Journal of Cleaner Production 256 (2020) 120358

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

A bibliometric review of research on simulations and serious games used in educating for sustainability, 1997–2019

Philip Hallinger [a, b, *], Ray Wang [a, c], Chatchai Chatpinyakoop [a], Vien-Thong Nguyen [a], Uyen-Phuong Nguyen [a]

[a] Mahidol University, Thailand
[b] University of Johannesburg, South Africa
[c] Thammasat University, Thailand

ARTICLE INFO

Article history:
Received 30 November 2019
Received in revised form
29 January 2020
Accepted 31 January 2020
Available online 3 February 2020

Handling editor: Prof. Jiri Jaromir Klemeš

Keywords:
Sustainability
Education for sustainable development
Simulations
Serious games
Bibliometric review
Role play games

ABSTRACT

Scholars have noted a recent proliferation of simulations and serious games developed for use in educating for sustainability. However, to date, reviews of research have focused on the use of simulations and games in specific subject domains of sustainability such as energy, climate change, and natural resource management. This bibliometric review addressed this gap by documenting and analyzing the full span of research on simulations and serious games used in educating for sustainability. The review aimed to document the growth trajectory, types of documents, topical foci, modes of delivery, and geographical distribution of this literature. Then the authors analyzed research designs and methods employed in this research. The authors applied descriptive statistics and content analysis to 376 relevant Scopus/Google Scholar-indexed documents describing the use of simulations and serious games in educating for sustainability. Key results highlighted the recent vintage of this literature as well as a predominance of studies from a relatively small set of Western societies. The simulations and serious games described in these documents encompass foci on environmental, economic and social sustainability. Technology-enhanced simulations and games are most prevalent, and higher education settings the most common venues of use in this literature. The knowledge base is overly weighted towards 'commentaries' (55%) and lacks a critical mass of empirical studies (33%). Moreover, the empirical knowledge base is dominated by studies that rely on non-experimental research designs and descriptive methods. The authors highlight a variety of stronger research designs and methods that can be used as models for future research. This aligns with a key recommendation for scholars in this domain to undertake programmatic research aimed at substantiating the effects of simulations and serious games on learner attitudes, knowledge and behavior.

Contents

* Corresponding author. College of Management, Mahidol University, 69 Vipavadee Rangsit Rd, Bangkok, Thailand.
E-mail address: Hallinger@gmail.com (P. Hallinger).

https://doi.org/10.1016/j.jclepro.2020.120358
0959-6526/

1. Introduction

The urgent sustainability challenges facing societies throughout the world have been well documented (Sachs, 2015). Climate change is transforming the underlying economic, political, social and environmental assumptions on which the nations have operated since the advent of the industrial revolution in the 19th century (Brundtland et al., 1987; Sachs, 2015). This was recently acknowledged by CEOs of America's 200 largest corporations in a statement that belatedly codified their entry into the 'era of sustainability'.

> Breaking with decades of long-held corporate orthodoxy, the [United States] Business Roundtable issued a statement on "the purpose of a corporation," arguing that companies should no longer advance only the interests of shareholders. Instead, the group said, they must also invest in their employees, protect the environment and deal fairly and ethically with their suppliers (Gelles and Yaffe-Bellany, 2019, n p.)

In response, a group of CEOs of smaller multinational firms asserted that even this statement of intent was insufficient. They challenged these (and all) companies to: "operate with a better model of corporate governance – which gives us, and could give you, a way to combat short-termism and the freedom to make decisions to balance profit and purpose" (Wood, 2019, n. p.). These extraordinary statements from corporate CEOs reaffirm the urgent need to reorient 21st century ways of working and living towards the triple bottom line of people, planet and profits (Elkington, 1998). Facilitating this change in human attitudes and behavior stands as the single greatest educational challenge facing the world today (Sachs, 2015; Wals, 2011). Specifically, how can we inform, motivate, and change the attitudes and behaviors of current and future generations towards the sustainability challenges that threaten life on our planet?

Scholars have proposed that simulations and serious games (SSGs) are ideally suited to meeting this challenge (Castro-Sánchez et al., 2016; Crookall, 2013; Hallinger and Wang, 2019). While traditional forms of instruction (e.g., lecture and discussion) may be efficient at fostering student recall and comprehension, simulation-based learning is superior at engaging students, developing higher-order thinking, and fostering retention and transfer of actionable skills (Gokhale, 1996; Gosen and Washbush, 2004). Indeed, research finds that SSGs even offer advantages over other active learning methods (e.g., problem-based learning, project based learning, case-based learning) in subjects where skill development and knowledge transfer are paramount (Littlewood et al., 2013; Steadman et al., 2006).

Recognition of this potential has led to the design of SSGs that address sustainability challenges for use in educational settings (Antle et al., 2011; Aragon-Correa et al., 2017; Bevilacqua et al., 2015; Ulrich, 1997). Indeed, a current review of research highlighted the recent proliferation of SSGs related to 'sustainability' topics (Hallinger and Wang, 2019). However, to date, scholars have only reviewed research on the use of SSGs in narrow sustainability domains such as energy, natural resource management, or climate change (Albertarelli et al., 2018; Barreteau et al., 2007; Katsaliaki and Mustafee, 2012; Liarakou et al., 2012; Madani et al., 2017; Reckien and Eisenack, 2013). Thus, the field lacks systematic documentation of the full range and scope of use of 'sustainability simulations and serious games' (S-SSGs).

The current review addressed this gap by examining the full range of relevant research on the use of simulations and serious games in educating for sustainability. The following research questions guided the review.

1. What are the volume, publication trajectory, and geographical distribution of research on the use of simulations and serious games in educating for sustainability?
2. How is research on the use of simulations and serious games in educating for sustainability distributed by topics, subject areas, modes of delivery, and educational settings?
3. What research designs and methods have been used in research on the use of simulations and serious games in educating for sustainability?

The authors identified 376 research papers that reported on the use of simulations and serious games in educating for sustainability. Bibliographic data exported from Scopus and Google Scholar were analyzed using MS Excel, Tableau and VOSviewer software programs. Bibliometric analyses were used to document and analyze the evolving landscape of research comprising this emerging knowledge base. The results offer empirical evidence on the breadth and nature of use of simulations and serious games in educating for sustainability, as well as a critical analysis of this emerging field of research and practice. By addressing these dual goals, the review provides a foundation on which to build future research and development efforts. This is an essential step aimed at ensuring that we tap the full potential of simulations and serious games in educating for sustainability (Baalsrud Hauge et al., 2014;

Dieleman and Huisingh, 2006; Katsaliaki and Mustafee, 2012).

2. Conceptual framework

In this section the authors introduce the two domains of knowledge that underlie this review of research. First, we introduce the conceptual perspective on 'sustainability' that guided the review. Then we provide conceptual background on the use of simulations and serious games for learning.

The related concepts of sustainability and sustainable development have gained ever-increasing traction since publication of the Brundtland Report in 1987 (Brundtland et al., 1987). The Brundtland Report defined sustainable development as *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs."* (Brundtland et al., 1987, p. 41). Curran subsequently defined sustainability as a, "*destination that we aspire to reach with the selection of the sustainable pathways that we choose as we proceed along the journey*" (Curran, 2009, p. 6). Taken together these perspectives on sustainability highlight the transgenerational challenges of balancing short-term economic priorities with the longer-term interests of society (Figueiro and Raufflet, 2015). In addition, the Brundtland Report (Brundtland et al., 1987) also highlighted the relationship between underlying environmental and social conditions of society and long-term economic prosperity (Sachs, 2015; Wals, 2011).

More recently, the interdependence of social, environmental and economic sustainability was highlighted by President Macron's efforts to raise France's commitment to ambitious environmental standards. The projected impact of raising environmental standards gave rise to resistance among stakeholders who felt threatened by the potential increase in prices and loss of jobs. These perspectives suggest that sustainable development can only be achieved when organizations and societies find a mutually reinforcing balance among the three bottom lines (Aragon-Correa et al., 2017; Bekebrede et al., 2017; Moratis et al., 2006; Sachs, 2015; Stanitsas et al., 2019).

Educating citizens about the challenges of sustainability requires methods capable of fostering a 'systemic perspective' and action competencies among learners (Wals, 2011). Thus, educators have been in search of teaching and learning methods suited to these goals. Kriz (2003) claimed that SSGs offer a more effective and holistic approach to understanding complex systems and generating ideas for change than other forms of instruction.

In a recent bibliometric review of 2812 studies, Hallinger and Wang (2019) highlighted the growing relevance of sustainability in the literature on simulations and serious games. Using temporal keyword analysis, they found that the 'hottest topics' in research on simulation-based learning were clustered around keywords associated with sustainability (i.e., 'sustainability', 'climate change', 'water management', 'risk management', 'complex systems'). This empirically derived finding yielded a recommendation for a follow-up review of the emerging literature on simulations and serious games used in educating for sustainability (Hallinger and Wang, 2019).

In this review, we adapted a conceptual model of simulations and games used for learning developed by Martens and colleagues (Martens et al., 2008) The model shown in Fig. 1 distinguishes simulations used for the purpose of 'learning' from those used for 'training' (e.g., flight simulators) or 'scientific modeling' (e.g., impact of climate change on water resources). Similarly, 'serious games' designed explicitly for 'learning' are distinguished from 'games' whose primary purpose is 'entertainment'. The category of serious games encompasses interactive role plays as well as board games. In the current review, the authors focus on both simulations and serious games used for learning about sustainability.

Fig. 1. Conceptual model of simulations and serious games used for learning (adapted from Martens et al., 2008, p. 173, p. 173).

3. Method

This review of research relied on a combination of bibliometricand document content analysis (Hallinger and Chen, 2015; Hallinger and Kovačević, 2019; Zupic and Čater, 2015). In contrast to narrative and meta-analytic reviews, bibliometric reviews neither examine nor synthesize the 'substantive findings' of a body of studies. Instead, bibliometric reviews examine 'bibliographic meta-data' associated with a corpus of documents with the aim of understanding trends in the production of knowledge. Given the recent vintage of literature on the use of simulations and serious games in educating for sustainability (S-SSGs), the descriptive-analytical capacities of bibliometric and content analysis were well suited to the goals of this review.

3.1. Identification of documents

This review relied on the Scopus database as the primary source of documents on S-SSGs. Scopus was chosen because it employs a consistent standard of document inclusion in its database, and also offers the ability to export bibliographic meta-data for use in bibliometric software packages. Moreover, compared to the Web of Science, Scopus offers more comprehensive coverage of relevant education and social science journals (Hallinger and Kovačević, 2019; Mongeon and Paul-Hus, 2016). Nonetheless, as described below, the main document search conducted in Scopus was supplemented by a secondary search for relevant documents in Google Scholar.

In terms of scope, this review sought a broad mix of documents including journal articles, book chapters, and conference proceedings. Although no boundary was set to limit the time period of publication, the earliest relevant documents appeared in 1997 (Applegate and Sarno, 1997; Ulrich, 1997). We adopted a similarly broad approach with respect to the educational settings in which S-SSGs were used. Thus, we included documents that described the use of S-SSGs in K-12, higher education, corporate training and professional development settings, as well as in public forums (e.g., open access online serious game or a simulation in a museum).

The topical scope of this review was delimited to 'simulations and serious games used for learning about sustainability'. This

topical scope was informed by our conceptualizations of 'simulations and serious games' as well as 'sustainability' described in the previous section of this paper. In operational terms, we included computer simulations, online simulations and games, board games, and role plays aimed at educating learners about sustainability issues in multiple subject domains (e.g., environment, corporate social responsibility, climate change, energy, management, building, water etc.). This contrasts with prior reviews of this literature that focused on subsets of the literature (e.g., environmental simulations).

The authors followed PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines for the document search (Moher et al., 2009). PRISMA requires the reviewer to make explicit all steps followed in the search and screening process (see Fig. 2). Due to our past experience with the limitations of the Scopus search engine, different combinations of search terms were used in both Scopus and Google Scholar in our search for relevant documents. A series of searches, were conducted that used different combinations of the following keyword string: ('Simulation' OR 'Game' AND 'Learning') AND ('Sustainable Development' OR 'Sustainability' OR 'Sustainable', OR 'Green', OR 'Lean' OR 'Social') AND ("Education' OR 'School').

In combination, these Scopus searches yielded 579 documents (see Fig. 2). Next we conducted a similar search in Google Scholar which yielded 18 additional documents. Three of these documents were subsequently located in Scopus and added to the Scopus list. The other 15 Google Scholar documents were retained as a separate list which was later combined with the Scopus data following the data extraction process. Together these procedures yielded a full list of 597 documents.

Next we filtered the document list of 597 documents excluding:

- 'duplicates' (e.g., conference paper later published as article, or article in press later published in final form),
- 'ineligible document types' (e.g., notes, editorials), and
- 'irrelevant documents' (i.e., not related to the core topical constructs).

During the topical screening, two researchers independently inspected each document to determine topical relevance using the conceptual definitions of 1) sustainability and 2) simulations and serious games offered earlier. Documents were typically excluded for one of two reasons. First, many ineligible documents focused on simulations that were used for 'modeling' (e.g., climate change or lean production) instead of learning. Second, quite a few learning games identified in the search did not focus sufficiently on social or environmental sustainability issues. Documents were also excluded that did not align with our definition of SSGs. For example, some papers described a problem-based or project-based activity that did not meet our definition of SSGs. At the conclusion of these filtering and screening steps, the final database was comprised of 361 Scopus-indexed documents and 15 Google Scholar documents that did not appear in Scopus for a total of 376 documents.

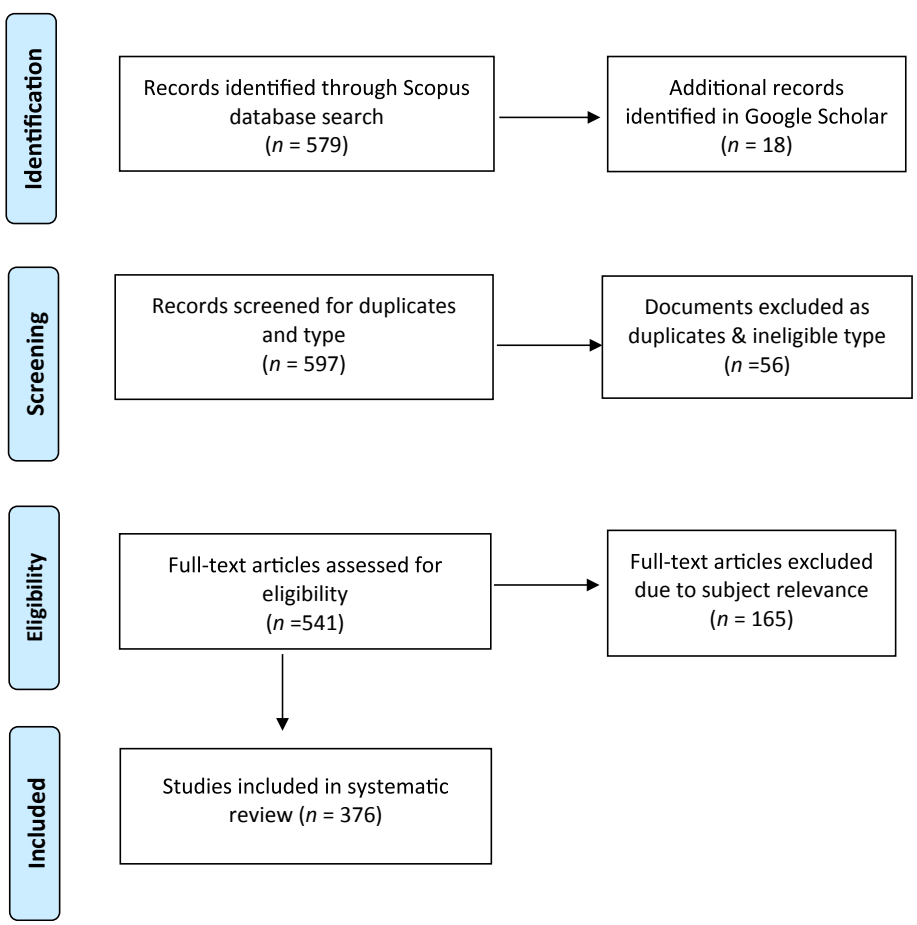

Fig. 2. Identification of sources for the review of sustainability simulations and serious games (Moher et al., 2009).

3.2. Data extraction and analysis

Bibliographic meta-data data associated with the Scopus documents were exported into an Excel file. These included the author name(s), document title, year of publication, source document (e.g., journal, book or conference name), citation information, and author affiliations. Next, comparable bibliographic data related to the Google Scholar documents were entered by hand into the same Excel worksheet. The combined worksheet consisted of initial information derived from Scopus and Google Scholar on the 376 documents.

In order to address our research questions, we identified additional categories relevant to our research questions (Hallinger and Chen, 2015). These included geographic region, document type, topical focus, mode of delivery, educational settings, type of research paper, research design, research method, statistics and sample size. In total, the resulting spreadsheet contained 376 rows representing the documents and 27 columns representing content categories.

Next the authors developed a coding scheme designed to facilitate content analysis of the 376 documents based on the identified categories. For example 'document type' was coded as 1 = book chapter, 2 = journal article, 3 = conference paper, 4 = other. Codes were developed for geographic regions (e.g., North America, Europe, Africa etc.), modes of delivery (e.g., computer, online, board game, role play, multiple, other), educational settings (K-12, higher education, professional development, multiple, other), topics, subject areas, research designs (experimental, quasi experimental, non-experimental), research methods (quantitative, qualitative, mixed), statistical tests (e.g., descriptive, correlation, correlation with single control, multiple factor), and sample size. The codes were applied initially to a small sample of actual documents and then revised for clarity and feasibility of coding and analysis.

Next we scanned each of the 376 documents with the goal of extracting information relevant to the content categories. Two researchers independently coded each of the 376 documents. Cases of disagreement on coding were quite common. For example, quite a few papers presented research findings without presenting a full description of the methodology. While these were sometimes coded as 'empirical papers', after discussion they were recoded as 'commentary' papers. Similarly, some papers that authors had presented as experiments did not meet our definition of an 'experiment' and were, therefore recoded as quasi-experimental or non-experimental studies.

Data analysis relied primarily on the use of descriptive statistics and graphing of trends (e.g., geographic distribution of the S-SSG studies). Data describing the 376 documents were analyzed with the dual objectives of identifying modal trends and highlighting variability. The broad goal of data analysis was to understand the scope of use of S-SSGs in educating for sustainability, the nature of these S-SSGs, topics covered in this research, and finally how scholars are studying the use of S-SSGs in practice.

The VOSviewer software program was used to conduct 'temporal keyword co-occurrence analysis' of topical foci in this literature (van Eck and Waltman, 2014). The 361 Scopus-indexed documents were uploaded into VOSviewer for this analysis. In this analysis the software first scans the titles, keywords and abstracts of documents in the review database in order to identify the frequency of 'co-occurring keywords'. Then, the software links the occurrence of keywords with the publication years of their associated documents. Finally, it creates a distribution of dates for each keyword and identifies the time period in which a given keyword (i.e., topic) has featured most prominently in the literature (van Eck et al., 2010; van Eck and Waltman, 2014; Zupic and Cater, 2015).

4. Results

In this section we begin by describing the landscape of literature on S-SSGs from multiple perspectives. Then we analyze foci and features of simulations and games used in educating for sustainability. Finally, we examine the research designs and methods used in this domain of educational research.

4.1. Landscape of research on SSGs in educating for sustainability

4.1.1. Size and composition

The 376 documents in our database included 205 journal articles (55%), 155 conference papers (41%), and 16 book chapters (4%). As noted earlier, the first documents uncovered in our search appeared in 1997. Applegate and Sarno (1997) authored a commentary paper that described the design and use of a particular environmental simulation game. Ulrich (1997) documented the 'early use' of simulations and serious games concerned with environmental sustainability.

4.1.2. Growth trajectory

The growth trajectory of publications in this knowledge base was low and relatively flat between 1997 and 2010 (see Fig. 3). During this phase of research and development on S-SSGs, publications averaged only 3.2 documents per year. It was not until 2011 that a sharp up-tick in relevant publications emerged. During the subsequent decade (2011–2019), S-SSG publications averaged 28.7 per year with a particularly sharp acceleration in the past five years (see Fig. 3).

4.1.3. Geographic distribution

Analysis of the geographic distribution of the 376 documents based on affiliation of the first author found that authorship of S-SSG publications is unevenly distributed across the globe (see Fig. 4). Fully 86% of the studies were authored in Western, economically developed societies (not tabled). Studies authored in Europe account for a majority (62%) of this literature. Yet, despite the general prominence of European scholarship, we noted that, by nationality, American authors have published the most documents (85) on S-SSGs, followed by scholars from the Netherlands (54), Germany (45), and the United Kingdom (40).

The relative paucity of papers authored in Latin America (Chaim et al., 2018; de Barros et al., 2018; Dos Santos et al., 2018; Ducrot et al., 2015; Ordaz et al., 2015; Speelman et al., 2014) and Africa (Lamrani et al., 2018; Le Bars et al., 2014; Rowntree and Fox, 2008; van der Merwe, 2017) raises questions about the frequency with

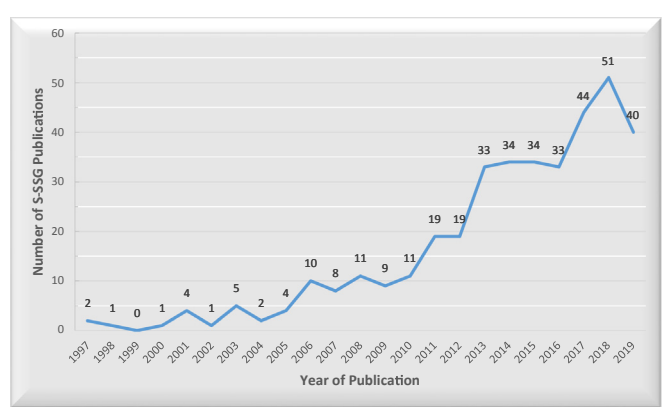

Fig. 3. Growth trajectory of publications on the use of simulations and serious games in educating for sustainability (S-SSG), 1997–2019, October (n = 376).

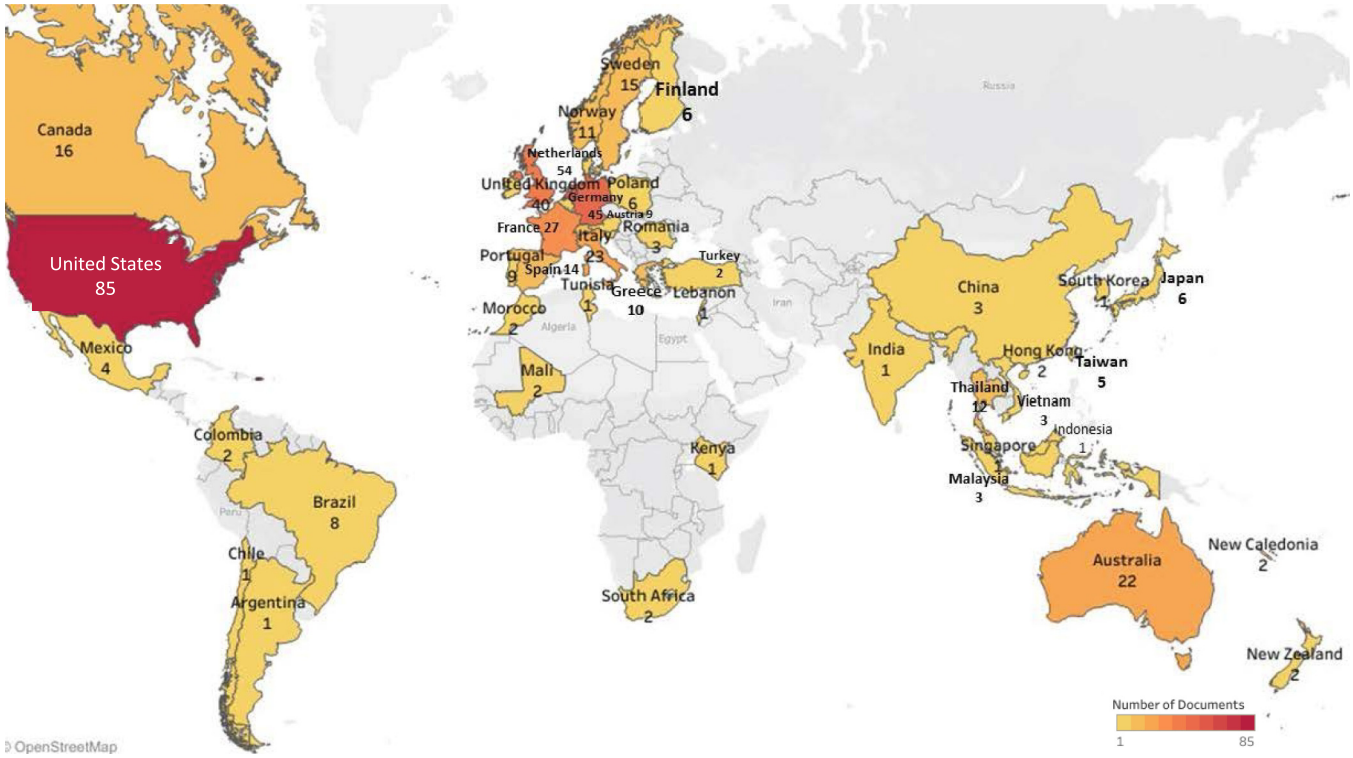

Fig. 4. Geographical distribution of the literature on simulations and serious games used in educating for sustainability, 1997–2019, October (n = 376 documents).
[1]Individual papers could be assigned multiple topics so the results are higher than the number of documents.

which SSGs are being to educate for sustainability in these developing regions of the world. However, it should be reiterated that this analysis was based on the affiliation of the first author of the papers so the analysis does not take into co-authorship by African and Latin American (or Asian) scholars. Indeed, during the process of scanning individual papers, we noted a number of additional studies that documented the use of SSGs in Latin American and African societies (e.g., Ayadi et al., 2014; Bellaubi and Pahl-Wostl, 2017; Daré and Barreteau, 2003; Juan and Chao, 2015; Speth et al., 2018). The most frequent topics for simulations used in these emerging regions concerned water, natural resource and agricultural management.

4.1.4. Types of research papers

Any knowledge base is comprised of a variety of different 'types of research papers' (e.g., empirical or non-empirical). In this review we followed a four-category rubric adopted by Hallinger and Chen (2015) to classify the 376 documents as empirical studies, commentaries, conceptual papers, or research reviews. Empirical studies report the systematic collection and analysis of quantitative and/or qualitative data (e.g., Ayer et al., 2016; Chow et al., 2017; Le Bars et al., 2014; Speelman et al., 2014). Commentaries critique the literature, report on broad trends with selective reference to the literature, or describe the development and use of a simulation in practice. Although commentaries often refer to preliminary results from field trials, they offer incomplete descriptions of research methods and results (e.g., Applegate and Sarno, 1997; Bellaubi and Pahl-Wostl, 2017; Moratis et al., 2006; Speth et al., 2018). Conceptual papers propose a means of conceptualizing S-SSGs in terms of design elements, instructional processes (e.g., debriefing) or assessment of learning outcomes (e.g., Aubert et al., 2019; Chaim et al., 2018 Tanenbaum et al., 2013). Reviews of research systematically analyzed an explicitly identified set of S-SSG documents (Albertarelli et al., 2018; Barreteau et al., 2007; Reckien and Eisenack, 2013; Madani et al., 2017; Ulrich, 1997).

We wish to emphasize that there is no single 'optimal' distribution of types of research documents in a literature against which to benchmark the results of this analysis. A knowledge base is a dynamic entity whose composition changes over time as it moves from birth towards maturity. During early periods of development there is often an emphasis on conceptualization, critique and commentary. This is reflected in scholarly discourse aimed at defining the conceptual foundations of the field, describing early practices and innovations, and proposing potential lines of inquiry (Hallinger and Kovačević, 2019). Research reviews are typically limited in number during this period due to the relative scarcity of empirical studies. Over time, however, the balance between types of papers shifts as empirical studies begin to accumulate. This gradually leads to a concomitant reduction in the proportion of commentaries, as well as a small but discernible uptick in the proportion of research reviews.

The distribution of research papers by 'type' is displayed in Fig. 5. The proportion of commentaries (55%) whose typical purpose was to 'describe' the design and use of a particular S-SSG seems much higher than desirable, and out of balance when compared with the much lower proportion of empirical studies (33%). Reviews of research account for 6% of the literature. Although this seems like a reasonable proportion of the literature, we noted that these reviews were generally formulated as 'surveys' of simulations in a particular domain (e.g., climate change, environment) rather than as reviews of 'research findings' (Albertarelli et al., 2018; Baalsrude Hauge et al., 2014; Barreateau et al., 2007; Ulrich, 1997; Wu and Lee, 2015).

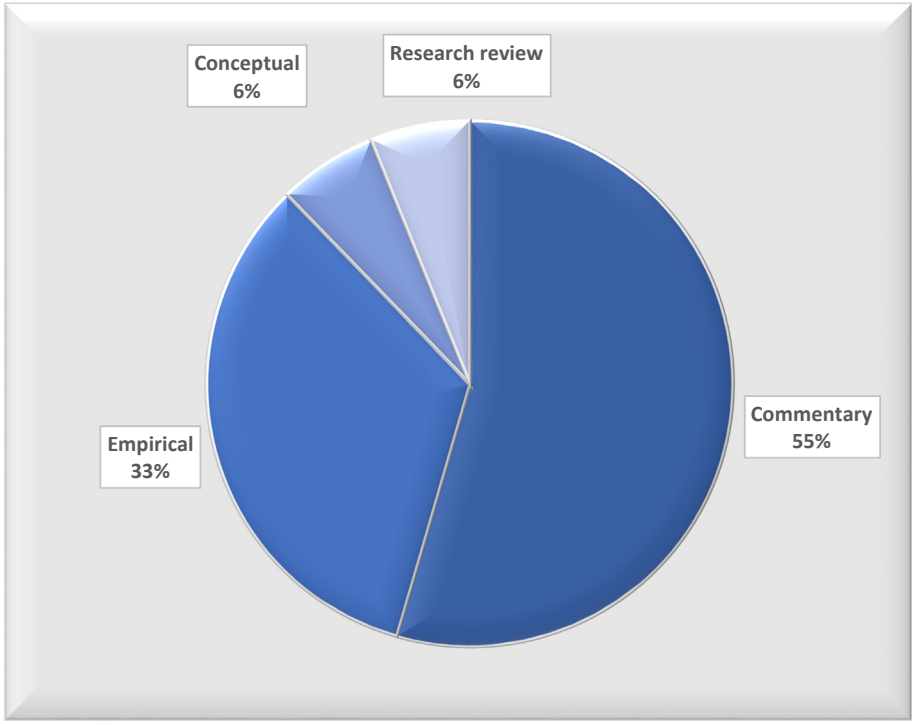

Fig. 5. Distribution of published documents on sustainability simulations and serious games by type of research paper, 1997–2019, October (n = 376 documents).
[1]Individual papers could be assigned multiple topics so the results are higher than the number of documents.

4.2. Subjects, topical foci and features of SSGs used in educating for sustainability

4.2.1. Subject and sustainability foci of S-SSGs

Initially, content analysis was used to identify the distribution of subject domains in which S-SSGs have been used. Fig. 6 affirms that simulations and serious games are being used across all three conceptual domains of sustainability (i.e., environmental, social, economic). These data also reflect the diversity of academic fields in which S-SSGs are being used. These include social sciences, computer science, engineering, management, architecture, agriculture, urban studies, geography, and the sciences.

A perusal of Fig. 6 suggests that studies of SSGs related to the 'environment' account for the largest portion of the database (e.g., Applegate and Sarno, 1997; Ducrot et al., 2015; Madani et al., 2017; Ulrich, 1997). Climate change (Crookall, 2013; Eisenack, 2013; Harker-Schuch et al., 2020; Jacquet et al., 2013; Meya and Eisenack, 2018), energy (Albertelli et al., 2018; Yang et al., 2012) and water (Aubert et al., 2019; Van der Wal et al., 2016; Zhou and Mayer, 2018) have become the focus of numerous S-SSGs. However, environmental S-SSG's encompassed a broader range of topical foci related to resource use, conservation, and management (Barreteau et al., 2007). These include recycling and waste management (Applegate and Sarno, 1997; Chow et al., 2017; Hirose et al., 2004), sustainable product design and production (Hidayatno et al., 2019; Moser and Mußhoff, 2016; Whitman et al., 2008), agriculture and land management (Ayadi et al., 2014; Daré and Barreteau, 2003; Speelman et al., 2014), forest management (Dumrongrojwatthana et al., 2015), transportation (Kurapati et al., 2018), green construction (Ayer et al., 2016; Dib et al., 2012; Juan and Chao, 2015), and urban planning (Bekebrede et al., 2017).

The second conceptual pillar of this literature, 'social sustainability', was represented in a large diverse group of S-SSG papers. These focused on corporate social responsibility (Maltseva et al., 2019; Moratis et al., 2006; Żmuda et al., 2015), sustainable consumption (Bevilacqua et al., 2015; Mulcahy et al., 2018), as well as personal, organizational and social change (Ahamer, 2006; Antle et al., 2011; Kriz, 2003; Svoboda and Whalen, 2004). Sometimes social sustainability issues related to stakeholder engagement were addressed in the context of S-SSGs that involved negotiation between stakeholder groups competing for access to resources such as land, water (Bellaubi and Pahl-Wostl, 2017) or other natural resources (e.g., Ahamer, 2006; Daré and Barreteau, 2003; Dumrongrojwatthana et al., 2015; Ducrot et al., 2015; Jean et al., 2018).

The third pillar of sustainability, organizational efficiency and profitably, was most often integrated into S-SSGs that challenged learners to consider how profitability can be balanced with environmental and social concerns. This was, for example, evident in S-SSGs centering on lean manufacturing and production (Chaim et al., 2018; Duin and Thoben, 2011; Ordaz et al., 2015). Srijumpa and Dejprasert (2018) and supply chain management (Baalsrud Hauge et al., 2014; Cuesta and Nakano, 2017; Hidayatno et al., 2019). Life cycle assessment figured prominently as a key sustainability tool in these S-SSGs.

Building on this broad topical analysis, we used VOSviewer software to conduct 'temporal co-word analysis' in order to visualize the evolution of topical foci in this literature (see Fig. 7). We set VOSviewer to generate a keyword map based on a threshold of at least five occurrences in the titles, keywords and abstracts of the review documents. While this is a rather low threshold, it reflects the relatively small size of the document database. This yielded a map comprised of 90 keywords that we interpreted as topics. Then we used the temporal overlay function in VOSviewer to highlight the time distribution of these keywords.

For our purposes, the keyword map in Fig. 7 should be interpreted according to two features. First, the size of the 'keyword nodes' reflects the 'relative frequency' with which keywords

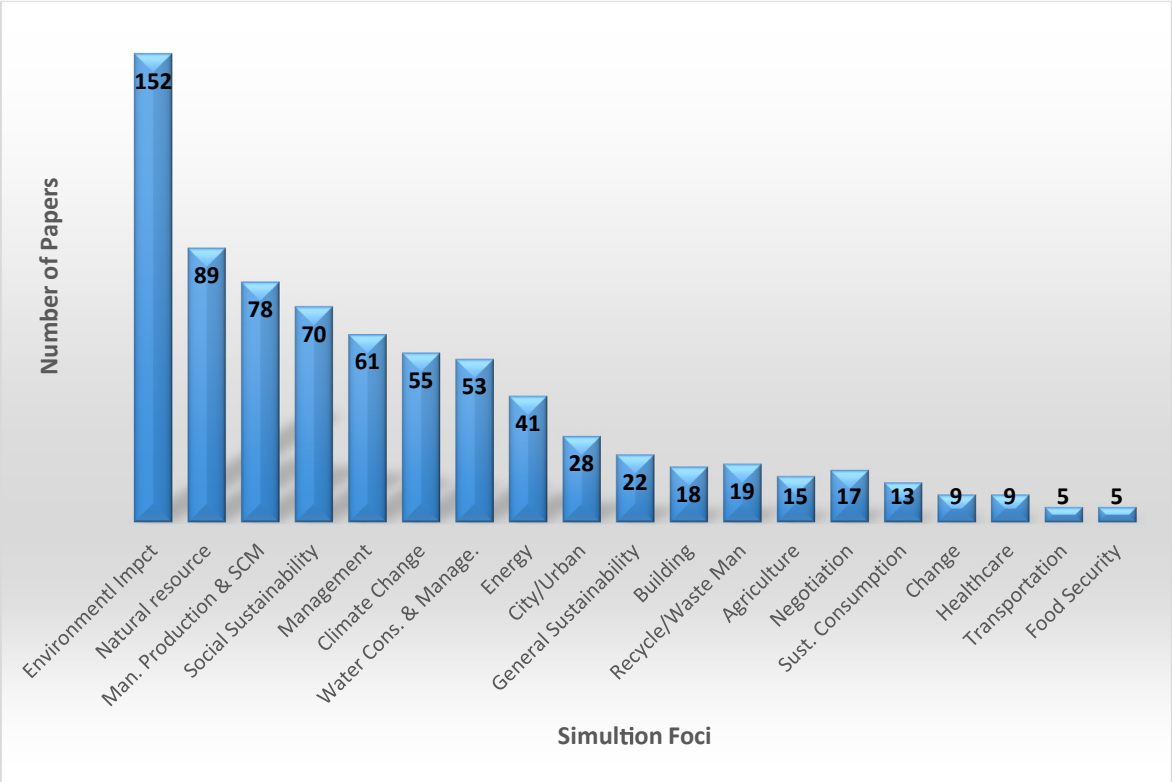

Fig. 6. Topical foci of simulations and serious games used in educating for sustainability, 1997–2019, October (n = 376 documents).
[1]Individual papers could be assigned multiple topics so the results are higher than the number of documents SCM = supply chain management.

occurred in our database. Larger nodes indicate keywords that occurred with greater frequency. Second, the color/shade of a node highlights the time period in which documents featuring the keyword were concentrated. Keywords that featured in documents during more recent years are indicated by yellow/lighter shade nodes.

Inspection of Fig. 7 reveals two periods in the evolution of this literature from 1997 to 2019. An initial period of development of sustainability simulations and games from 1997 to 2007. During this period role play games (e.g., Daré and Barreteau, 2003; Svoboda and Whalen, 2004), board games (Applegate and Sarno, 1997; Hirose et al., 2004), and desktop computer simulations (Dieleman and Huisingh, 2006; Moratis et al., 2006) were pioneered for the purpose of helping students learn how to address sustainability challenges. As indicated by the darker color of the nodes in Fig. 7, the early literature on sustainability simulations and serious games tended to focus on natural resource management, industrial management, and the environment (Barreteau et al., 2007; Ulrich, 1997).

A second phase characterized by new trends in delivery and content focus emerged in the mid to late 2000s. While role plays, board games and computer simulations continued to be produced and used, online simulations (keywords: e-learning, virtual learning environments, software design, gamification) began to emerge. This heralded a new generation in the delivery of S-SSGs (Antle et al., 2011; Ayer et al., 2016; Dos Santos et al., 2018; Mulcahy et al., 2018; Yang et al., 2012). These new online simulations offer enhanced capabilities for creating rich contexts for problem-solving, as well as the capacity to reach users anywhere and anytime.

We also observed indications of a content shift during this second phase of S-SSG development. Stimulated by publication of the United Nation's Millennium Development Goals and later Sustainable Development Goals, concerns for social sustainability (keyword: stakeholder) began to feature more prominently in this generation of S-SSGs (Den Haan and Van der Voort, 2018; Van der Wal et al., 2016; Żmuda et al., 2015). While environmentally-focused S-SSGs retained their relevance, energy, risk management, and spatial planning gained greater currency (Albertarelli et al., 2018; Bekebrede et al., 2017; Stanitsas et al., 2019). Finally, Fig. 7 also highlights the growing relevance of 'education for sustainability' as a context for the use of S-SSGs.

4.2.2. Contexts for use of S-SSGs

The broad-based application of simulations and serious games for addressing sustainability issues was further reflected in the varied settings in which they have been used. S-SSGs are being used in higher education (41%), professional development/corporate training settings (17%), and K-12 schools (15%). Some papers also described S-SSGs that are being used across multiple settings (16%). These patterns of use affirm the broad-based interest in 'sustainability' as well as perceived relevance of SSGs for developing actionable knowledge about sustainability among learners (Castro-Sánchez et al., 2016; Chappin et al., 2017; Crookall, 2013; Jean et al., 2018; Moratis et al., 2006).

4.2.3. Modes of delivering S-SSGs

Simulations and serious games also vary in terms of their mode of delivery to learners (see Fig. 8). Technology-enhanced simulations are by far the most popular form of SSG. Together papers describing the use of technology-driven simulations and games accounted for 68% of our database. Nonetheless, papers describing the use of board games (15%) and role play games (12%) still represented over 25% of the 376 documents, thereby attesting to their

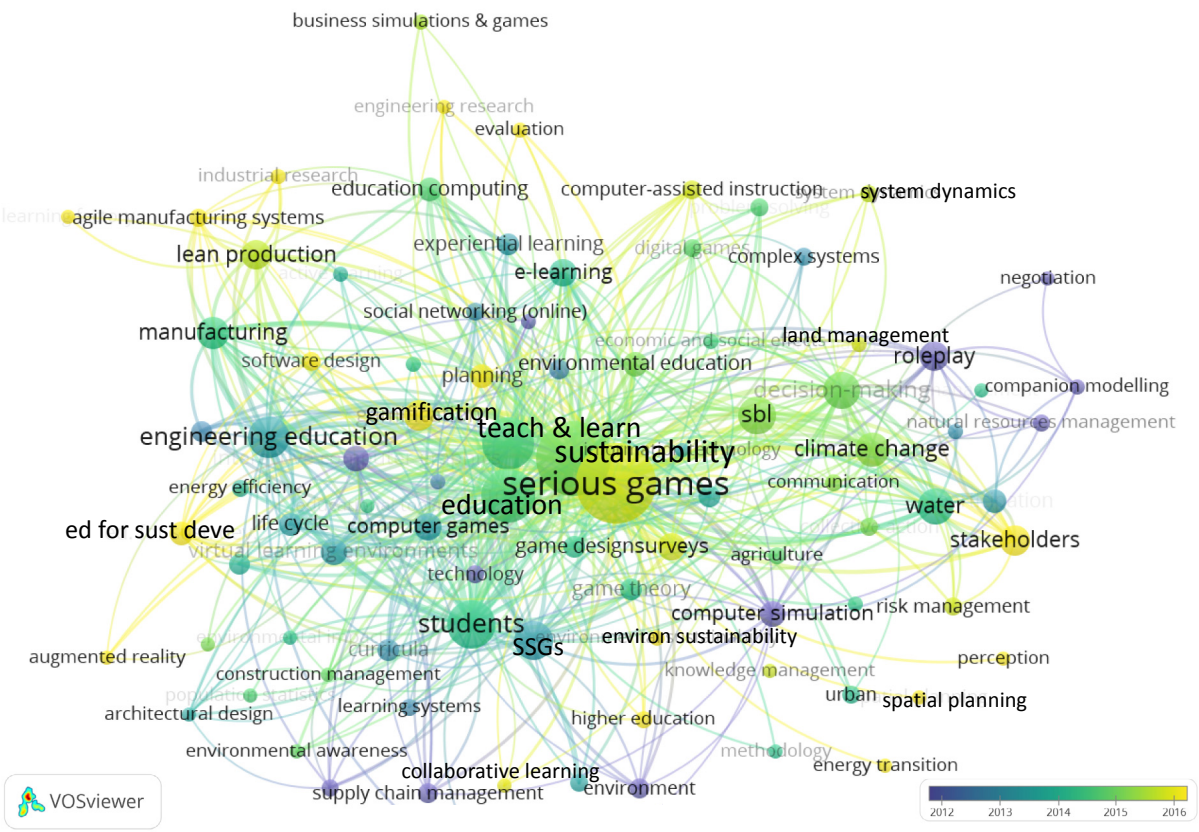

Fig. 7. Temporal keyword co-occurrence analysis of topical foci in the literature on simulations and serious games used in educating for sustainability, 1997–2019, October (threshold 5 occurrences, display 90 keywords; based on the analysis of 361 Scopus-indexed documents).

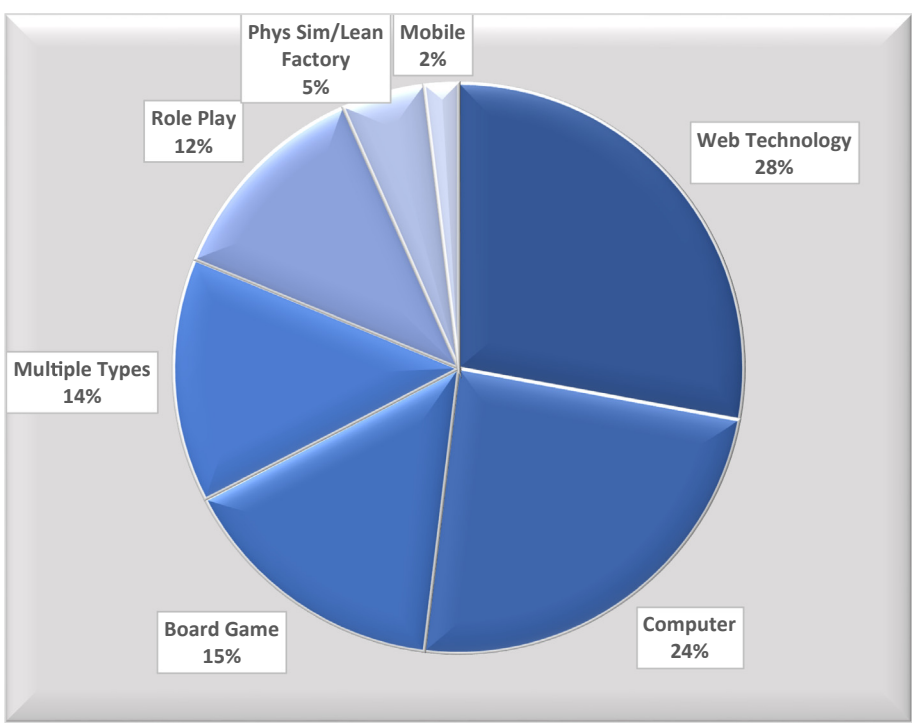

Fig. 8. Distribution of research documents on the use of sustainability simulations and serious games by mode of delivery, 1997–2019, October ($n = 376$).

continued popularity. There were also cases in which S-SSGs employed multiple modes of delivery. For example, sometimes role play was combined with technology or a board game. An innovative variant on traditional role play games has also evolved in the area of learn production whereby 17 different papers reported on the use 'learning factories' (i.e., physical simulations). These provide learners with a simulated 'hands-on' experience in working with products in a physical rather than virtual environment (e.g., Abele et al., 2017; Nitu and Gavriluta, 2019).

4.3. Research designs and methods used in S-SSG studies

We earlier noted that this literature included 125 empirical studies representing 33% of the 376 S-SSG documents in our database. In order to address the third research question, we analyzed the research designs and methods used in these empirical studies. Although this bibliometric review did not analyze the findings of studies, the distribution of research designs and methods used in a knowledge base offers insight into the nature of research questions being addressed and the potential for providing evidence on the efficacy of educational interventions (Bridges, 1982; Hallinger and Chen, 2015).

4.3.1. Research designs

We used a three-part classification, coding the 125 empirical papers as experimental, quasi-experimental or non-experimental studies. Applying this classification was, however, less straightforward than expected. As noted earlier, many authors who claimed to report the results of 'experiments' did not, in fact, conduct experiments as we understand them. Campbell and Stanley (2015) stated that experimental research designs involve measurement of the pre/post status of relevant variables using treatment and control groups whose participants have been randomly selected and assigned. Experimental research represents the gold standard for determining the causal effects of interventions (e.g., S-SSGs). Thus, for example, the Institute of Education Sciences in the USA only provides research funding for experimental studies. Based on descriptions provided in these empirical reports, few of them met Campbell and Stanley's (2015) standard of an 'experiment'.

For the purposes of this review, we coded studies as 'experiments' if the authors applied a pre/post-test on relevant variables with a treatment and a control group. Our operational definition did not require random selection and assignment of participants. Studies that employed a pre-test and post-test design without a control group were classified as quasi-experimental. Other studies were coded as non-experimental.

Fig. 9 displays the distribution of research designs used in the 125 empirical studies as a proportion of the full database. Even using our less rigorous definitions, the results highlight the paucity of experimental (13 studies) and quasi-experimental (22) studies in this knowledge base. These accounted for only 3% and 6% of the full literature respectively. There were 90 non-experimental studies (e.g., cross-sectional surveys, case studies, qualitative studies) representing 24% of the full literature (see Fig. 9).

4.3.2. Research methods and statistical tests

Table 1 offers additional insight into the research methods (i.e., quantitative, qualitative, mixed methods) used within each kind of research design. Both quantitative and mixed methods are being used in experimental (e.g., Ayer et al., 2016; Chow et al., 2017; Maltseva et al., 2019) and quasi-experimental (e.g., Bevilacqua et al., 2015; Harker-Schuch et al., 2020; Hirose et al., 2004) studies of S-SSGs. The number of mixed methods studies within each of these categories was somewhat larger than expected. Mixed methods studies frequently used quantitative methods to address the main research question and then supplemented the results with formative assessment questions analyzed through qualitative methods (Chappin et al., 2017; Mulcahy et al., 2018; Meya and Eisenack, 2018). Although experimental and quasi-experimental studies hold the greatest potential for shedding light on 'causal relationships', the current corpus of experimental and quasi-experimental S-SSG studies remains too small to identify if and how S-SSGs are achieving their learning goals.

Next we analyzed the 105 quantitative and mixed methods according to the statistical methods used to analyze data. We coded this portion of the empirical studies using a four-level rubric that had been employed in earlier research reviews (Bridges, 1982; Hallinger and Chen, 2015). Level one refers to descriptive statistics (e.g., mean, standard deviation etc.). Level two refers to tests of correlation and difference without control variables (e.g., *t*-test, Kruskall Wallace, Spearman, Pearson tests). Level three refers to tests of correlation and difference with inclusion of a single control variable (e.g., ANOVA). Level four statistical tests offer the capability to test for relationships within a multi-factor structure (e.g., multiple regression, structural equation modeling, factor analysis).

The data presented in Table 1 indicate that 51% of the quantitative and mixed methods studies relied wholly on descriptive statistics (Level one) and 81% on Level one and two tests. To our surprise, there were numerous studies presented as 'experiments' that relied on simple descriptive statistics to compare pre-test/post-test results. When the empirical research was broken out in this fashion, we can see that the current knowledge base is sorely lacking in studies capable of shedding light on research questions concerning the effects not only of S-SSGs, but also of different design elements.

This critical view of the S-SSG knowledge base is based on a broad analysis of trends across studies rather than a fine-grained evaluation of individual studies. Thus, we acknowledge that this knowledge base does contain some strong studies. In the interest of providing useful models for future studies, we wish to highlight some of these.

4.3.3. Examples of strong research designs and methods

Among the experimental studies, several used strong research designs combined with Level three and four statistics, and moderate to large samples (70–1000) of learners (e,g., Juan and Chao, 2015; Maltseva et al., 2019; Mulcahy et al., 2018; Su, 2018). Several additional experimental studies were well designed, but employed smaller samples and/or relied on simple correlational tests to determine differences between the treatment and control groups (Ayer et al., 2016; Chow et al., 2017; Nussbaum et al., 2015).

In order to illustrate why stronger designs make a difference, we refer to Mulcahy et al.'s (2018) experimental study of 'gamified apps' focusing on energy use in homes. This study used a valid sample of 326 online players in a treatment group as well as a control group for comparison. Pre-test/post-test measures were applied to evaluate changes in the knowledge and attitudes of the treatment group (only). Pre/post analysis of home energy consumption of the treatment and control groups was also compared over a nine-month period following the treatment. The study's design is notable for its measures of knowledge, attitude and behavior change over time. Furthermore, the use of structural equation modeling (SEM) allowed the researchers to examine the effects of the treatment under different conditions (e.g., number of times played) as well as the impact of mediators (e.g. design elements included in the games). As a result, the study yielded a wide range of useful findings on the effects of the games on learners as well as offering indications of how different game elements contributed to their effectiveness.

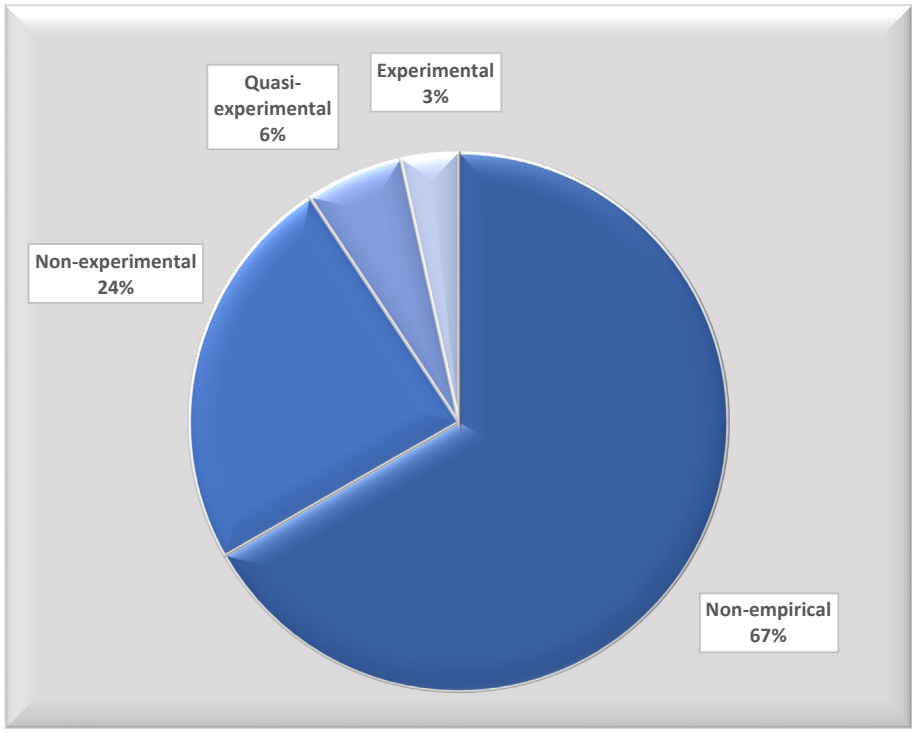

Fig. 9. Research designs used in studies of simulations and serious games used in educating for sustainability, 1997–2019, October ($n = 376$).

Table 1
Research designs and methods used in empirical studies of simulations and serious games used in educating for sustainability, 1997–2019, October.

Research Design	Method				Statistics (quant + mixed)				
	Quant-itative	Mixed	Quali-tative	Total	Descri-ptive	Single Correl-ation	Correlation w/Control	Mult- Factor	Total
Experiment	6	7	0	**13**	1	8	1	3	**13**
Quasi-exp	15	7	0	**22**	5	7	6	4	**22**
Non-exp	47	24	19	**90**	48	16	1	5	**70**
Total	**68**	**38**	**19**	**125**	**54**	**31**	**8**	**12**	**105**

There were also several notable quasi-experimental studies. Some of these used quantitative methods (e.g., Bevilacqua et al., 2015; Harker-Schuch et al., 2020; Hirose et al., 2004; Jacquet et al., 2013; Lohmann, 2019; Moser and Mußhoff, 2016), while others employed mixed methods (Chappin et al., 2017; Meya and Eisenack, 2018). In one of the strong quasi-experimental studies, Meya and Eisenack (2018) used a pre-test/post-test design to analyze quantitatively the effects of a climate change simulation on the knowledge and beliefs of German high school students. The study expanded on a basic pre/post-test design by comparing the results of the treatment group against the responses of a comparable group of students drawn from a nationally representative climate change study. The use of regression analysis enabled the authors to draw broad conclusions on change in learners' beliefs as well as how 'in-game decision-making' influenced these beliefs. The multi-variate analysis also allowed the authors to explore how selected learner characteristics (e.g., self-perception of being 'cooperative') impacted decision-making and results in the simulation. The multiple positive findings that accrued from this study can be traced to use of a more sophisticated design and more powerful statistical methods.

As indicated in Table 1, the non-experimental studies included quantitative, qualitative and mixed methods studies. While non-experimental studies can make useful contributions to the literature, those which comprise the S-SSG literature studies often fell short on key design criteria. For example, 33% of the quantitative and mixed methods studies in this group employed samples comprised of less than 20 learners, and 66% relied solely on descriptive statistics. Thus, as a group, the non-experimental studies represent a largely 'descriptive' literature.

At the same time, however, there were some strong studies that illustrate the potential of non-experimental research on S-SSGs. For example, Wang and Tseng studied the response of 224 learners (19–21 years of age) to an online, strategy game focusing on climate change and environmental awareness in cities. The authors drew upon motivation, flow, and cognitive load theories to, "investigate how learner characteristics (skill, challenge, incentives, and cognitive load) and attitudes (playfulness) influence the learning outcomes" (Wang and Tseng, 2014, p. 311). Using SEM, the authors were able to link several learner characteristics to the mediator of 'playfulness' and then to the dependent variable, learning performance.

Well-designed qualitative research also has a role to play in the formation of a strong knowledge base by offering complementary insights into 'how' and 'why' questions. The qualitative studies in this literature used observation, interviews and video analysis as means of understanding teacher and learner experiences and responses to S-SSGs (e.g., Eränpalo, 2014; Daré and Barreteau, 2003; Tehran et al., 2013; Van der Wal et al., 2016). However, with but a few exceptions, most of the qualitative studies tended to focus on identifying how the SSGs could be improved from the perspectives

of users (i.e., teachers and learners) rather than on researchable questions. Therefore, as a group, they do not yet offer meaningful contributions to the accumulation of knowledge.

Nonetheless, consistent with our prior analyses of quantitative studies, we wish to highlight how qualitative methods can also make a useful contribution to this literature. Daré and Barreteau (2003) used qualitative interviews with participants (i.e., farmers) in a role play game that focused on the management of irrigated water systems in Senegal. The purpose of their research was to gain insights into how the social roles and relationships of the learners shaped their perceptions of the game as well as their forms of engagement in the negotiation role play. As the authors observed, "Because people in action are dynamic, the analysis of their interactions should encompass all elements (about norms, behaviors, rules really followed in negotiations, …)" (Daré and Barreteau, 2003, p. 3). We agree that qualitative methods are well suited to the goal of gaining an understanding of the 'norms, behaviors, rules really followed in negotiations'. A notable feature of this study's design was the incorporation of qualitative data collected both within the role play game and in the village where it was played. In the end, the study offered fascinating insights into both how participants view 'role play' as a form of learning, as well as how social relations shaped the learning process.

5. Discussion

This bibliometric review of research sought first to document the growth and range of simulations and serious games being used in educating for sustainability, and then to examine research approaches being used to study them in practice. The review analyzed a corpus of 376 Scopus-indexed documents that described the use of simulations and serious games in educating for sustainability in schools, homes, and the workplace. In this section of the paper, we highlight limitations of the review, offer our interpretations of the findings, and discuss several implications for research and practice.

5.1. Limitations of findings

First, while this review examined a significant range of published literature on S-SSGs, this is not the same as examining the S-SSGs themselves. Moreover, given the documented recency and accelerating growth of interest in this domain of education, we conclude that there are additional sustainability-oriented simulations and serious games that have yet to be described in Scopus and Google Scholar research documents. Thus, we caution that this 'review of the literature' has neither examined specific S-SSGs in detail (see Albertarelli et al., 2018; Baalsrud Hauge et al., 2014; Madani et al., 2017; Wu and Lee, 2015), nor has it captured the entire collection of extant simulations and serious games focusing on sustainability issues.

Second, the bibliometric method of review employed in our analysis did not focus on synthesizing substantive findings of research on the use of S-SSGs. The review was, instead, limited to the description and analysis of this literature from the perspective of knowledge base evolution and development (Hallinger and Kovačević, 2019; Hallinger and Wang, 2019; Zupic and Čater, 2015). Therefore, although our review offers implications for future research, we have not addressed implicit questions concerning if and how simulations and serious games are meeting the goals of educating for sustainability (Figueiró and Raufflet, 2015; Lozano et al., 2015; Wals, 2011). At the same time, we assert that high-level inferences based on the analysis of research designs and methods can be drawn about the current capacity of this knowledge base to yield actionable findings. Thus, we assert that the results of this review provide useful information that can guide both educators and researchers in this domain of educational research and practice.

5.2. Interpretation of findings

This review identified 376 documents that describe the use of simulations and serious games designed for use in educating for sustainability. After making adjustments for differences in dates and sources of documents covered in the respective reviews, we estimate that the S-SSG literature represents about 8% of the full literature on simulations and serious games (see Hallinger and Wang, 2019). The growth trajectory of S-SSG research documents since 1997 mirrors the evolution of the broader literatures in educating for sustainable development (Figueiró and Raufflet, 2015; Hallinger and Chatpinyakoop, 2019; Lozano et al., 2015) and simulation-based learning (Hallinger and Wang, 2019). This suggests a convergence of accelerating interest in the use of simulations and serious games and educating for sustainability over the past two decades (Crookall, 2013; Dos Santos et al., 2018; Hallinger and Wang, 2019; Lozano et al., 2015).

The geographic distribution of this literature is also consistent with patterns identified in prior bibliometric reviews of related literatures (Hallinger and Chatpinyakoop, 2019; Hallinger and Wang, 2019). European scholars have led the way in contributions to this knowledge base, supported by scholars from the USA. At the same time, however, less than 15% of this literature has been authored by scholars from Asia (8%), Latin America (5%), and Africa (2%). These data highlight a notable geographical imbalance in this literature. This finding implies a need for expanding the design and use of S-SSGs in emerging regions of the world. While some existing simulations may 'transfer' to these emerging regions, other may require 'contextualization' (see Hallinger and Wang, 2019). In many cases, simulations that are grounded in the 'local context' may offer the greatest potential for changing beliefs and bheaviors (e.g., Daré and Barreteau, 2003; Rowntree and Fox, 2008).

Given predictions that non-sustainable development is already having a disproportionately negative effect on developing societies (Sachs, 2015), we urge the global community of scholars to respond to the need for culturally-relevant S-SSGs that can be used in emerging regions of the world. This review identified specific examples where computers simulations, board games and role plays have been used in emerging regions of Latin America (Chaim et al., 2018; de Barros et al., 2018; Dos Santos et al., 2018; Ducrot et al., 2015; Ordaz et al., 2015; Speelman et al., 2014; Speth et al., 2018), Africa (Ayadi et al., 2014; Bellaubi and Pahl-Wostl, 2017; Daré and Barreteau, 2003; Le Bars et al., 2014; Speth et al., 2018), and Asia (Dumrongrojwatthana et al., 2015; Juan and Chao, 2015; Wang and Tseng, 2014; Zhou and Mayer, 2018). Thus, both designers and users can draw inspiration and practical guidance from these studies concerning adaptations that may be required for the successful use of S-SSGs outside of mainstream Western societies (see also Hallinger and Wang, 2019).

At the outset of this review we highlighted three pillars of the sustainability literature: environmental, social, and economic (Elkington, 1998). Several different analyses led us to conclude that this multidisciplinary literature addresses all three of these sustainability themes. This was, for example, reflected in the wide range of topics on which S-SSGs have been designed. Temporal co-word analysis revealed the emergence of social sustainability (e.g., CSR) as a focus for S-SSGs over the past 10 years, a trend we expect to continue.

Similarly, the use of sustainability simulations and serious games has not only penetrated the social and physical sciences, but also numerous professional fields of education. This rapidly accelerating growth of multi-disciplinary research on S-SSGs in just over a decade

further accentuates the impressive traction 'sustainability' has gained in the world of simulations and serious games. Indeed, the analysis of keywords in this literature also surfaced a relationship between S-SSGs and 'education for sustainable development' which became legitimized over the past decade. We suggest that this linkage is due to the fact that, among all approaches to teaching and learning, SSGs are perhaps best suited to addressing the 'systemic' nature of sustainability challenges (Barreteau et al., 2007; Crookall, 2013; Rooney-Varga et al., 2018; Speelman et al., 2014; Sterman, 2014). Thus, these analyses give cause to believe that the production and use of S-SSGs will come into its own in the next decade.

Given controversy in the literature over conceptual distinctions between 'simulations' and 'serious games' the authors chose a broad rubric to guide the inclusion/exclusion of documents in this review. Analysis of the modes of delivery of S-SSGs yielded a frequency distribution that favored technology-enhanced simulations over board games and role plays. Moreover, temporal co-word analysis further highlighted the increasing use of e-learning and virtual learning environments for the delivery of S-SSGs, a trend that is likely to continue as we move forward.

This recognizes the potential of technology to both 'contextualize' learning and capture the complex, interactive decision rules that are central to understanding and addressing sustainability challenges (Dalgarno and Lee, 2010; Klopfer and Squire, 2008; Mayer, 2010). Moreover, one could argue that technology-enhanced simulations have the potential to impact the greatest number of learners. Another recent development in the design of online S-SSGs lies in their enhanced capacity to connect users to relevant online resources via embedded links. This has the power to transform S-SSGs from 'closed learning systems' into open systems for extended online learning.

Online S-SSGs also offer superior access to data on users' decision-making and learning outcomes. Indeed, the studies in our database that employed the largest samples (>300 learners) fell exclusively in the category of online S-SSGs (e.g., Knol and De Vries, 2011; Rooney-Varga et al., 2018; Mulcahy et al., 2018; Tellioglu et al., 2014). This contrasted sharply with the broader trend in which the average sample size of empirical studies was only 62 learners. Therefore, although scholarly discourse on web-based SSGs has tended to emphasize their advantages for 'learning' (e.g., Dalgarno and Lee, 2010; Klopfer and Squire, 2008), we also wish to highlight their potential for advancing research.

Despite these trends favoring the increased use of technology-enhanced simulations, the results also reaffirmed the continuing relevance of board games and role plays. For example, role play games have been used to engage learners in active negotiations in the context of water resource management, land management, and climate change politics (e.g., Ahamer, 2006; Daré and Barreteau, 2003; Jacquet et al., 2013; Rooney-Varga et al., 2018; Svoboda and Whalen, 2004). The use of 'learning factories' has also emerged as a blend between role play games and simulations in the domain of lean production. These 'physical simulations' offer learners the opportunity to engage directly with the physical environment in which their work will take place and experiment with different methods of organizing production. Thus, despite the rising use of technology-enhanced S-SSGs, we believe that the persisting eclecticism among S-SSGs is a positive finding. It suggests that different sustainability problems, contexts, and learning goals may be addressed creatively through alternate modes of delivery.

Empirical studies are essential to the development of an evidence-based literature. As noted throughout this review, the attraction of educators to 'simulations and serious games' has been based largely on their perceived 'potential' for bridging the gap between classrooms and the living and working worlds. However, only empirical research can determine if S-SSGs are achieving their potential in educating for sustainability. Empirical studies are not only required to assess the magnitude of S-SSG 'effects' on learners, but also how and under what conditions those effects are achieved. While the broader literature on simulations and serious games offers support for the 'potential' of S-SSGs, the complexity of sustainability challenges and urgent need to foster 'behavioral change' make it imperative to validate the use of SSGs used in educating for sustainability (Liarakou et al., 2012; Stanitsas et al., 2019).

The current balance of research documents comprising the S-SSG literature reinforces our impression of an emerging literature that requires clearer direction. Our review of this literature identified an imbalance with more commentaries (55%) and fewer empirical studies (33%) than we deem healthy in the long term. This is a largely 'prescriptive' literature, which highlights an urgent need for programmatic empirical research of a higher standard. While the proportion of research reviews (6%) in this literature does not appear problematic, we do suggest a need for reviews that analyze the conceptual models, research questions and design elements being addressed in S-SSG studies. Scholarship in this domain will, of course, continue to benefit from developments in the broader literature on simulations and serious games.

Our conclusion concerning the need for more empirical research was further bolstered by findings from the analysis of research designs and methods. Empirical studies were heavily weighted towards descriptive, non-experimental research designs and methods. Descriptive studies dominate the empirical literature. Moreover, in the relatively few cases when 'experiments' were conducted, the designs often fell below common standards. Thus, we conclude that the current literature lacks the critical mass of robust empirical studies needed to shed light on key issues concerning the design, instructional use and effects of S-SSGs. In light of this conclusion, the authors identified a number of strong experimental, quasi-experimental and non-experimental studies with the goal of providing useful models for future research.

Finally, we wish to reiterate the need for empirical studies capable of shedding light on how learner characteristics (e.g., age, gender, motivation, prior knowledge), conditions (e.g., time, culture, group size, background knowledge), design elements (e.g., context veracity, problem complexity, decision tools), and instructional processes (e.g., goal setting, degree of structuring, type of debriefing) influence the effectiveness of S-SSGs. These studies should assess the efficacy of S-SSGs on change in learner knowledge attitudes and behavior related to different sustainability foci. Where feasible, 'hard measures' of behavioral change, like reduction in energy consumption used by Mulcahy et al. (2018), are desirable. Achieving the goal of an evidenced-based literature on S-SSGs will require a long-term, multi-faceted program of empirical research guided by theories of learning and change (e.g., Ajzen and Fishbein, 1977; Issenberg et al., 2011; Kolb, 1984; Kriz, 2003). The authors hope that the current bibliometric review has provided benchmarks against which future progress can be measured.

Credit statement

Philip Hallinger: Conceptualization, Data validation, Data analysis, Draft Preparation, Writing; **Ray Wang:** Conceptualization, Data collection, Data validation; Writing;

Chatchai Chatpinyakoop: Data validation, writing; Thong Nguyen Vien: Data collection and validation, Writing; Uyen Phuong Nguyen: Data collection and validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abele, E., Chryssolouris, G., Sihn, W., Metternich, J., ElMaraghy, H., Seliger, G., et al., 2017. Learning factories for future oriented research and education in manufacturing. CIRP Annals 66 (2), 803–826.

Ahamer, G., 2006. Ready-to-use simulations: surfing global change: negotiating sustainable solutions. Simulat. Gaming 37 (3), 380–397.

Albertarelli, S., Fraternali, P., Herrera, S., Melenhorst, M., Novak, J., Pasini, C., et al., 2018. A survey on the design of gamified systems for energy and water sustainability. Games 9 (3), 38.

Ajzen, I., Fishbein, M., 1977. Attitude-behavior relations: a theoretical analysis and review of empirical research. Psychol. Bull. 84 (5), 888.

Antle, A.N., Tanenbaum, J., Bevans, A., Seaborn, K., Wang, S., 2011. Balancing act: enabling public engagement with sustainability issues through a multi-touch tabletop collaborative game. September. In: IFIP Conference on Human-Computer Interaction. Springer, Berlin, Heidelberg, pp. 194–211.

Applegate, J.S., Sarno, D.J., 1997. Futuresite: an environmental remediation game-simulation. Simulat. Gaming 28 (1), 13–27.

Aragon-Correa, J.A., Marcus, A.A., Rivera, J.E., Kenworthy, A.L., 2017. Sustainability management teaching resources and the challenge of balancing planet, people, and profits. Acad. Manag. Learn. Educ. 16 (3), 469–483.

Aubert, A.H., Medema, W., Wals, A.E., 2019. Towards a framework for designing and assessing game-based approaches for sustainable water governance. Water 11 (4), 869.

Ayadi, H., Le Bars, M., Le Grusse, P., Mandart, E., Fabre, J., Bouaziz, A., Bord, J.P., 2014. SimPhy: a simulation game to lessen the impact of phytosanitaries on health and the environment—the case of Merja Zerga in Morocco. Environ. Sci. Pollut. Control Ser. 21 (7), 4950–4963.

Ayer, S.K., Messner, J.I., Anumba, C.J., 2016. Augmented reality gaming in sustainable design education. J. Architect. Eng. 22 (1), 04015012.

Baalsrud Hauge, J.B., Kalverkamp, M., Forcolin, M., Westerheim, H., Franke, M., Thoben, K.D., 2014. Collaborative serious games for awareness on shared resources in supply chain management. September. In: IFIP International Conference on Advances in Production Management Systems. Springer, Berlin, Heidelberg, pp. 491–499.

Barreteau, O., Le Page, C., Perez, P., 2007. Simulation and gaming in natural resource management. Simulat. Gaming 38 (2), 181–184.

Bellaubi, F., Pahl-Wostl, C., 2017. Corruption risks, management practices, and performance in water service delivery in Kenya and Ghana: an agent-based model. Ecol. Soc. 22 (2) no page numbers.

Bekebrede, G., van Bueren, E., Wenzler, I., van Veen, L., 2017. Challenges in the transition towards a sustainable city: the Case of GO2Zero. July. In: International Simulation and Gaming Association Conference. Springer, Berlin, pp. 67–74.

Bevilacqua, M., Ciarapica, F.E., Mazzuto, G., Paciarotti, C., 2015. "Cook &teach": learning by playing. J. Clean. Prod. 106, 259–271.

Bridges, E.M., 1982. Research on the school administrator: the state of the art, 1967-1980. Educ. Adm. Q. 18 (3), 12–33.

Brundtland, G.H., Khalid, M., Agnelli, S., Al-Athel, S., Chidzero, B., 1987. Our Common Future. World Commission on Environment and Development, New York.

Campbell, D.T., Stanley, J.C., 2015. Experimental and Quasi-Experimental Designs for Research. Ravenio Books, London.

Castro-Sánchez, E., Kyratsis, Y., Iwami, M., Rawson, T.M., Holmes, A.H., 2016. Serious electronic games as behavioural change interventions in healthcare-associated infections and infection prevention and control: a scoping review of the literature and future directions. Antimicrob. Resist. Infect. Contr. 5 (1), 34.

Chaim, O., Muschard, B., Cazarini, E., Rozenfeld, H., 2018. Insertion of sustainability performance indicators in an industry 4.0 virtual learning environment. Procedia Manuf. 21, 446–453.

Chappin, E.J., Bijvoet, X., Oei, A., 2017. Teaching sustainability to a broad audience through an entertainment game—The effect of Catan: oil Springs. J. Clean. Prod. 156, 556–568.

Chow, C.F., So, W.M.W., Cheung, T.Y., Yeung, S.K.D., 2017. Plastic waste problem and educating for plastic waste management. In: Emerging Practices in Scholarship of Learning and Teaching in a Digital Era. Springer, Singapore, pp. 125–140.

Crookall, D., 2013. Climate change and simulation/gaming: learning for survival. Simulat. Gaming 44 (2–3), 195–228.

Cuesta, V., Nakano, M., 2017. Chain of command: a sustainable supply chain management serious game. Int. J. Autom. Technol. 11 (4), 552–562.

Curran, M.A., 2009. Wrapping our brains around sustainability. Sustainability 1 (1), 5–13.

Dalgarno, B., Lee, M., 2010. What are the learning affordances of 3-D virtual environments? British Journal of Educational Technology 41 (1), 10–32. https://doi.org/10.1111/j.1467-8535.2009.01038.x.

Daré, W.S., Barreteau, O., 2003. A role-playing game in irrigated system negotiation: between play and reality. J. Artif. Soc. Soc. Simulat. 6 (3).

de Barros, M.A., Andrade, V., Moura, A.B., Borgmann, L., Terton, U., Vieira, F., et al., 2018. ReadAct-alternate reality, serious games for reading-acting to engage population and schools on social challenges. In: Proceedings of the 10th International Conference on Computer Supported Education, vol. 2. SciTe Press, pp. 238–245.

Den Haan, R.J., Van der Voort, M.C., 2018. On evaluating social learning outcomes of serious games to collaboratively address sustainability problems: a literature review. Sustainability 10 (12), 4529.

Dib, H., Adamo-Villani, N., Niforooshan, R., 2012. A serious game for learning sustainable design and LEED concepts. In: Issa, R., Flood, I. (Eds.), International Conference on Computing in Civil Engineering (2012). Computing in civil engineering, pp. 137–144.

Dieleman, H., Huisingh, D., 2006. Games by which to learn and teach about sustainable development: exploring the relevance of games and experiential learning for sustainability. J. Clean. Prod. 14 (9–11), 837–847.

Dos Santos, A.D., Strada, F., Bottino, A., 2018. Approaching sustainability learning via digital serious games. IEEE Trans. Learn. Technol. 12 (3), 1–18.

Ducrot, R., Van Paassen, A., Barban, V., Daré, W.S., Gramaglia, C., 2015. Learning integrative negotiation to manage complex environmental issues: example of a gaming approach in the peri-urban catchment of São Paulo, Brazil. Reg. Environ. Change 15 (1), 67–78.

Duin, H., Thoben, K.D., 2011. Serious gaming for sustainable manufacturing: a requirements analysis. In: Paper Presented at the 2011 *17th International Conference on Concurrent Enterprising, ICE 2011* (Aachen, Germany).

Dumrongrojwatthana, P., Le Page, C., Trébuil, G., 2015. Designing a Livestock Rearing System with Stakeholders in Thailand Highlands: Companion Modelling for Integrating Knowledge and Strengthening the Adaptive Capacity of Herders and Foresters. European Society of Agronomy-Agropolis International, pp. 305–306.

Eisenack, K., 2013. A climate change board game for interdisciplinary communication and education. Simulat. Gaming 44 (2–3), 328–348.

Elkington, J., 1998. Accounting for the triple bottom line. Meas. Bus. Excel. 2 (3), 18–22.

Eränpalo, T., 2014. Exploring young people's civic identities through gamification: a case study of Finnish, Swedish and Norwegian adolescents playing a social simulation game. Citizen. Soc. Econ. Educ. 13 (2), 104–120.

Figueiró, P.S., Raufflet, E., 2015. Sustainability in higher education: a systematic review with focus on management education. J. Clean. Prod. 106, 22–33.

Gelles, D., Yaffe-Bellany, D., 2019. Shareholder value is no longer everything: Top CEOs say. August 19. The New York Times. Available at: www.nytimes.com/2019/08/19/business/business-roundtable-ceos-corporations.html.

Gokhale, A.A., 1996. Effectiveness of computer simulation for enhancing higher order thinking. J. Ind. Teach. Educ. 33 (4), 36–46.

Gosen, J., Washbush, J., 2004. A review of scholarship on assessing experiential learning effectiveness. Simulat. Gaming 35 (2), 270–293.

Hallinger, P., Chatpinyakoop, C., 2019. A bibliometric review of research on higher educating for sustainable development, 1998–2018. Sustainability 11 (8), 2401.

Hallinger, P., Chen, J., 2015. Review of research on educational leadership and management in Asia: a comparative analysis of research topics and methods, 1995–2012. Educ. Manag. Adm. Leader 43 (1), 5–27.

Hallinger, P., Kovačević, J., 2019. A bibliometric review of research on educational administration: science mapping the literature, 1960 to 2018. Rev. Educ. Res. 89 (3), 335–369.

Hallinger, P., Wang, R., 2019. The Evolution of Simulation-Based Learning across the Disciplines, 1965–2018: A Science Map of the Literature. Simulation & Gaming, 1046878119888246.

Harker-Schuch, I.E., Mills, F.P., Lade, S.J., Colvin, R.M., 2020. CO2peration—Structuring a 3D interactive digital game to improve climate literacy in the 12-13-year-old age group. Comput. Educ. 144, 103705.

Hidayatno, A., Hasibuan, R.G., Nimpuno, G.C.W., Destyanto, A.R., 2019. Designing a serious simulation game as a learning media of sustainable supply chain management for biofuel production. Energy Procedia 156, 43–47.

Hirose, Y., Sugiura, J., Shimomoto, K., 2004. Industrial waste management simulation game and its educational effect. J. Mater. Cycles Waste Manag. 6 (1), 58–63.

Issenberg, S.B., Ringsted, C., Østergaard, D., Dieckmann, P., 2011. Setting a research agenda for simulation-based healthcare education: a synthesis of the outcome from an Utstein style meeting. Simulat. Healthc. J. Soc. Med. Simulat. 6 (3), 155–167.

Jacquet, J., Hagel, K., Hauert, C., Marotzke, J., Röhl, T., Milinski, M., 2013. Intra-and intergenerational discounting in the climate game. Nat. Clim. Change 3 (12), 1025.

Jean, S., Medema, W., Adamowski, J., Chew, C., Delaney, P., Wals, A., 2018. Serious games as a catalyst for boundary crossing, collaboration and knowledge co-creation in a watershed governance context. J. Environ. Manag. 223, 1010–1022.

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

Katsaliaki, K., Mustafee, N., 2012. A survey of serious games on sustainable development. December. In: Proceedings of the Winter Simulation Conference. Winter Simulation Conference, Berlin, Germany, p. 136.

Klopfer, E., Squire, K., 2008. Environmental detectives: the development of an augmented reality platform for environmental simulations. Educ. Technol. Res. Dev. 56 (2), 203–228.

Knol, E., De Vries, P.W., 2011. EnerCities-A serious game to stimulate sustainability and energy conservation: preliminary results. eLearning Papers (25) (online). Available at: SSRN. https://ssrn.com/abstract=1866206.

Kolb, D.A., 1984. Experience as the Source of Learning and Development. Prentice Hall, Upper Saddle River, NJ.

Kriz, W.C., 2003. Creating effective learning environments and learning organizations through gaming simulation design. Simulat. Gaming 34 (4), 495–511.

Kurapati, S., Kourounioti, I., Lukosch, H., Tavasszy, L., Verbraeck, A., 2018. Fostering sustainable transportation operations through corridor management: a simulation gaming approach. Sustainability 10 (2), 455.

Lamrani, R., Chraibi, S., Qassimi, S., Hafidi, M., 2018. October). Gamification and serious games based learning for early childhood in rural areas. In:

International Conference on Model and Data Engineering. Springer, Cham, Berlin, pp. 79–90.
Le Bars, M., Le Grusse, P., Albouchi, L., 2014. AquaFej: a simulation game for planning water management–An experiment in central Tunisia. Int. J. Sustain. Dev. 17 (3), 242–260.
Liarakou, G., Sakka, E., Gavrilakis, C., Tsolakidis, C., 2012. Evaluation of serious games, as a tool for educating for sustainable development. Eur. J. Open Dist. E Learn. 15 (2).
Littlewood, K.E., Shilling, A.M., Stemland, C.J., Wright, E.B., Kirk, M.A., 2013. High-fidelity simulation is superior to case-based discussion in teaching the management of shock. Med. Teach. 35 (3), e1003–e1010.
Lohmann, R., 2019. Effects of simulation-based learning and one way to analyze them. J. Polit. Sci. Educ. 1–17.
Lozano, R., Ceulemans, K., Alonso-Almeida, M., Huisingh, D., Lozano, F.J., Waas, T., et al., 2015. A review of commitment and implementation of sustainable development in higher education: results from a worldwide survey. J. Clean. Prod. 108, 1–18.
Madani, K., Pierce, T.W., Mirchi, A., 2017. Serious games on environmental management. Sustain. Cities Soc. 29, 1–11.
Maltseva, K., Fieseler, C., Trittin-Ulbrich, H., 2019. The challenges of gamifying CSR communication. Corp. Commun. Int. J. 24 (1), 44–62.
Martens, A., Diener, H., Malo, S., 2008. Game-based learning with computers – learning, simulations, and games. In: Pan, Z., Cheok, A.D., Müller, W., El Rhalibi, A. (Eds.), Transactions on Edutainment I. Springer-Verlag, Heidelberg, Germany, pp. 172–190.
Mayer, R.E., 2010. Learning with technology. In: Dumont, H., Instance, D., Benavides, F. (Eds.), The Nature of Learning: Using Research to Inspire Practice. OECD Publishing, Paris, pp. 179–198.
Meya, J.N., Eisenack, K., 2018. Effectiveness of gaming for communicating and teaching climate change. Climatic Change 149 (3–4), 319–333.
Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Ann. Intern. Med. 151 (4), 264–269.
Mongeon, P., Paul-Hus, A., 2016. The journal coverage of Web of Science and Scopus: a comparative analysis. Scientometrics 106 (1), 213–228.
Moratis, L., Hoff, J., Reul, B., 2006. A dual challenge facing management education: simulation-based learning and learning about CSR. J. Manag. Dev. 25 (3), 213–231.
Moser, S., Mußhoff, O., 2016. Ex-ante evaluation of policy measures: effects of reward and punishment for fertiliser reduction in palm oil production. J. Agric. Econ. 67 (1), 84–104.
Mulcahy, R., Russell-Bennett, R., Iacobucci, D., 2018. Designing gamified apps for sustainable consumption: a field study. J. Bus. Res. 106, 377–387.
Nitu, E.L., Gavriluta, A.C., 2019. Lean learning factory at the University of Pitesti. August. In: IOP Conference Series: Materials Science and Engineering, vol. 591. IOP Publishing, 012095, 1.
Nussbaum, E.M., Owens, M.C., Sinatra, G.M., Rehmat, A.P., Cordova, J.R., Ahmad, S., et al., 2015. Losing the Lake: simulations to promote gains in student knowledge and interest about climate change. Int. J. Environ. Sci. Educ. 10 (6), 789–811.
Ordaz, N., Romero, D., Gorecky, D., Siller, H.R., 2015. Serious games and virtual simulator for automotive manufacturing education & training. Procedia Comput. Sci. 75, 267–274.
Reckien, D., Eisenack, K., 2013. Climate change gaming on board and screen: a review. Simulat. Gaming 44 (2–3), 253–271.
Rooney-Varga, J.N., Sterman, J.D., Fracassi, E., Franck, T., Kapmeier, F., Kurker, V., et al., 2018. Combining role-play with interactive simulation to motivate informed climate action: evidence from the World Climate simulation. PloS One 13 (8), e0202877.
Rowntree, K.M., Fox, R.C., 2008. Active learning for understanding land degradation: African catchment game and riskmap. Geogr. Res. 46 (1), 39–50.
Sachs, J.D., 2015. The Age of Sustainable Development. Columbia University Press, New York.
Speelman, E.N., García-Barrios, L.E., Groot, J.C.J., Tittonell, P., 2014. Gaming for smallholder participation in the design of more sustainable agricultural landscapes. Agric. Syst. 126, 62–75.
Speth, M., Müller, J., Rist, T., Seidl, J., Faschina, M., 2018. November). ECO CHAMPION: a transcultural educational eco game for children. In: European Conference on E-Learning. Academic Conferences International Limited. 523-XVII.
Srijumpa, R., Dejprasert, N., 2018. The automotive factory strategic board game for fostering business sustainability. December. In: 2018 3rd Technology Innovation Management and Engineering Science International Conference (TIMES-iCON). IEEE, pp. 1–5.
Stanitsas, M., Kirytopoulos, K., Vareilles, E., 2019. Facilitating sustainability transition through serious games: a systematic literature review. J. Clean. Prod. 208, 924–936.
Steadman, R.H., Coates, W.C., Huang, Y.M., Matevosian, R., Larmon, B.R., McCullough, L., Ariel, D., 2006. Simulation-based training is superior to problem-based learning for the acquisition of critical assessment and management skills. Crit. Care Med. 34 (1), 151–157.
Sterman, J., 2014. Interactive web-based simulations for strategy and sustainability: the MIT Sloan LearningEdge management flight simulators, part I. Syst. Dynam. Rev. 30 (1–2), 89–121.
Su, C.H., 2018. Exploring sustainability environment educational design and learning effect evaluation through migration theory: an example of environment educational serious games. Sustainability 10 (10), 3363.
Svoboda, S., Whalen, J., 2004. Using experiential simulation to teach sustainability. Greener Manag. Int. 48, 57–65.
Tanenbaum, J.G., Antle, A.N., Robinson, J., 2013. April). Three perspectives on behavior change for serious games. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. ACM, pp. 3389–3392.
Tehran, B.P., Taisch, M., Fradinho, M., 2013. Using serious game in sustainable global manufacturing education. September. In: IFIP International Conference on Advances in Production Management Systems. Springer, Berlin, Heidelberg, pp. 99–107.
Tellioglu, U., Xie, G.G., Rohrer, J.P., Prince, C., 2014. July). Whale of a crowd: quantifying the effectiveness of crowd-sourced serious games. In: 2014 Computer Games: AI, Animation, Mobile, Multimedia, Educational and Serious Games (CGAMES). IEEE, pp. 1–7.
Ulrich, M., 1997. Games/simulations about environmental issues: existing tools and underlying concepts. In: Gaming/Simulation for Policy Development and Organizational Change: Proceedings of the 28th Simulation and Gaming Association, pp. 301–311.
van der Merwe, K.R., 2017. A longitudinal study of the efficacy of lean learning experienced through a simulated working environment (SWE). Int. J. Prod. Perform. Manag. 66 (5), 651–661.
Van der Wal, M.M., De Kraker, J., Kroeze, C., Kirschner, P.A., Valkering, P., 2016. Can computer models be used for social learning? A serious game in water management. Environ. Model. Software 75, 119–132.
van Eck, N.J., Waltman, L., 2014. Visualizing bibliometric networks. In: Ding, Y., Rousseau, R., Wolfram, D. (Eds.), Measuring Scholarly Impact. Springer, Cham, pp. 285–320.
van Eck, N.J., Waltman, L., van den Berg, J., 2010. A comparison of two techniques for bibliometric mapping: Multidimensional scaling and VOS. Journal of the American Society for Information Science and Technology 61 (12), 2405–2416. https://doi.org/10.1002/asi.21421.
Wals, A.E., 2011. Learning our way to sustainability. J. Educ. Sustain. Dev. 5 (2), 177–186.
Wang, T.L., Tseng, Y.F., 2014. An empirical study: Develop and evaluation a mobile serious game on environmental education. *9th International Conference on Computer Science & Education*. IEEE, pp. 311–315.
Whitman, L.E., Cheraghi, S.H., Twomey, J., 2008. Production systems simulator: a learning tool. In: IIE Annual Conference. Proceedings. Institute of Industrial and Systems Engineers (IISE), p. 1730.
Wood, Z., 2019. US Companies Tell Apple and Amazon to Put Planet before Profits. August 25. *Guardian* (online), no page number.
Wu, J.S., Lee, J.J., 2015. Climate change games as tools for education and engagement. Nat. Clim. Change 5 (5), 413–418.
Yang, J.C., Chien, K.H., Liu, T.C., 2012. A digital game-based learning system for energy education: an energy conservation PET. Turkish Online J. Educ. Technol-TOJET 11 (2), 27–37.
Zhou, Q., Mayer, I.S., 2018. Models, simulations and games for water management: a comparative q-method study in The Netherlands and China. Water 10 (1), 10.
Żmuda, G., Prokopowicz, P., Król, M., 2015. The sustainable gamer: developing corporate social responsibility through games. In: O'Riordan, L., Zmuda, P., Heinemann, S. (Eds.), New Perspectives on Corporate Social Responsibility. Springer Gabler, Weisbaden, pp. 411–425.
Zupic, I., Čater, T., 2015. Bibliometric methods in management and organization. Organ. Res. Methods 18 (3), 429–472.