Gamification for Visualization Applications in the Construction Industry

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Abstract With the advancement of computer and information technologies in recent years, visualization applications such as virtual reality (VR), augmented reality (AR), and mixed reality (MR) have been applied widely across the architecture, engineering, construction, and operation (AECO) industry. Game features and mechanisms have been integrated with these visualization applications, expanding their impact. The core structure of these gamified applications echoes the essence of serious games (SGs). SGs have been identified as video games with serious purposes rather than pure entertainment, such as education, training, and analysis. With SGs principles, various impacts are expected as an outcome of human–computer interaction. In the context of the AECO sector, SGs have been applied to construction health and safety education, professional skill training, evacuation training, behavioural analysis, emergency studies, and decision-making processes. This chapter introduces SGs and their theoretical backgrounds, outlines the development principles of SGs tailored to AECO practitioners, discusses the state-of-the-art applications and impacts on the AECO industry, and draws future expectations and potential implications concerning gamification for visualization applications in the Industry 4.0 era.

Keywords Serious Games · Gamification · Built environment · Health and safety · Emergency · Training · Human behaviours

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1 Introduction

The rapid evolvement of visualization technologies including virtual reality (VR), augmented reality (AR), and mixed reality (MR) (see Chapter "From Building Information Modeling to Extended Reality") has implications in architecture, engineering, construction, and operation (AECO) industry in various ways. These visualization technologies are providing new avenues of communication and collaboration among stakeholders, promoting the transition of the management and operation of AECO practices. On top of that, with the integration of gamification to visualization technologies, more applications and impacts are emerging, such as skill training, health and safety training, and behavioural studies. These gamified visualization applications (GVA) incorporate the core principles of serious games (SGs). SGs are classified as digital games designed for a primary purpose beyond pure entertainment [1]. SGs engage and motivate users through the interaction with computer simulations across a range of domains, such as education, emergency management, engineering, training, and healthcare [2].

SGs have been seen as creative technologies to bring innovation and high payoffs to industries [3]. The Australian Trade and Investment Commission (Austrade) has highlighted the importance of SGs and recognized the value added by SGs to industries, promoting innovation, diversity, and scope [4]. The SGs' global market is projected to reach 8.91 billion USD by 2025, with a compound annual growth rate of 16.1% from 2020 to 2025 [5]. Academia and industries have been investing heavily to explore the benefits and challenges of SGs. As such, it is important to introduce SGs to the researchers and practitioners in the AECO industry.

This chapter focuses on SGs in the context of GVA for the Built Environment, providing an overview of the theoretical backgrounds, development principles, and major applications and impacts of SGs in the construction industry.

2 Theoretical Backgrounds

There is a need to clarify the differences and similarities between gamification and SGs. Gamification refers to the use of game elements and principles to non-gaming contexts, delivering enhanced user experience, engagement, and outcomes [6]. Gamification is a design approach to gamify scenarios, activities, and tasks using game-based concepts, rather than replacing them entirely with video games [6]. As such, gamification is applicable for non-digital contexts as well, such as class-teaching activities using gamified quizzes with points, leaderboards, and rewards [7]. Regarding SGs, they typically represent digital games with the intention to achieve goals other than entertainment [8]. In particular, a SG is a self-contained digital application, fulfilling intended objectives, which is different from gamification [6].

The similarity between these two concepts lies in gameful designs; in other words, the practice of game elements and principles [6]. In the case of visualization applications (e.g. VR or AR applications), they are digital applications in essence. When gamification is applied to them, they become a type of SGs with advanced visualization technologies, such as VR SGs or AR SGs, echoing the nature of SGs which are commonly seen on other types of visualization media (e.g. tablets and desktop screens).

2.1 SGs Classifications

The general definition of SGs implies that it is a piece of software integrated with serious purposes and gameplay elements, which leads to a range of interpretation on how to classify a SG. One of the approaches to classify SGs is to divide them into different domains. Chen and Michael [1] identified eight domains to accommodate SGs: military, government, educational, corporate, healthcare, political, religious, and art. Similarly, Alvarez and Michaud [9] categorized SGs into seven domains: defence, training and education, advertising, information and communication, health, culture, and activism. One of the major limitations of this domain-based classification approach is that the coverage of the classification is not inclusive, with new domains being discovered to apply SGs [10].

Another classification approach is called purpose-based approach, which pays attention to the purpose of SGs. For instance, Alvarez et al. [11] proposed six categories based on the intention of SGs: edugames, advergames, newsgames, activism games, edumarket games, and training and simulation games. However, this approach has limitations as well due to the focus on the single dimension of SGs only (i.e. the serious purpose of SGs).

Given the dual nature of SGs (i.e. digital games with serious purposes), Djaouti et al. [10] developed a Gameplay/Purpose/Scope (G/P/S) model to classify SGs, capturing both “serious” and “game” dimensions. Gameplay refers to the way a SG is played, including play-based (i.e. an open-world game without dominant storylines and goals) and game-based (i.e. a game with dominant storylines and goals); purpose stands for the designed outcome to be achieved by playing a SG, and scope represents the targeted domains of a SG [10].

The SGs introduced in this chapter fall in the scope of AECO sector, with either type of the gameplay delivering different outcomes, including pedagogical outcomes, behavioural outcomes, and simulation-related outcomes (see Sect. 4).

2.2 SGs Capabilities

SGs come with several capabilities: interaction, immersion and the sense of presence, assessments and feedback, engagement, and adaptability.

Interaction. SGs offer the users opportunities to interact with virtual environments and objects [12]. Users can make responses to the events within a SG and observe the consequences of their behaviours [13]. This kind of interaction enables experiential learning, in which case users learn through direct sense experience and in-context actions [14]. Users can learn by doing and by solving problems in SGs. For instance, users can obtain evacuation knowledge by escaping from a virtual building which is on fire and full of smoke. If users make inappropriate actions, they can observe direct consequences. Continuing the previous example, users can be virtually trapped and suffocated if they try to use a lift to escape. Human–computer interaction is embedded in visualization applications, with attention on contents, user interface, and user experience [15]. In the context of SGs, the interaction serves the delivery of the primary purpose of SGs, such as knowledge acquisition and behavioural changes.

Immersion and the sense of presence. The interaction between users and SGs leads to the second capability of SGs, which is to provide immersion and the sense of presence [16]. Immersion is a result of a range of sensory channels engaged by virtual environments, which is an objective measure on the fidelity of virtual environments [17]. The sense of presence is subjective to user experience, which is the cognitive and emotional response to virtual environments, representing the feeling of being in a particular place or a time period [18].

With the help of advanced visualization technologies (e.g. VR or AR), the virtual environments of SGs have the possibility to be a twin of reality, simulating and presenting realistic scenarios to users. Benefiting from this, users can be exposed to credible hazards without being in real dangers [19]. With such life-like simulation and real-time interaction, users can gain self-efficacy by familiarizing with the scenarios and learning from mistakes, if they make any [20].

Meanwhile, the realistic scenarios of SGs can induce users to make responses as they would in the real world, facilitating the investigation of human behaviours [13]. The simulation in SGs can be treated as laboratory settings, ideal for controlled experiments to study human behaviours [21].

It is worth to note that, although the simulation is close to reality, it is still an abstraction of the real world [22]. As such, the ecological validity (the ability to generalise study findings to real-world settings) of SGs is argued to be less than real-world cases [22]. Regarding internal and external validity (internal validity: the extent to which evidence supports causal relationships within a study; external validity: the ability to generalise study findings to other research settings), both of them could be higher than real-world cases and conventional laboratory experiments, on account of the high level of experimental control [22].

Assessment and feedback. SGs have the capability to offer assessments and feedback to each individual user [23]. Game elements such as scores, levels, status bars, hints, and awards can visualize the progress and performance of users in SGs [24]. Along with assessments, visual, auditory, and textual feedback can be triggered when users take certain actions or reach designated milestones, providing instructional information to facilitate learning or guide behaviours [24].

In general, there are two types of feedback: immediate feedback and delayed feedback [25]. Immediate feedback follows closely after taking action or reaching a milestone, while delayed feedback can be presented in the form of a summary or wrap-up at the end of a SG [26]. The assessments and feedback delivered by SGs can be regarded as a type of human–computer interaction, giving an additional layer of information to users. This is different from the aforementioned interactions with virtual environments and objects.

Engagement. High-level engagement can be yielded in SGs [27]. Engagement is linked to interaction, immersion, and the sense of presence, which motivates users to actively keep concentrated on the contents and activities within SGs, giving effects on the learning and behavioural outcomes of SGs [28]. The engagement within SGs consists of three-dimensional constructs: behaviour, cognition, and affect [29]. Highly engaged users always show constant behavioural, cognitive, and emotional involvement in activities [30].

While users keep involvement in activities, they are likely to enter a state of flow [31]. Flow is a state of mind in which users are managing activities in high functional capacities, with deep concentration and enjoyment [32]. Flow can be maintained when users do not get bored or frustrated, in which case, the challenges of activities fall in the range of users' skillsets [32]. If activities are too challenging or too easy, the level of involvement from users will drop, leading to the break of flow and the loss of engagement [32].

Adaptability. Adaptability is also one of the main capabilities of SGs [33]. Specifically, an SG can be adapted to suit to heterogeneous types of users. Users have different backgrounds, knowledge, experiences, capabilities, and objectives, leading to different kinds of interactions with SGs and different levels of expectations from SGs [34]. An SG is a set of a computer program in essence, which has the possibility to make adjustments across the stages of gameplay.

In general, there are two ways of adaptation, which are user-controlled adaptation and system-controlled adaptation [35]. User-controlled adaptation relies on the configurations from users, changing the settings of SGs to suit users [35]. In most cases, user-controlled adaptation occurs before actual gameplay, completed by users. In turn, system-controlled adaptation is accomplished by SG itself [35]. With the capturing of real-time progress and performance of users, SG can make adjustments accordingly in order to better deliver outcomes. This type of adaptation can be implemented in a way to adjust game difficulties, provide hints, give navigation support, or change instructional approaches [36]. The adaptability of SGs could expand the influence of SGs by delivering personalized and customized game experience to broad types of users.

3 Development Principles

SGs consist of a set of characteristics, such as play, rules, challenges, and storytelling [37]. Accordingly, the development of SGs can follow the full principles and methodologies deployed in the game industry. However, this may not be feasible for the SGs for the AECO sectors as the industry practitioners do not have sufficient

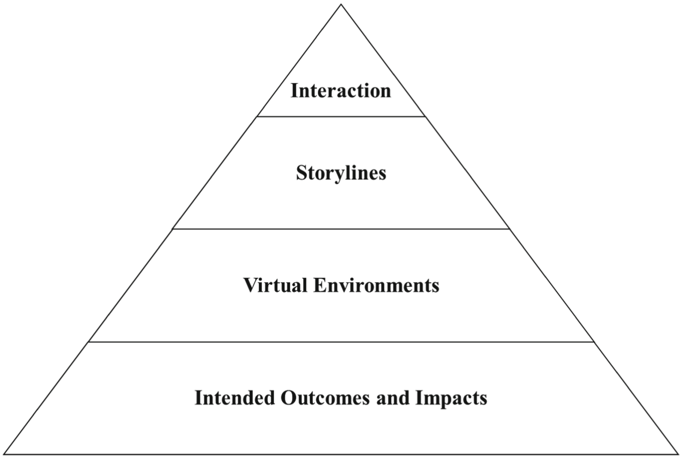

Fig. 1 The four layers of the development principles for SGs

knowledge and experience to implement the principles. In this case, this section introduces a set of basic principles for the development of SGs (see Fig. 1), trying to cater to the appetite of the AECO practitioners.

3.1 Intended Outcomes and Impacts

The intended outcomes and impacts from a SG should be identified in the first place. This is a fundamental step which sets the overall tuning of a SG [34]. In the case of pedagogical outcomes, this step involves the articulation and scrutiny of learning or training objectives, such as the skills to be trained, the knowledge to be acquired or the persuasive messages to be received by target users [2]. Similarly, regarding behavioural outcomes, this step defines the deliverables of a SG for behavioural analysis, such as understanding safety compliance behaviours, validating behaviours in specific circumstances, or recognizing hazard perceptions from target users [13].

3.2 Virtual Environments

Next, a virtual environment should be established to accommodate game scenarios, with the intention to deliver identified outcomes. In the traditional game industry, this can be done via various 3D modelling tools, such as Autodesk 3ds Max®, Autodesk Maya®, or Blender®. This is also applicable to game engines, which can put objects and models together to construct virtual environments. Game engines are development environments or platforms to build video games. They are the integration hubs providing core features for game development, such as rendering, physics, graphics, audio, scripting, and animation [38]. Popular game engines include Unity® and Unreal Engine 4® (UE4).

In the context of SGs for the AECO industry, the virtual environments of SGs are the representation of Built Environment in most cases, such as a construction site, an existing building, or a building yet to be built. As such, there are alternative solutions to get virtual environments for game development (see Fig. 2). Bille et al. [39] proposed a Building Information Modelling (BIM)-based workflow (see Chapter "Building Information Modelling and Information Management"). A BIM model can be converted to a 3D mesh model in Filmbox (FBX) file format, which can be then imported to game engines served as a virtual environment for further game development. The third-party plugins of game engines such as PiXYZ® support the direct import of computer-aided design (CAD) and BIM models to Unity® as well.

In addition to the use of CAD and BIM models, another rapid development approach for virtual environments is to use reality-capture techniques, such as laser scanners, drones, and 360° cameras [40] (see Chapter "Reality Capture: Photography, Videos, Laser Scanning and Drones"). All the outputs produced by reality-capture techniques can be imported into game engines as virtual environments.

There are strengths and limitations associated with each solution to generate virtual environments for SGs [40]. The BIM-based virtual environment provides the most capability for dynamic changes in SGs as the virtual environment consists of stand-alone objects. Developers can manipulate individual objects straightaway in game engines to simulate events. However, BIM-based virtual environment may contain too many levels of details that are beyond the requirement for a game environment, which is a result of rich information contained in BIM models. Extra efforts may be required to simplify the virtual environment in order to lessen the burden on computing and rendering. In the case of BIM models not available, it could be time consuming to develop a BIM model, especially for large scales of buildings. Regarding laser scanners and drones, they enable rapid reconstruction of

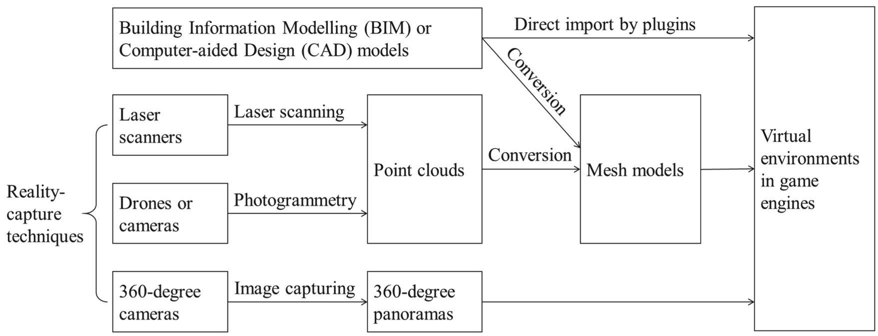

Fig. 2 The workflows to get virtual environments in game engines

Built Environment into 3D mesh models. The virtual environments based on these models have high-level of fidelity. One major limitation of these virtual environments is that everything in a model is attached to each other, making up a single mesh model (i.e. the virtual environment is a single mesh model without individual objects). Resulting from this, these virtual environments have less dynamic capability as compared to BIM-based virtual environments. Developers can either split an individual object from the entire mesh model or add an additional layer of objects to make simulation. In addition, the mesh models produced from laser scanning and photogrammetry usually contain a huge number of polygons. This can put lot of pressure on computing and rendering if no actions are taken to reduce polygons. In terms of the 360° panorama approach, this is the fastest way to obtain a virtual environment for SGs. The panoramas taken by 360° cameras can be directly used by game engines. The user experience of SGs based on panoramas is similar to using Google Street View®. The virtual environment is the closest to reality as it is a photo in nature. It also requires the least computational effort to render and run the SGs based on it. However, this approach has two major limitations. First, just like the laser scanning and photogrammetry approach, developers need to add an additional layer of objects to make simulation and they cannot manipulate anything from the virtual environment as it is just a photo. Second, the navigation within the virtual environment is limited. Users can only teleport from one panorama to another, following the predefined routes (i.e. the orders of panoramas are taken and provided). Think about using Google Street View®, users can travel from one place to another following the panoramas taken by Google Street View® vehicles in an order but nowhere else and no other routes if there are no panoramas provided.

3.3 Storylines

Based on the virtual environment, storylines should be defined and added into it. A storyline consists of a series of events to be encountered by users, motivating users to be engaged with SGs [41]. The integration of storylines with virtual environments makes game scenarios, where messages are conveyed to users in context [42]. A storyline should be built based on the outcomes identified in the first step [34].

For instance, Fig. 3 illustrates the storyline of a SG suited to earthquake emergency training. The intended outcome of the SG is defined to educate users about best evacuation practices for earthquakes (see Fig. 5b). The intended knowledge to be acquired by users is divided and embedded into individual events. The storyline of this SG starts with the presence of users in a building. The first event occurs, in which case, an earthquake strikes the building. In this event, users can interact with virtual environments and learn how to make a response to an earthquake strike (in this case, “drop, cover, and hold” according to Fig. 3). Following the first event, the next event happens where users can learn what to do

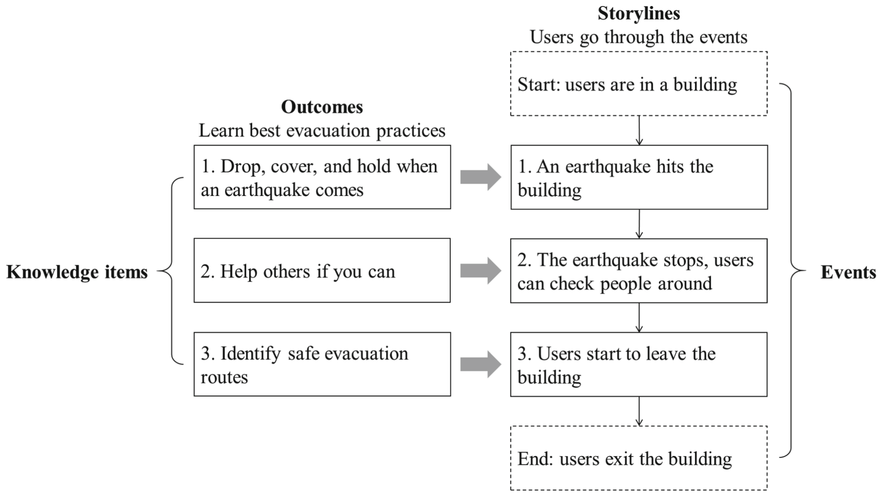

Fig. 3 From identified outcomes to the formation of storylines

immediately after an earthquake (e.g. help others if you can). Then, users can face another event in which they can learn how to choose a safe route to evacuate. After going through all the events of a storyline, the intended knowledge should be entirely presented to users.

In this way, the storyline of an SG exposes its full objectives to users, enabling the delivery of identified outcomes. Once a storyline is defined, additional objects and animation then can be added accordingly into virtual environments to contextualize each event in game engines. This includes visual simulation and sound effects.

Continuing the previous earthquake example, in the event of an earthquake strike, the animation and sound effects of falling and shaking objects are added in the virtual environment of that building, contextualizing an earthquake event with simulation. In the event where users need to check other people around, the animation and sound effects of building occupants can be loaded into the virtual environment, using non-player characters (NPCs). With simulation to contextualize the events of storylines, game scenarios are enriched with the representation of storylines and virtual environments [34].

3.4 Interaction

In the end, human–computer interaction should be completed. Human–computer interaction refers to all kinds of interaction that are going to happen between users and SGs, echoing the capabilities of SGs introduced in Sect. 2.2. The interaction may include but not limited to navigation, storytelling, consequences, assessments and feedback, instructional approaches, behaviour inducers, and tracking and

Table 1 Interaction between users and SGs

Items	Explanation	Examples
Navigation	This implies how a user can navigate or make movement in the virtual environment of SGs	Fixed route: waypoint systems [34] Open route: users manipulate joysticks or keyboards in four directions
Storytelling	This refers to the ways to expose a storyline to users, by which users can follow and complete the storyline	Action-driven: a storyline is progressed based on the actions taken by users [13] Instruction-driven: users make progress on storylines based on the instructions received [13]
Consequences	This refers to the simulation in SGs to show the consequences of the actions taken by users. The necessity, fidelity, and severity of consequences depend on the intended outcomes of SGs	Examples in Sect. 2.2: users get trapped and suffocated if they choose to use a lift to evacuation in fire emergencies
Feedback	This refers to the information presented to users to report their progress and performance	Game elements, such as scores, levels, status bars, awards, hints, texts, and sound effects
Instructional approaches	This refers to the ways to convey knowledge and messages to users in order to achieve pedagogical outcomes	Textual messages are presented to users, delivering knowledge [26]
Behaviour inducers	This refers to the in-game simulation and conditions to induce or imply certain behaviours form users in order to achieve behavioural outcomes	A hazard is going on around users. Users may or may not make responses to it
Tracks and records	This refers to the ways to track and record the movement, actions, and performance of users for further analysis	A map to show the popular evacuation routes in a building [43]

recording [13, 34]. Table 1 demonstrates the explanation and examples of the items to be considered for the interaction between users and SGs. Game elements and game mechanisms are heavily invested in this step.

4 Applications and Impacts

In the AECO industry, SGs have been mainly applied in three domains: pedagogical applications, behavioural applications, and simulation-related applications.

- Pedagogical applications involve the design and delivery of educational or training modules via SGs, allowing users to acquire knowledge or equip skills.

- In the case of behavioural applications, user behaviours are studied according to the actions taken by users in response to confronting game scenarios.
- Simulation-related applications involve the simulation on Built Environment, which achieve other types of outcomes, such as facilitating the decision-making of users.

The following subsections elaborate these SG applications in detail.

4.1 Pedagogical Applications

In recent years, researchers have pointed out that traditional education is becoming less engaging compared with the emergence of new technologies, which cannot fully prepare students and fresh graduates to become effective employees for the AECO industry [44]. The prosperity of today's game industry has gradually attracted more and more attention from researchers and practitioners to develop SG-based innovative tools to support learning experiences [45].

A great number of studies have revealed that incorporating SG concepts into educational functions can largely engage individuals in embedded learning activities with considerable enjoyment and fulfilment [46]. For instance, it is imperative for students to have practical experience with construction projects and gain the basic ideas of how to solve the problems arise from the dynamic and complex nature of the AECO industry [45]. However, traditional education (e.g. classroom lectures) emphasizes on the delivery of knowledge and lacks a platform to allow students to interact with construction dynamics and gain necessary practical experience before entering actual workplaces [44]. SGs can be utilized to supplement construction education in order to address the problems [47]. Users can interact with objects and NPCs (see Fig. 4) in SGs to practise the operation of tools and machinery, the communication with colleagues on scheduling and planning, the measures for health and safety, and the procedure of site inspection [48].

Without the evaluation of the effectiveness of SGs in the construction education context, SGs may remain a questionable strategy. In recent years, a growing number of evidences have been provided, including the comparisons between SGs and traditional education methods in the areas of construction health and safety training and skills development. Studies across the world have demonstrated the empirical evidence of greater effectiveness of SGs over traditional training methods [49–65]. In particular, traditional methods may include the means of class teaching, toolbox talks, handouts, audio-visual materials, and computer-based instructions [44].

In the literature [49–65], the following construction workplace topics were investigated by both training methods: ergonomic awareness, machinery operation, hearing protection, first-aid, fall prevention (i.e. working from height), working near machinery, electricity safety, personal protective equipment (PPE), trench safety, and scaffolding safety.

(a) NPCs: virtual colleagues

(b) NPCs: virtual colleagues

(c) Objects: virtual machinery

(d) Objects: virtual machinery

Fig. 4 Virtual colleagues and machinery in SGs

(a) A workplace scenario: a construction site

(b) An emergency scenario: a school after an earthquake

Fig. 5 Built Environment under different circumstances in SGs

- Ergonomic awareness programs help users develop awareness of the risk of ergonomic hazards in workplaces and attain necessary knowledge on the ways to protect their backs, necks, shoulders, hands, wrists, elbows, and knees [65].
- Machinery operation programs teach the safe operation of construction machinery [64].
- Hearing protection programs emphasize the effects of noise on hearing and attempt to increase the use of hearing protection devices [63].

- First-aid programs teach users how to carry out effective first-aid treatment to casualties in the event of injuries or sudden illness [62].
- Fall prevention programs train users in fall prevention practices relating to ladder usage, leading-edge work, truss setting, and scaffolding usage [61].
- Electricity safety programs help users understand the potential risks associated with electricity in workplaces [60].
- Trench safety programs foster self-protective measures against trench collapse [59].
- Scaffolding safety programs present dangerous occurrences in relation to the improper use of scaffolding, for instance, insufficient overlaps between planks [58].
- PPE programs give lessons on the proper use of PPE, such as use welding gloves for welding work [57].

In the literature [49–65], certain criteria were considered to evaluate the effectiveness of SGs and traditional education methods, namely, health and safety knowledge acquisition, unsafe behaviour reduction, and injury rate mitigation. Zhao et al. [56], Zhao and Lucas [60], and Guo et al. [55] showed that users in treatment groups who received SG training had a higher proportion of keeping a safe distance from electrical wires than control groups who received traditional training. Dickinson et al. [59] revealed that SG training contributed to a greater mean score than toolbox talks regarding safety compliance behaviours near trenches. Newton et al. [54], Le et al. [53], Pedro et al. [52], and Dawood et al. [51] compared users' safety behaviours between SG and traditional training groups, and discovered that users in SG groups exhibited significantly greater improvement on the use of power tools, access to height, and the use of PPE. Similarly, in the case of using hearing protection devices, Leong et al. [50] and Lin et al. [49] reported that users trained by SGs acquired more knowledge than traditional training methods.

In addition to the applications for construction projects, the pedagogical impacts of SGs have reached other domains in the AECO sector. Moloney et al. [66] proposed an SG to introduce integral sustainable design (ISD). Users learn the concepts of ISD gradually by progressing game levels. Sharing the similar features and advantages of those for construction education and training, SGs have been heavily investigated for emergency and evacuation training as well, covering various types of Built Environment and emergencies, such as tunnel fire, building fire and earthquakes, industrial plants emergencies, maritime facility emergencies, aviation and spacecraft emergencies, and train station terror attacks [13]. For instance, Feng et al. [20] demonstrated a VR SG aimed to enhance the preparedness of users to indoor earthquakes and post-earthquake evacuation. Results suggested users had gained knowledge and increased self-efficacy immediately after the training. Kawai et al. [67] introduced an AR SG to conduct evacuation drills, teaching users about appropriate responses to fire emergencies. SGs can educate and train users about practices, self-protection skills, and spatial knowledge to deal with emergencies [13].

4.2 Behavioural Applications

Understanding the behavioural patterns of construction workers is critical to ensure their health and safety in workplaces [68]. It has been pointed out that a proper behavioural study method can enable valid insights into the behaviours and intentions of investigated subjects [21]. Questionnaire survey and field observation have been widely utilized as the prevalent methods to study human behaviours. These techniques have limitations. For instance, the hazardous nature of construction sites makes it risky for researchers to observe workers behaviours on-site. It is also unethical to ask workers to undertake certain tasks that may involve unsafe situations for research purposes [69].

SGs have the potential to significantly impact the ways to study human behaviours [70]. SGs permit the following distinct advantages for behavioural study:

- SGs participants can encounter hazards in VR without getting physically injured [70].
- SG-based behaviour studies can be conducted off-site using portable devices, which no longer interferes with the work progress on construction sites [71].
- By involving game mechanisms in behavioural decision-making scenarios, users are engaged in in-game activities and tasks, enabling more credible and accurate behavioural data than conventional techniques [70].

Given that, SGs have been extensively adopted in the AECO industry to investigate human behaviours [70]. For instance, Shi et al. [70] developed a VR SG to study the safety behaviours of construction workers in the context of working from height. Albert et al. [72] utilized an AR SG to investigate the tolerance of risk-taking behaviours from construction workers. Kamkuimo et al. [47] developed a VR SG to understand the tolerance of being exposed to silica dust from construction workers, providing a safe virtual environment in which users went through the experience of working around silica dust. Kanal et al. [73] adopted a VR SG to study the behaviours of users under fatigue conditions.

In addition to the advantages of SG as aforementioned, studies have also highlighted a further benefit of utilizing SG: text-free interfaces [74]. The workers on construction sites tend to have, on average, lower educational attainment as compared to other industries [75]. In the US, according to an industrial survey by National Safety Council in 2003, more than 70% of construction workforce had low English proficiency (LEP) or low literacy (LL) issues [76]. In New Zealand, 7,485 Asian construction workers, who might have LEP or LL issues, were employed in the construction sector in 2013, representing almost 5% of the whole workforce [77]. Traditional behavioural analysis techniques (e.g. questionnaire survey) rely heavily on paper-based materials and textual descriptions. Therefore, investigated subjects should meet a certain standard to communicate. Having LEP or LL issues from investigated subjects could jeopardize the validity of behavioural studies [78]. For instance, a study of construction workers in Hong Kong revealed that undereducated workers had difficulties in reporting and communicating during on-site meetings [79]. This highlights the importance of establishing valid research settings for LEP or LL workers. It is argued that the use of SGs can mitigate language barriers for LEP or LL workers during experiments because the interaction between SGs and users is less dependent on texts [80]. Lin et al. [81] further pointed out that using 3D simulated virtual workplaces in experiments is expected to reduce the required level of language proficiency and literacy and increase the understanding as well as engagement of those who cannot speak or read much English in the construction industry.

Similar to pedagogical applications, SGs have been widely applied to study human behaviours in emergencies [13]. For instance, Feng et al. [21] integrated verbal protocol analysis with a VR SG to investigate the decision-making of evacuees in earthquake emergencies in a hospital. Lin et al. [43] utilized a VR SG to study whether evacuees follow the crowd in metro station evacuation. As discussed in Sect. 2.2, SGs are ideal for behavioural studies thanks to the high level of experimental controls. This gives a great potential to investigate human behaviours in various types of Built Environment under different circumstances (see Fig. 5). SGs have been used to validate evacuation facilities and evacuation behaviours, recognize evacuation behaviours, study evacuation behavioural compliance, identify hazard awareness and wayfinding behaviours, and investigate the social influence on evacuation behaviours [13].

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4.3 Simulation-Related Applications

Thanks to the simulation enabled by SGs, other types of outcomes for the AECO sector become possible. For instance, SGs have been widely used to simulate hydrological status such as water quality or water levels, facilitating the decision making for water management [82]. In addition, with the integration of advanced visualization technologies (e.g. VR or AR), SGs give enhanced effects on the outcomes resulted from simulation. These applications may not show explicit game designs; however, they still feature some capabilities and values of SGs, such as interaction, immersion and sense of presence, and engagement. Following are some brief examples. More discussion of VR or AR topics can be found in Chapter "From Building Information Modeling to Extended Reality" of this book.

Abdelhameed [83] developed a VR prototype to assist in the decision-making on construction scheduling, including decomposed tasks such as material supply and storage, labour and machinery planning, and tower crane trajectory planning. Getuli et al. [84] and Hosny et al. [85] utilized VR to help the planning of workspace, trying to avoid potential interferences and collisions caused by unexpected spatiotemporal overlaps of components on construction sites. Alizadehsalehi et al. [86] developed a VR prototype to allow visual inspection in design stages by walking freely in building models.

In the literature, the future trends of simulation-related applications in the AECO industry have been suggested: (1) user-centred adaptive design; (2) attention-driven virtual reality information systems; (3) construction planning systems incorporating human factors; and (4) occupant-centred facility management prototypes [87].

5 Conclusion

Gamification can be applied to visualization applications, enabling additional outcomes, including pedagogical outcomes, behavioural outcomes, and simulation-related outcomes. The primary concept is to enrich human–computer interaction with SG principles. Therefore, gamified visualization applications can support problem-solving in a variety of domains in the AECO sector, giving effects on upskilling workforce, understanding human behaviours in Built Environment, improving personnel health and safety, and facilitating decision-making processes. With the entering into the Industry 4.0 era, innovative approaches are emerging to solve traditional problems in the Built Environment. Therefore, the AECO industry practitioners and academia researchers should be prepared to embrace disruptive technologies. The transition can take place starting from educational institutions and training centres, setting up the mindset of multidisciplinary integration and developing the skills to apply gamification on visualization applications.

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