Research in Engineering Education Symposium &
Australasian Association for Engineering Education Conference
5 – 8 December, 2021 - Perth, WA

A Framework for Game-based Learning on Sustainability for Construction and Engineering Students

Sherif Mostafa[a]; Hengky Salim[a]; Rodney A. Stewart[a]; Edoardo Bertone[a], Tingting Liu[a]; Ivan Gratchev[a]
School of Engineering and Built Environment, Griffith University, Southport QLD 4222, Australia[a]
Corresponding Author Email: sherif.mostafa@griffith.edu.au

ABSTRACT

CONTEXT

The United Nations Agenda 2030 indicated that higher education institutions need to be at the front line of achieving sustainable development goals through knowledge transformation and innovative learning and teaching of next generation professionals. The increasing global push for sustainable construction means that decision-makers need to be more agile in responding to this demand. Unfortunately, students have been passive knowledge receptors in a traditionally deductive instructor-centred learning approach. Serious gaming can be an engaging tool to support effective sustainable construction education to enable active experimentation, exploration, competition, cooperation and realistic experience.

PURPOSE OR GOAL

This study aims to develop a preliminary framework for serious gaming on sustainable construction. The objectives of this paper are: (i) to develop a conceptual model highlighting the complexity of sustainable construction system; (ii) to identify the underpinning pedagogy principles of the game and discuss how the game can improve students' understanding of sustainable construction; (iii) to describe the key design components, including gameplay, game mechanisms, and students' performance evaluation system.

APPROACH OR METHODOLOGY/METHODS

The literature review was conducted to retrieve key decision and performance variables related to sustainable construction. A system thinking approach was employed to develop the conceptual model based on the identified variables. The literature review also extended to the serious game framework development to identify and compare pedagogy principles and game design elements suitable for sustainable construction problems.

ACTUAL OR ANTICIPATED OUTCOMES

The overall findings indicated that: (i) sustainable construction is a complex system where decision-making activities involve conflicting objectives between different actors in the supply chain; (ii) a card game concept will be utilised where players can take different roles and objectives; (iii) cyclical design will be used in the game where participants make choices, take actions, get the results, reflect on the results and proceed to take another action; and (iv) students' understanding will be measured through in-game quizzes.

CONCLUSIONS/RECOMMENDATIONS/SUMMARY

Using the systems thinking approach, this study provided a holistic insight into the serious game framework for sustainable construction education by revealing the system's complexity, pedagogy principles, game design elements and the students' evaluation system. The framework is a precursor for the game development process to plan and design a serious game that effectively conveys the learning objectives.

KEYWORDS

Serious games, Sustainable construction, Experiential learning, Game-based learning, system thinking

Introduction

The United Nations (UN) Agenda 2030 indicated that higher education institutions need to be at the front line of achieving sustainable development goals (SDGs) through knowledge transformation and innovative learning and teaching of next generation decision-makers (United Nations, 2015). The increasing global push for implementing sustainable construction such as energy and water efficiency, responsible material uses and management throughout the building life-cycle means that decision-makers need to be more agile in responding to this demand. From a higher education perspective, students have frequently been passive knowledge receptors in a traditionally deductive instructor-centred learning approach (El-adaway et al., 2015). An engaging educational tool should be incorporated into the higher education curriculum to engage students in an experiential learning environment; thus, increasing their collaboration and decision-making skills.

Serious games have been popularly used in an education setting to increase student interaction, collaboration, and engagement (Vogel et al., 2006). They support experiential learning by providing students with a virtual replica of an existing system and enabling active experimentation, exploration, competition, cooperation and concrete experience (Sadowski et al., 2013; Whalen et al., 2018), which is usually not addressed in a traditional teaching approach. A serious game in higher education challenges students with a complex problem that allows multiple solutions and requires intelligent reasoning, problem-solving strategies, and interaction with fellow learners. According to Westera et al. (2008), higher education students should be confronted with problems that require multiple solutions and the application of certain methods, tools and collaboration. Despite the rapid development of gaming industries in the last few decades, the use of games for education remains limited.

Several serious games have been built for sustainable construction problems. Dib and Adamo-Villani (2014) created a serious game that allows students to take a role as designers, constructors and building owners to improve their buildings' environmental and economic performance such as water and energy efficiency, waste reduction and low emission transportation. Juan and Chao (2015) developed a board game that allows students to implement various strategic actions to develop an ecologically sound city. However, these games lack consideration into systems thinking given that sustainable construction systems consist of conflicting objectives between stakeholders and feedback mechanisms. Another gap that needs to be addressed in the serious game literature is the need to establish indicators or a system to measure students' learning performance.

Integrating systems thinking into game design framework development is imperative to capture system complexity and dynamics into the pedagogy (Madani et al., 2017). In this paper, a preliminary design framework for a sustainable construction serious game was proposed by integrating systems thinking approach. A literature review was conducted first to retrieve variables related to project management practices in sustainable construction. The variables were used in a causal loop diagram (CLD) to describe the complexity and dynamics of the system. Then, the proposed serious game's pedagogical principles and design elements were identified and discussed based on the framework by Annetta (2010).

Methodology

Firstly, a conceptual model needs to be developed to gain a systemic understanding of sustainable construction. This will help to inform the game development process, especially in creating game mechanisms and learning objectives. Secondly, the game design framework was built to describe the pedagogy principles and design elements that will be utilised during the game development process.

Model conceptualisation

This research capitalised on the systems thinking approach to create a causal loop diagram (CLD) for describing the structure and dynamics of the sustainable construction system. Systems thinking helps to create dynamics hypotheses to understand better the multi-faceted consequences of a decision and the trade-offs between different strategies (Sahin et al., 2020). This approach is well-suited for this system since sustainable construction is underpinned by conflicting objectives and decisions between different actors in the supply chain (Solaimani & Sedighi, 2020). There were two steps to create the conceptual model: 1) problem scoping and 2) causal loop diagram development.

Problem scoping

The problem scoping stage aims to clarify the purpose of the model by selecting the boundary of a problem (Sterman, 2000). The preliminary problem scoping was conducted through the literature review. Firstly, this study reviewed and summarised the key drivers and barriers to sustainable construction. Secondly, the authors discussed and selected the variables which suit to be integrated into the system model following the *Sustainable Construction (1605ENG)* course profile at Griffith University. Model boundary and selected variables will still need to be confirmed and validated with experts to ensure they are relevant and up to date.

Causal loop diagram development

After model boundary and key system variables had been established, a preliminary CLD was developed. CLD is the most common systems thinking tool to map and visualise a collection of relationships forming a complex system (Sahin et al., 2020; Sterman, 2000; Suprun et al., 2018). The advantage of employing a CLD is its ability to challenge entrenched mental models and test assumptions which enable a counterintuitive understanding of system structure and behaviour (Hovmand, 2014).

A CLD consists of causal relationships between different variables and the underpinning feedback loops. A pair of variables is connected using an arrow with an assigned positive (+) or negative (–) polarity. The positive relationship indicates that the cause-and-effect variable is moving in the same direction (i.e. when the cause variable increases, the effect variable will increase too), whereas the negative relationship indicates otherwise (i.e. when the cause variable increases, the effect variable will decrease). The double lines across the arrow indicate information delay. Feedback loops also exist within a CLD, which can be reinforcing (R) or balancing (B). A reinforcing loop accelerates growth in the system, whereas a balancing loop counteracts change to produce stabilising system behaviour.

Creating the game design framework

Fotiadis and Sigala (2015) suggested that pedagogy principles, design elements, information provision and students' evaluation system are the critical aspects in developing a serious game that can effectively convey the learning objectives. To identify these aspects, this research followed the framework for serious game design by Annetta (2010). The study suggested six elements to be considered in serious game development in order of magnitude: identity, immersion, interactivity, increasing complexity, informed teaching, and instructional (Figure 1).

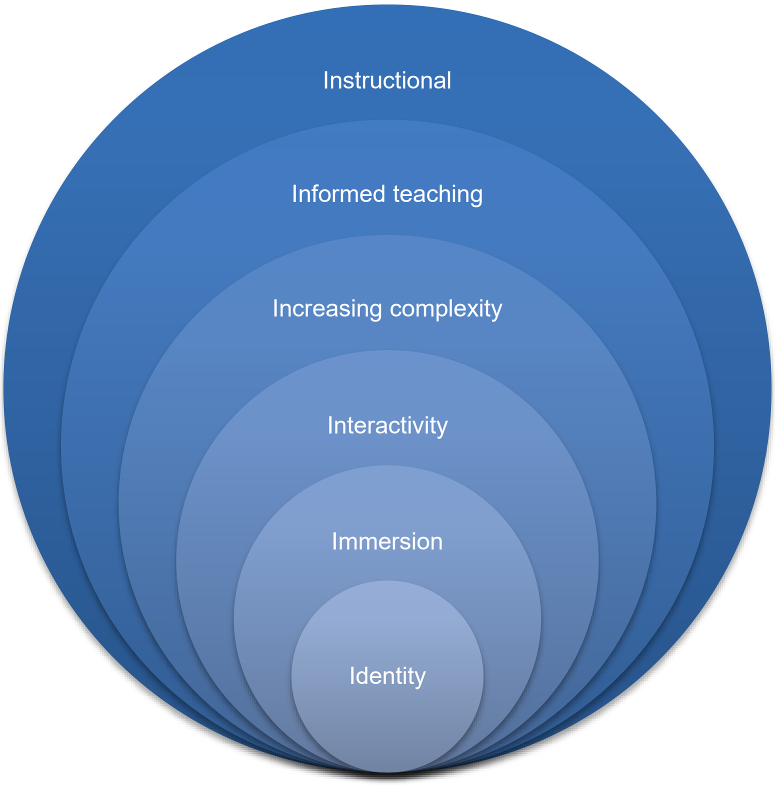

Figure 1: Elements in serious game design (Annetta, 2010)

Identity refers to representing a player in the game such as an avatar to convey their identity, presence, location and activities to other players. The provision of identity in a serious game will induce immersive gameplay. An immersive game means that players feel their presence in the game and are engaged in the content; consequently, motivated intrinsically to succeed in the challenge presented. A well developed serious game must also increase its complexity such as increasing difficulty level as the player progresses. Informed teaching means that player data related to decisions and results should be obtained to capture students' experience and understanding of the subject. Instructional refers to the provision of information or recommendation systems that will guide players through the game. Considering the elements mentioned above, this research reviewed different game elements and designs and selected the suitable elements to be applied in a sustainable construction context.

A Systemic View on Sustainable Construction

To design a serious game with effective pedagogy elements, a systemic view needs to be considered as the underpinning game decision support system design (Madani et al., 2017). When examining a problem, feedback mechanisms and the interrelationship between different subsystems need to be drawn. Systems thinking is one of the important professional skills in addressing sustainable development issues; therefore, students can improve their ability to deal with complex systems through serious games (Miguel et al., 2020). Integrating systems thinking into the game decision support system will enable students to learn this skill implicitly through the reflective process during the game session.

Figure 2 visualised the sustainable construction system complexity through a CLD. The sustainable construction concept attempts to integrate environmental, social and economic aspects into construction business practices and management. It adheres to the principles of sustainable development from the extraction of raw materials, through the planning, design and construction of buildings and infrastructure, until their final deconstruction and waste management (El-adaway et al., 2015).

The economic dimension involves the initial cost of construction and building life-cycle costs. The initial cost is affected by transportation use, material consumption, construction time and the use of renewable energy. To achieve a low building life-cycle cost, the constructed building must minimise its energy and water consumption (Sev, 2009). This can be achieved by promoting a better indoor environmental quality, using renewable energy, and using eco-friendly fixtures (e.g. water efficient water tap, low flow toilets, recycled water system, rainwater tanks, and automatic sensors for lightings).

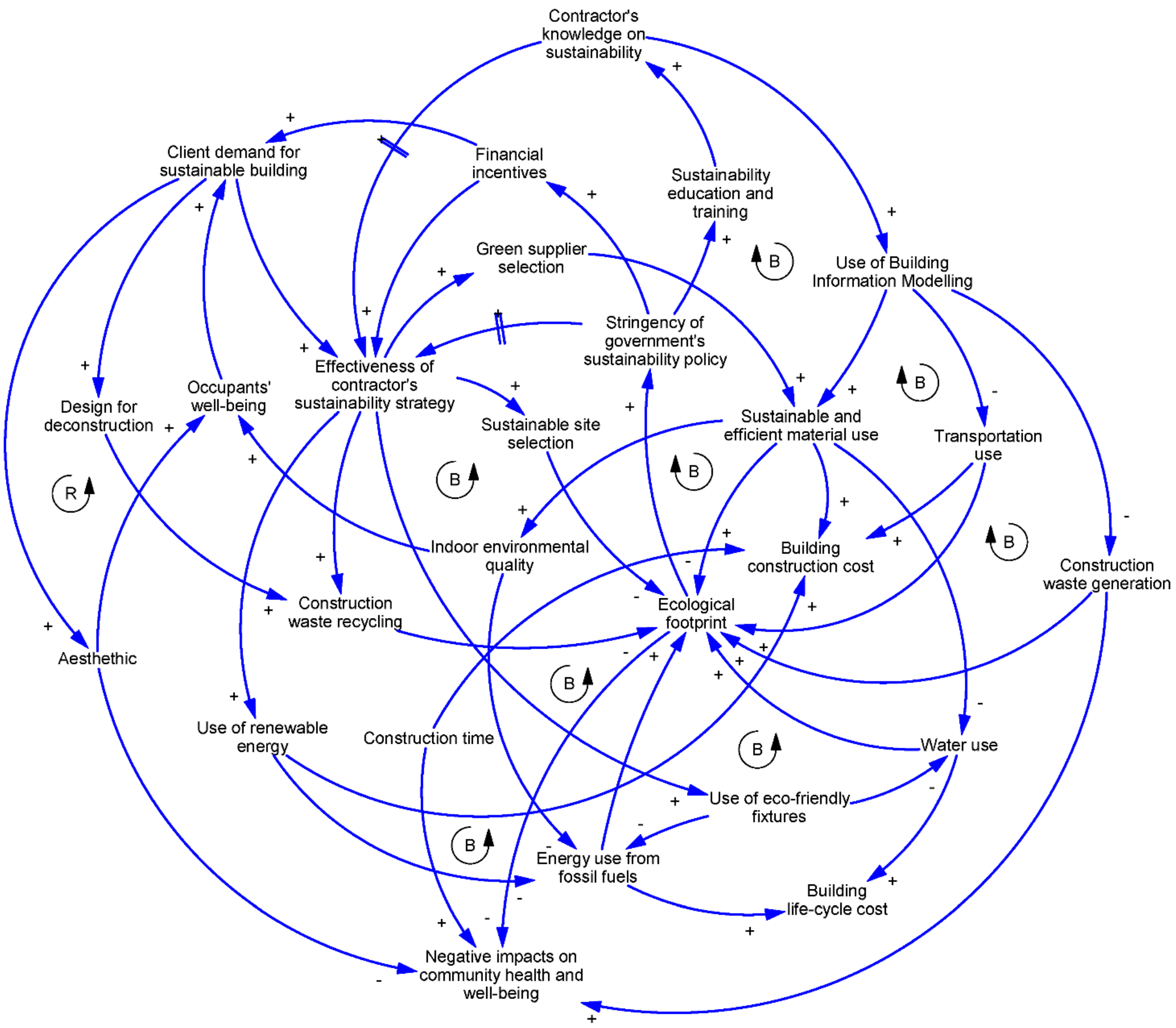

Figure 2: Preliminary causal loop diagram for sustainable construction system

The environmental dimension involves the ecological footprint derived from energy and water use, material use, land use, waste generation, and transportation. Construction managers must work together with other stakeholders to minimise consumption and on-going maintenance of the building. It was suggested that reducing the ecological footprints of a building will have economic benefits from initial cost reduction and on-going maintenance costs (Ries et al., 2006). An example is using materials that can promote better indoor environmental quality, thus reducing energy use from fossil fuels.

The social aspects cover community health and well-being and occupants' well-being. The literature has strongly suggested that indoor environmental quality strongly links occupants' well-being (Al horr et al., 2016). Studies highlight sick building syndrome, thermal comfort, acoustic comfort and visual comfort as the most critical issues surrounding the building's indoor environment. Furthermore, construction should minimise its adverse impacts on community health and well-being by minimising construction waste generation, construction time and delivering an excellent aesthetic (van Kamp et al., 2003).

Several interventions representing actions from different stakeholders were also outlined in the CLD based on the variables identified from the literature review. For example, the government can action different incentives such as green bonds, standardisation and sustainability policy for buildings (Häkkinen & Belloni, 2011; MacAskill et al., 2020). Construction industries can employ Building Information Modelling (BIM), sustainability education and training, and green supplier selection to support their sustainability strategy (Mills & Glass, 2009). Architects can improve the aesthetic and indoor environmental quality and create a building designed for deconstruction to avoid large waste generation during decommissioning phase (Murtagh et al., 2016). Surveyors can work closely with construction professionals to perform life-cycle assessment and sustainable site selection to minimise the ecological impacts (Sfakianaki, 2019).

Design Framework for the Serious Game

Pedagogy principles

Construction managers are required to handle critical problems such as material planning and calculation, determine construction methods, communicate with other parties (e.g. architects, clients and suppliers) and oversee the construction process to deliver sustainable construction projects effectively (Mills & Glass, 2009). The educational implication of this game is to expose construction and engineering students to the project management decision options throughout the construction life-cycle available to different actors in the sustainable construction supply chain and how the decisions will impact construction sustainability. Furthermore, by integrating the systems thinking approach, students will learn about the feedback mechanisms (i.e. how their decisions will affect other variables and the decisions of other actors in the value chain) in the system. The combination of Kolb's experiential learning theory and collaborative learning theory will form an engaging and immersive education tool that improves students' understanding through active experimentation, collaboration and negotiation.

The sustainable construction serious game will be based on the cyclical design, where players can make choices, take action, retrieve the results, reflect on their action, and based on their outcomes proceed to take further actions (Fotiadis & Sigala, 2015). A cyclical design follows experiential learning (Kolb, 1984), where it bridges students' understanding from active experimentation to abstract conceptualisation. The game will be designed to allow students to learn and reflect on the positive and negative outcomes resulting from their decision experimentation (Ypsilanti et al., 2014). It is based on a continual improvement principle where students will pick different decisions each round, review the sustainability condition and make another decision in the subsequent round.

Collaborative learning theory involves a group of learners working together to solve a problem or complete a task (Laal & Ghodsi, 2012). In this game, students will take different roles with different goals and balance the sustainability indicators within the construction system. Students will bring and improve their negotiation skills and implement effective solutions to achieve their goals through discussions with their peers. This design also allows students to better understand their roles and tasks within the sustainable construction system.

Design elements

Game interface and mechanism

Before playing the game, players will have to input their username and select a role they intend to take (e.g. construction managers, architects, civil engineers or surveyors). When the game starts, players in the same lobby will be presented with a sustainable construction challenge. A clear goal should exist in the game for an immersive experience and effective knowledge acquisition of players (Poplin, 2012). The challenge will be randomised representing different building types, designs and sustainability requirements.

Each player can pick different decisions representing the roles and project management options applicable to different stakeholders in the supply chains. Players can negotiate with each other to select their decisions throughout the game session. Each decision will have different impacts on the completion time of the building and its sustainability performance and each player must understand the trade-off between building performance, economic, environment and social objectives. The building must be completed within the given timeframe; otherwise, all players in the group will be penalised. A time compelling game is important in a sustainable construction problem as timely delivery is one of the main factors determining client satisfaction (Yang & Peng, 2008).

Game information system

An information system (i.e. recommendation system, tutorial and e-learning materials) will be in place to guide players in understanding the problems and goals and making decisions. Firstly, the game will have a recommendation system to guide students in making the right decisions. Player data will be collected in real-time in order to derive a recommendation for the players. For example, if there is a large gap between the sustainability goal and the current game status, the game will recommend specific players to pick certain decisions to improve their future performance (Annetta, 2010).

Secondly, students will be able to access e-learning materials related to sustainable construction and the underpinning systems model used in the game (Fotiadis & Sigala, 2015). These materials will be in the form of books, articles and videos. This will provide students with in-depth knowledge on how systems thinking works and how it applies to sustainable construction problems. Thirdly, a tutorial on how to play the game will also be provided within the game.

Students' performance evaluation system

To evaluate the effectiveness of the game, a mixed method approach by Mayer et al. (2014) will be employed such as interviews, focus group, and surveys during the game test session. This game test session will be held with sustainable construction students at Griffith University after the game's first release. This approach allows direct interactions with students to capture user experience and gain their feedback and inputs of how effective the game mechanics are in conveying the learning objectives and curriculum and improving their learning outcomes (Harteveld, 2012).

Randomised quizzes will be placed at the start and end of the game to measure changes in students' understanding of the roles and tasks performed by their respective roles in the game. It is the most common approach in learning and teaching system in measuring higher education students' performance (Cook & Babon, 2017). According to Cook and Babon (2017), online quizzes were proven to incentivise student completion and time efficiency. A quiz is also a good instrument to determine if the serious game effectively conveys students' knowledge acquisition and problem-solving ability (Riemer & Schrader, 2015). The quizzes will focus on evaluating students' understanding and knowledge of each stakeholder's actions and reflecting on the long-term implications of their decisions.

Conclusions and Future Directions

This paper is the first step of developing a serious game for sustainable construction to develop its design framework. Firstly, a causal loop diagram focusing on the interlinkages between sustainability aspects (i.e. environment, economic and social aspects) of construction and different interventions was developed using the systems thinking approach. In addition, key variables were identified through the literature review. Secondly, the game will integrate experiential and collaborative learning to facilitate active experimentation and collaborative actions to solve a specific sustainable construction problem. Thirdly, design elements such as interface, information system and students' performance evaluation system have been established following the framework by Annetta (2010) to enable an immersive, interactive game, possess good complexity, informative and instructional.

The limitation of this study is the use of literature review as a primary means to create the conceptual model and design framework. Future research should utilise an expert consultation approach to validate the systems model and confirm the pedagogical principles and design elements suitable for the sustainable construction course. A preliminary concept of integrating the systems model, pedagogical principles, and user interface should also be developed to better understand how the game is developed and convey the key learning objectives.

References

Al horr, Y., Arif, M., Katafygiotou, M., Mazroei, A., Kaushik, A., & Elsarrag, E. (2016). Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature. *International Journal of Sustainable Built Environment, 5*(1), 1-11.

Annetta, L. A. (2010). The "I's" have it: A framework for serious educational game design. *Review of General Psychology, 14*(2), 105-113.

Cook, B. R., & Babon, A. (2017). Active learning through online quizzes: better learning and less (busy) work. *Journal of Geography in Higher Education, 41*(1), 24-38.

Dib, H., & Adamo-Villani, N. (2014). Serious sustainability challenge game to promote teaching and learning of building sustainability. *Journal of Computing in Civil Engineering, 28*(5), A4014007.

El-adaway, I., Pierrakos, O., & Truax, D. (2015). Sustainable construction education using problem-based learning and service learning pedagogies. *Journal of Professional Issues in Engineering Education & Practice, 141*(1), 05014002.

Fotiadis, A. K., & Sigala, M. (2015). Developing a framework for designing and Events Management Training Simulation (EMTS). *Journal of Hospitality, Leisure, Sport & Tourism Education, 16*, 59-71.

Häkkinen, T., & Belloni, K. (2011). Barriers and drivers for sustainable building. *Building Research & Information, 39*(3), 239-255.

Harteveld, C. (2012). *Making sense of virtual risks - A quasi-experimental investigation into game-based training* [Doctoral dissertation, TU Delft]. Delft.

Hovmand, P. (2014). *Community Based System Dynamics*. Springer-Verlag.

Juan, Y., & Chao, T. (2015). Game-based learning for green building education. *Sustainability, 7*(5), 5592-5608.

Kolb, D. A. (1984). *Experiential Learning: Experience as the Source of Learning and Development*. Prentice-Hall International

Laal, M., & Ghodsi, S. M. (2012). Benefits of collaborative learning. *Procedia - Social and Behavioral Sciences, 31*, 486-490.

MacAskill, S., Roca, E., Liu, B., Stewart, R. A., & Sahin, O. (2020). Is there a green premium in the Green Bond market? Systematic literature review revealing premium determinants. *Journal of Cleaner Production*, 124491.

Madani, K., Pierce, T. W., & Mirchi, A. (2017). Serious games on environmental management. *Sustainable Cities and Society, 29*, 1-11.

Mayer, I., Bekebrede, G., Harteveld, C., Warmelink, H., Zhou, Q., van Ruijven, T., Lo, J., Kortmann, R., & Wenzler, I. (2014). The research and evaluation of serious games: Toward a comprehensive methodology. *British Journal of Educational Technology, 45*(3), 502-527. (10.1111/bjet.12067)

Miguel, N. P., Lage, J. C., & Galindez, A. M. (2020). Assessment of the development of professional skills in university students: Sustainability and serious Games. *Sustainability, 12*(3), 1014.

Mills, F. T., & Glass, J. (2009). The construction design manager's role in delivering sustainable buildings. *Architectural Engineering and Design Management, 5*(1-2), 75-90.

Murtagh, N., Roberts, A., & Hind, R. (2016). The relationship between motivations of architectural designers and environmentally sustainable construction design. *Construction Management and Economics, 34*(1), 61-75.

Poplin, A. (2012). Playful public participation in urban planning: A case study for online serious games. *Computers, Environment and Urban Systems, 36*(3), 195-206.

Riemer, V., & Schrader, C. (2015). Learning with quizzes, simulations, and adventures: Students' attitudes, perceptions and intentions to learn with different types of serious games. *Computers & Education, 88*, 160-168.

Ries, R., Bilec, M. M., Gokhan, N. M., & Needy, K. L. (2006). The economic benefits of green buildings: A comprehensive case study. *The Engineering Economist, 51*(3), 259-295.

Sadowski, J., Seager, T. P., Selinger, E., Spierre, S. G., & Whyte, K. P. (2013). An experiential, game-theoretic pedagogy for sustainability ethics. *Science and Engineering Ethics, 19*, 1323-1339.
Sahin, O., Salim, H., Suprun, E., Richards, R., MacAskill, S., Heilgeist, S., Rutherford, S., Stewart, R. A., & Beal, C. D. (2020). Developing a preliminary causal loop diagram for understanding the wicked complexity of the COVID-19 pandemic. *Systems, 8*(2), 20.
Sev, A. (2009). How can the construction industry contribute to sustainable development? A conceptual framework. *Sustainable Development, 17*(3), 161-173.
Sfakianaki, E. (2019). Critical success factors for sustainable construction: A literature review. *Management of Environmental Quality, 30*(1), 176-196.
Solaimani, S., & Sedighi, M. (2020). Toward a holistic view on lean sustainable construction: A literature review. *Journal of Cleaner Production, 248*, 119213.
Sterman, J. D. (2000). *Business Dynamics: Systems Thinking and Modeling for a Complex World*. McGraw-Hill Education.
Suprun, E., Sahin, O., Stewart, R. A., Panuwatwanich, K., & Shcherbachenko, Y. (2018). An integrated participatory systems modelling approach: Application to construction innovation. *Systems, 6*(3), 33.
United Nations. (2015). *Transforming our world: The 2030 agenda for sustainable development*. Retrieved 28 May from https://sdgs.un.org/2030agenda
van Kamp, I., Leidelmeijer, K., Marsman, G., & de Hollander, A. (2003). Urban environmental quality and human well-being: Towards a conceptual framework and demarcation of concepts; a literature study. *Landscape and Urban Planning, 65*(1-2), 5-18.
Vogel, J. J., Vogel, D. S., Cannon-Bowers, J., Bowers, C. A., Muse, K., & Wright, M. (2006). Computer gaming and interactive simulations for learning: A meta-analysis. *Journal of Educational Computing Research, 34*(3), 229-243.
Westera, W., Nadolski, R. J., Hummel, H. G. K., & Wopereis, I. G. J. H. (2008). Serious games for higher education: a framework for reducing design complexity. *Journal of Computer Assisted Learning, 24*(5), 420-432.
Whalen, K. A., Berlin, C., Ekberg, J., Barletta, I., & Hammersberg, P. (2018). 'All they do is win': Lessons learned from use of a serious game for Circular Economy education. *Resources, Conservation and Recycling, 135*, 335-345.
Yang, J.-B., & Peng, S.-C. (2008). Development of a customer satisfaction evaluation model for construction project management. *Building and Environment, 43*(4), 458-468.
Ypsilanti, A., Vivas, A. B., Räisänen, T., Viitala, M., Ijäs, T., & Ropes, D. (2014). Are serious video games something more than a game? A review on the effectiveness of serious games to facilitate intergenerational learning. *Education and Information Technologies, 19*, 515-529.

Acknowledgements

This research was fully supported by Griffith University's Learning and Teaching Grant. The authors would also like to acknowledge two anonymous reviewers for their valuable feedback during the peer-review process.

Copyright statement