore, the students emphasized that both the interactive learning systems strongly motivated and engaged them in learning safety issues. With regard to the effectiveness of visualization, the users pointed out that the eCSE system visualized a real-world construction jobsite better than the 3D-VR platform. From a user perspective, panoramic virtual photoreality can provide a more realistic view of a virtual construction jobsite than the 3D-VR technology. Hence, the users felt more comfortable during the jobsite experience with the eCSE system than with the 3D-VR platform.

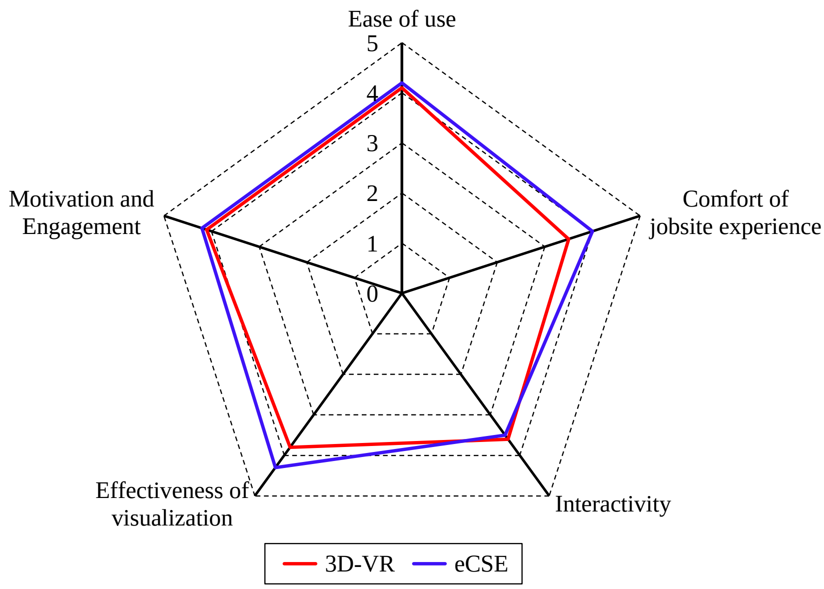


Figure 8. Functional evaluation results.

7.2. Technical Performance

Figure 9 illustrates the cumulative energy consumptions of the 3D-VR and eCSE systems over the 30 min experiment duration. A numerical analysis of the results showed that the 3D-VR system consumed a total of 177.32 kJ during that time, which was 38.27% greater than the total consumption of the eCSE system (128.24 kJ). According to the tracking information of system resource utilization provided by Resmon, the energy consumption mainly depended on the CPU usage, memory storage, and data acquisition. Both these systems consumed greater energy during the initial time, while a differential between their energy consumption was obtained during the operational time. More particularly, the 3D-VR system required significant energy for 3D model handling (e.g., drag-n-drop, zoom-in/out, and rotation), while the eCSE system used almost all its energy for on-demand actions such as image loading and multimedia executions when the corresponding point of view was changed for the first time. In other words, low-complexity and on-demand VR rendering results in energy-efficiency improvements of the eCSE compared to the performance of 3D-VR.

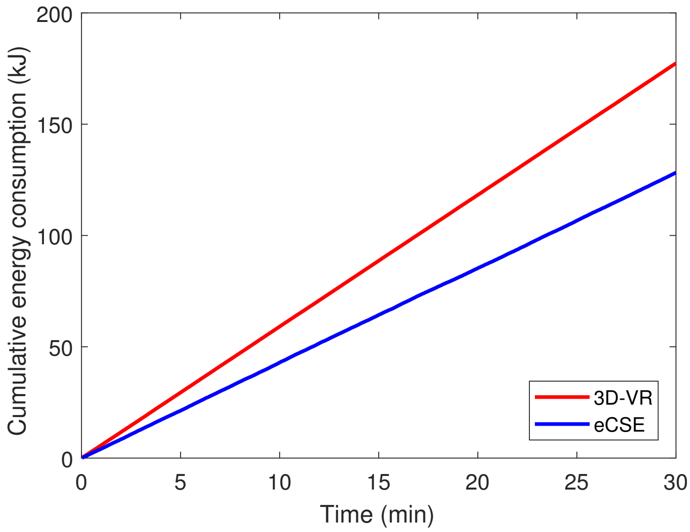


Figure 9. Cumulative energy consumption over the 30 min experiment duration.

The box plot in Figure 10 shows the power usage diversity among 1000 monitoring samples in these evaluated systems. The advantages of the eCSE system are 3-fold:

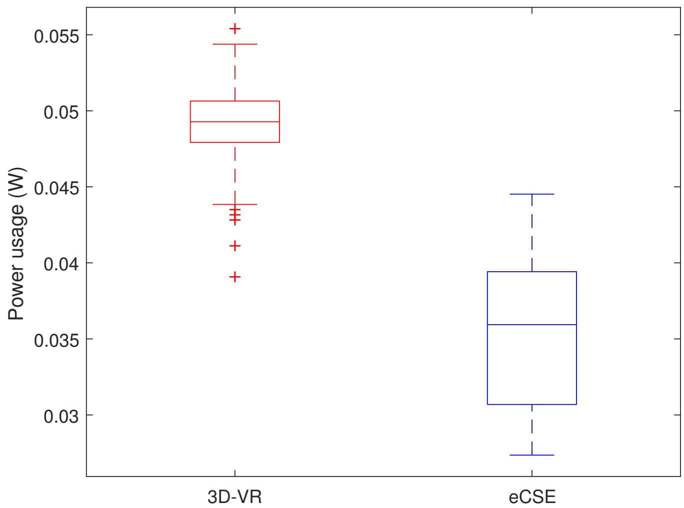


Figure 10. Power usage.

- A larger size of the box for a system indicates better diversity of power usage. The system power usage for eCSE had a larger box size as a result of on-demand power utilization according to user activities. On the contrary, the 3D-VR system's power usage had a smaller box size, as the system loads the entire 3D modeling data and functions during all times. When the user interacts with a feature, additional executions increase the power usage. The statistical analysis showed that the 3D-VR and eCSE results achieved standard deviations of 0.001798 and 0.0047527, respectively; see Table 2.
- The average value of power usage revealed that the eCSE operation used a smaller amount of power (i.e., 0.027 W) than that of the 3D-VR (i.e., 0.039 W). This is because the eCSE system (i)

performs on-demand response to react to user activities, and (ii) utilizes an image-based VR projection method for scene rendering.

- The 3D-VR's box-plot had many outliers that indicate instability and peak times at which the system showed abnormal behavior. On the other hand, the eCSE system did not have these issues.

Table 2. Descriptive statistics of power usage (W) by using SPSS tool.

	Mean	Minimum	Maximum	Std. Deviation
3D-VR	0.039	0.055	0.049	0.001798
eCSE	0.027	0.045	0.036	0.004753

Figure 11 depicts the memory usage of the evaluated systems. The memory usage includes both virtual memory (which the OS assigns to run the systems) and physical memory, consisting of private and shareable memories (which the systems utilize during operations). Numerical results showed that the 3D-VR system utilized approximately {976, 920} GB of {*virtual*, *private*} memories, which was {3.75, 3.87} times greater than the memory utilization of the eCSE system (approximately {261, 238} GB). In addition, the shareable memory used by the 3D-VR system was 42.73% less than the memory used by the eCSE system. In summary, the eCSE system utilized dynamic and much less memory than the 3D-VR system.

Figure 12 shows the timeline of the CPU usage metrics collected during the 30 min operation. The average CPU utilizations of the 3D-VR and eCSE systems were 41.93% and 20.27% (recalling that the CPU was a 2.93 GHz quad-core), respectively. As mentioned in the previous analysis, the main reasons for these achievements were on-demand response and the image-based VR projection method implemented in the eCSE system.

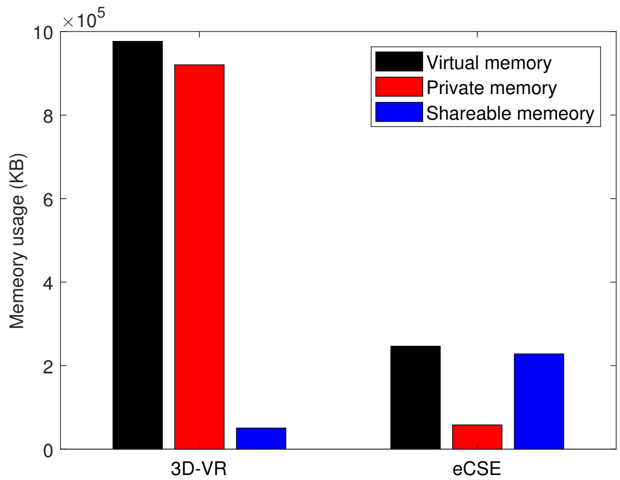


Figure 11. Memory usage, including virtual memory and physical memory (private and shareable memories).

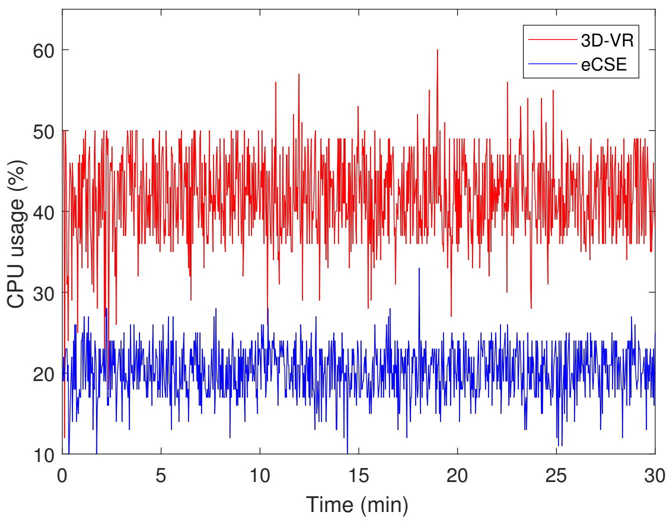


Figure 12. CPU usage over the 30 min experiment duration.

8. Discussion and Concluding Remarks

This paper proposes an energy-efficient learning system (named eCSE) using Web-based panoramic virtual photoreality technology for interactive construction safety education. The eCSE system consists of three key modules, namely, LD, PE, and KA, focusing on mobile experience. Both functional and technical evaluation results revealed that the eCSE system not only overcomes the limitations of 3D-VR in terms of energy efficiency, user device adaptability, and easy implementation, but also improves almost all other aspects of the learning usability. To evaluate learning outcomes, future work should conduct an objective comparison between students' paper-based examinations after learning with the full-scale eCSE and 3D-VR systems for comprehensively evaluating the effectiveness of the proposed systems.

In order to implement eCSE, a building environment faculty needs information technology (IT) experts who have technical expertise in Web-based application development, particularly in the VR framework, for developing the Web-based photoreality platform. For didactic content, educators with a comprehensive construction industry and professional safety knowledge in various types of construction projects (such as buildings, roads, bridges, infrastructures, plants, etc.) are necessary. These educators play a crucial role in designing safety education content, jobsite investigation, and hazard-inspection experiences to educate learners, as well as game-based testing to assess their safety knowledge. Afterwards, the educators can initiate and set up eCSE with the IT experts' support at the beginning. Subsequently, the educators and admins can easily utilize the system without support from IT experts, as eCSE enables educators or admins to upload and manage new virtual construction scenarios as well as e-materials through functions of construction site management.

The trial system implementation and evaluation results reveal that a 3D-VR scene takes much effort to be programmed and built, particularly for completing a 3D-VR model, and cannot obtain real-world visibility. By contrast, photoreality technology makes it easy to overcome these issues. That is, a photoreality scene can be captured by a portable device (e.g., Samsung Gear 360) by one-click action, and the captured scene presents the real-world view well. Furthermore, the recent proliferation of wearable devices (such as VR-glasses) provides major potential applications to support both the industry and education. Therefore, future eCSE implementations will focus on applying VR-glasses to develop immersive platforms for improving learning experiences within virtual construction sites.

Despite advantages, photoreality technology itself cannot provide float object interactions in a virtual scene as the 3D-VR model does. Thanks to the emergence of Web3D technology, these limitations can be addressed by an integration of photoreality and the *three.js* framework [41]. In order to harmonize the advantages of these technologies, future research, therefore, should study the interoperability between real-world photoreality-based environments and existing 3D-VR objects for providing construction students with more interactive learning content. In this study, both the client and server components of the eCSE system were installed in one device to ensure a 1:1 comparison with the standalone 3D-VR system. Indeed, the proposed eCSE system certainly worked well with the distributed model, whereby a central server can be remotely located in the network while multiple clients (i.e., built-in Web browsers) access the services via an Internet connection. By applying this model, multiple cross-platform user devices can use the system simultaneously. Moreover, because almost all the heavy executions are performed by the central server, the user devices are expected to consume much lower energy. Therefore, a comprehensive technical analysis needs to be performed in future research in order to evaluate the distributed eCSE system in terms of service quality, service stability, and resource consumption.

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Abbreviations

The following abbreviations are used in this manuscript:

3D-VR	Three-dimensional model-based virtual reality
CPU	Central processing unit
CSS3	Cascading Style Sheets version 3
eCSE	Energy-efficient construction safety education
HTML5	Hypertext Markup Language version 5
HTTP	Hypertext Transfer Protocol
JHA	Job hazard analysis
KA	Knowledge assessment
LD	Lesson delivery
OS	Operating system
OSHA	Occupational safety and health administration
PE	Practical experience
RAM	Random access memory
VR	Virtual reality
XML	Extensible Markup Language

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