Approaching sustainability learning via digital serious games

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Alysson Diniz dos Santos, Francesco Strada and Andrea Bottino

Abstract—Finding proper ways to address learning about sustainability is a relevant issue. Sustainability learning has to face some inherent complexities, due to two main factors: a) the interdisciplinary domains related to sustainability issues, such as ecology, economics, politics and culture, and b) the involvement of several social structures, such as individuals, families and communities. One recent research proposal is to exploit serious games to foster learning in this area. This resulted in a significant increase in the number of approaches discussed in the literature over the last few years. Notwithstanding this growing scenario, sustainability serious games still lack a reasoned evaluation, in order to clarify their possible applications and to define effective design strategies to approach them. To this end, in this paper we investigate the current state of the art of serious games for sustainability, identifying and discussing the most common applications. The research process included both scientific publications and unpublished materials. References were searched according to guiding questions, which helped focus the extraction of information, and through recursive browsing of their citations. Based on the research results, we propose a taxonomy for sustainability serious games and a classification of reviewed works according to this taxonomy. We also analyze design strategies, drawn from the literature, expressly conceived for the development of effective sustainability serious games. Finally, we discuss the current challenges and present possible areas of research in this field.

Index Terms—educational games, sustainability, learning, simulation.

1 Introduction

Sustainable development – or sustainability – is the search of significant shifts in technologies, techniques or infrastructures, meeting today's demands, without compromising the needs of the future generations [1]. Since the publication of the Stockholm Declaration on the Human Environment, in 1972 [2], there has been an increasing interest in supporting sustainable development [3]. Although much progress has been made - e.g. the United Nations Sustainable Development Summits in Rio de Janeiro (1992 and 2012), Johannesburg (2012) and New York (2015), and the definition of the Millennium Development Goals (2010 and 2015) - there is still a need to improve sustainability awareness on both individual and societal levels. To this end, it has become of critical relevance to disseminate information and foster learning of environment and development issues [4].

However, this task is not trivial, since sustainability has specific requirements. First, sustainability is characterized by three tightly coupled and often conflicting aspects [5]:

- *economic sustainability*, i.e. the ability to maintain an adequate and continuous production of goods and services with manageable levels of government and external debt;
- *environmental sustainability*, i.e. the ability to maintain adequate levels of renewable resource harvesting, pollution production and depletion of non-renewable resources;
- *social sustainability*, i.e. the ability of a social system to provide "social well–being", characterized by equal access to and delivery of basic facilities and social services (water, food, houses, health, education), equal opportunities and political accountability and participation.

In addition, sustainability issues need to be framed bearing in mind the points of view of different stakeholders, such as householders, policy-makers, families, communities and society in general [6]. This interplay of multiple aspects and perspectives gives origin to complex scenarios, whose dynamics cannot be predicted by merely examining the isolated behaviors of their individual parts [3]. This complexity is one of the main challenges that sustainability education has to deal with and, as a consequence, it rules out educational methods based on direct instruction, which analyze wholes in parts and structure learning in terms of the gradual accumulation of pieces of information [7].

In contrast, recent research highlights the potentialities of constructivist perspectives to help learning about complex systems [8]. Constructivist teaching is based on the assumption that learners construct knowledge and skills as they try to make sense of their experiences. That is, learners are the makers of meaning and knowledge [9]. Developing an effective constructivist educational approach to complex systems requires to take into account several elements. These include the need (i) to create *experiential learning environments* (where students can directly experience and analyze phenomena related to complex systems), (ii) to make the *core concepts explicit* to the students (thus, unveiling the connections between the phenomena observed and their underlying framework) and (iii) to involve students in *collaborative and cooperative activities*, which encourage

- *A. D. dos Santos, F. Strada and A. Bottino are with the Computer Graphics and Vision Group at the Department of Control and Computer Engineering, Politecnico di Torino, Italy.*
E-mail: alysson@virtual.ufc.br,francesco.strada,andrea.bottino@polito.it
- *A. D. dos Santos is also with Instituto Universidade Virtual, Universidade Federal do Ceara, Brazil.*

discussion and reflection, helpful to generate deeper insight and understanding.

Based on these premises, recent research [3], [10] recognizes that serious games (SG), i.e. those that do not have entertainment as their primary purpose [11], [12], [13], [14], [15], offer unique possibilities for sustainability learning. There are a number of reasons to support this argument.

First, SGs can be seen as a perfect example of experiential learning environments. They allow the creation of virtual representations of complex scenarios that can be explored and analyzed by learners to highlight the dynamics and interactions between the elements and the actors involved. The effects of players' actions on the system can become readily understandable and learners can analyze them on both a global scale and a large time span. As opposed to the real world, players can analyze things repeatedly from different observation points and explore different solutions in a safe scenario (i.e., without actually endangering the real system).

Then, the game scenario, the storytelling and the gameplay can be effective to motivate learners and engage them in interactive and dynamic activities, which in turn provide benefits for the development of cognitive skills (e.g., players will learn to deal with complex facts because they need this knowledge to progress in the game).

In addition, computer games can exploit visual communication, which has three potential effects [16]: *cognitive* (since it increases the information available, reduces the cognitive workload and clarifies patterns of value and relationships), *affective* (being able to trigger instant emotional responses to displayed elements) and *behavioural* (being able to influence players' attitudes and behaviours [17]).

Finally, computer games allow the creation of situated and socially mediated learning contexts by enabling shared experiences (e.g., by providing multiplayer settings or allowing learners to share information and results through the social networks).

Given the relevance of serious games, recent works have started to clarify the link between sustainability learning and specific game groups. For instance, Katsaliaki and Mustafee (2014) [18], Fabricatore and Lopez (2012) [3], Liarakou et al. (2012) [19] and Coakley and Garvey (2015) [10] surveyed the area of sustainability educational games. From another perspective, Huber and Hilty (2015) [20], and Walz and Deterding (2015) [21] focused their surveys on gamification approaches to sustainability, i.e. on those applications that use game elements to motivate users towards more environment friendly actions.

However, in our opinion, there is still a lack of a comprehensive study that discusses the different ways to approach sustainability learning through serious games, especially considering the decisions that underlie the game design. Such analysis could also represent a useful reference to guide developers and, possibly, to identify gaps in the state of the art [12]. Therefore, the main objectives of our work are the following:

- detail the current state of the art of the various forms of digital gaming approaches to sustainability,
- present possible design strategies for sustainability games,
- summarize research questions that may be approached by further research in the field.

The rest of the paper is organized as follows. Section 2 defines a possible taxonomy of sustainability serious games (SSGs). Sections 3 and 4 present a detailed analysis of the different classes of SSGs. Then, we discuss some design frameworks explicitly defined for SSGs (Section 5) and, finally, in Section 6, we highlight open problems and open areas of research.

2 Serious Games for Sustainability

Approaching sustainability learning through serious games has been an active research area during the last years. As a result, the number of works in this area has grown exponentially. Even after careful selection and screening, a combined search of scholarly literature, online games and resources might result in hundreds of hits. As an example, the number of unique games referenced in the "games for change" portal and in the two surveys [18] and [3] already sums up to 91.

Therefore, the approach followed in our review was the following. First, we defined a rigorous search and selection protocol, which is detailed in the Appendix A. Then, we analyzed the relevant works identified to define a basic taxonomy related to the main objectives that SSGs try to achieve. Finally, we further expanded each category into sub–groups and, for each group, we selected works capable of spotting and exemplifying the different approaches to the issues considered. In other words, rather than compiling a "complete" list of the relevant sustainability games identified, we preferred to base our discussion on some "good examples" of how to approach the various problems to be addressed, by collecting a number of works that provide a representative picture of the current state of the art.

The taxonomy introduced in this paper is based on two main purposes for which SSGs have been conceived (Table 1): to inform players (*educational games* [10], [18]) or to motivate them to adopt environment friendly behaviors (*motivational games* [20], [21]).

In the first class, educational games, we find works that try to communicate some information to the players. They are based on the assumption that providing knowledge about specific phenomena, it is possible to raise awareness towards sustainability issues [22]. These games enable experimentation in simulated environments, useful for depicting possible catastrophic scenarios related to resource scarcity, poverty, global warming and so on [10]. Players are usually required to find creative solutions for the challenges to face, which demand critical thinking from the learners [23].

The second class, motivational games, comprises works that aim at stimulating players towards more "sustainable actions" by using different mechanics and metaphors. The rationale of these approaches is that, in general, people are willing to undertake environment friendly behaviors, but they find it difficult to start and maintain them [24]. Therefore, these games try to act as facilitators, both alerting users of improper behaviors and showing the effect on the surrounding natural environment of the actions that can be taken. To reach these objectives, a) most of these games

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are based on data sensed from the real world (e.g., energy consumption at home, participation in recycling programs, driving style and so on [21]), b) they leverage concepts such as individual, social and economic incentives, and c) they often exploit multiplayer activities to foster behavior changes not only in individuals, but also in groups (i.e., families, employees and communities [25]).

Two other useful dimensions that can be used to characterize a serious game are, according to Djaouti et al. [26], the *target audience* and the *interaction pattern*.

The target audience classifies players according to their age. In this paper we adopt the North American Entertainment Software Rating Board (ESRB) age-based classification system [27], i.e. *early childhood* (6 years old and below), *youngsters* (7-12 years old), *teen* (13-17 years old) and *mature* (17 years old and above).

The interaction patterns encompass the interaction between a player, the game system and any other player [28]. In this dimension, we can summarize the player patterns in the *single* and *multiplayer* classes and multiplayer games can be further divided into *cooperative* and *competitive* ones.

In addition, the games can also be classified according to the sustainability aspects they approach, i.e., *economic*, *environmental* and *social*.

Together, these three dimensions (target audience, interaction patterns and sustainability aspects) allow transversal comparisons based on *who* actually plays, *how* the games are played (i.e., single or multi–player mode), and *which content* they intend to deliver. Such analysis is specifically relevant to sustainability games since they require targeting different audiences, involving them in both individual and group activities related to various sustainability elements. Furthermore, these dimensions are useful to discover possible gaps in the literature (i.e. identifying combinations of audiences, patterns and sustainability aspects that could be further explored by the research). Table 1 introduces a synopsis of the games reviewed in this paper according to the proposed classification dimensions. A more detailed characterization of each game, which includes as well other features related to the game design, is presented in Table 4.

3 Educational Games

In order to simplify the discussion, we grouped educational games according to their genre. We identified the following five main categories: *construction and management simulation*, *interactive fiction*, *role-playing games*, *simple game activities* and *procedural rhetoric games*. In the following, we detail the characteristic of each group.

3.1 Construction and Management Simulation

Construction and management simulation (CMS) games aim to engage players in creating and maintaining infrastructures towards environmental awareness. Usually, the players' objective is the expansion of an area (a village, a city, a country...) in a determined amount of time and respecting the balance between production and consumption of resources. As another constraint, usually players have to manage limited amounts of resources (e.g. coal, gas and oil) to accomplish their goals.

Some CMSs, as *City Rain*, *Clim'way*, *EcoVille*, *Futura*, and *Plan it Green* approach sustainable city planning. In these games, the players' score is a function of several elements, such as popularity among citizens, population size, the city's environmental impact and the security of supplies (i.e., the lack of blackouts or water shortages). A different and innovative approach is *Perfect–Ville* [29], [30], a city planning game that explores the role of game modding (i.e., the possibility to "mod" a game by changing its contents and rules) in supporting sustainability learning. The game is played in groups and the underlying assumption about the initial game rules and contents is that winning in Perfect–Ville requires adopting a hedonic life-style based on a greedy and consumerist model. These (provocative) features aim at triggering critical discussion among participants. Then, in design mode, players can transform their ideas about the game in new rules and contents that support a sustainable way of living in the city. The underlying pedagogic approach is that of constructionist perspective, since in this work learning about sustainability is not an objective per se, but the instrument that allows player to redefine their game experience.

Other CMSs focus on specific issues. This is the case of *ElectroCity* and *EnerCities*, where player controls the energy matrix of a city, choosing between fossils and renewable resources, controlling their depletion and administrating taxes and prices for the population. In *Super Energy Apocalypse* the player has to produce energy to strengthen the city defenses against monsters, which are fed by the player's waste, a metaphor of the harmful effects of pollution [31]. Therefore, succeeding in the game requires players to find a sustainable balance between the production of energy and the environment pollution it causes. In *Catchment Detox* (see Figure 1), players have to balance the food production rate with a sustainable water consumption.

Finally, there is a group of purely managerial games, which are usually multiplayer. A first example is *Green & Great*, a complex simulation whose goal is to run a company and achieve business sustainability. Players have to manage the impact of their decisions on different sustainability dimensions (nature, economy, society and wellbeing) and learn to communicate and negotiate with other players to reach their objectives. A similar game is *Ecopolicy*, where players have to govern a fictitious state in order to maintain a sustainable balance between different life areas, such as politics, production, environmental pollution, quality of life, land development and population growth.

The educational approach of all these CMSs aims at fostering content transfer between game actions and real world concepts [3], which is one of the objectives of experiential and constructivist teaching. To this end, most of the games emulate realistic scenarios (e.g., Futura depicts the Fraser River basin in Canada, Catchment Detox simulates the real water behavior in Australia's waterways) and players assume policy-maker roles (mayor, president) that take real-life decisions (building structures, choosing a specific energetic matrix, managing resource consumption).

Most of these works address multiple sustainability aspects and, given the topics discussed, even when not explicitly stated, all these games are suited to an audience ranging from youngsters to adults. We highlight as well that

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TABLE 1
Synopsis of the reviewed games for each classification dimension

Dimension		**Educative**	**Motivational**
Target Audience	Early childhood	Alberto Gravimente's Toys, EPA games suite, Discover Water, Games Planet Arcade, PBS Kids, MiniMonos	-
	Youngsters (7-12)	Catchment Detox, Citizen Science, City Rain, Clim'way, Desertification story, EcoVille, Electro City, EnerCities, Futura, Heroes of Koskenniska, Perfect-Ville, Precipice, Riverbed	Climate Race, Eco Island, Energy Battle, GAEA, LEY!, Power Agent, Power Explorer
	Teen (13-16)	Ludwig, Oiligarchy, Oil God, Plan It Green!, PowerUP, Super Energy Apocalypse	Pipe Trouble
	Mature 17+	ecoCampus, EcoPolicy, Green & Great	Eco.system, MSSG, SuMo, Toyota Prius Hybrid telemetry, Fiat eco:Drive, Honda Eco score, Ford SmartGauge with EcoGuide, OPower, WaterSmart
Interaction Pattern	Single player	Alberto Gravimente's Toys, Catchment Detox, City Rain, Clim'way, ecoCampus, Desertification story, EcoVille, Electro City, EnerCities, EPA games suite, Discover Water, Games Planet Arcade, PBS Kids, Plan It Green!, Citizen Science, MSSG, Precipice, Riverbed, Ludwig, Heroes of Koskenniska, Oiligarchy, Oil God, Super Energy Apocalypse, Pipe Trouble	Toyota Prius Hybrid telemetry, Honda Eco score
	Cooperative multiplayer	Futura, EcoPolicy, MiniMonos, Perfect-Ville, PowerUP	Climate Race, Eco Island, Energy Battle, GAEA, LEY!, Power Agent, Power Explorer, OPower, WaterSmart
	Competitive multiplayer	Green & Great	Eco Island, Energy Battle, GAEA, LEY!, Power Agent, OPower, WaterSmart, Eco.system, SuMo, Fiat eco:Drive, Ford SmartGauge with EcoGuide
Sustainability Aspects	Environmental	Alberto Gravimente's Toys, Citizen Science, Desertification story, Discover Water, ecoCampus, EPA games suite, Games Planet Arcade, PBS Kids, Heroes of Koskenniska, Ludwig, MSSG, PowerUP, Precipice, Riverbed, Super Energy Apocalypse	Climate Race, Eco Island, Eco.system, Energy Battle, Fiat eco:Drive, Honda Eco score, Ford SmartGauge with Eco Guide, Toyota Prius Hybrid telemetry GAEA, LEY!, OPower, Power Agent, Power Explorer, SuMo, WaterSmart
	Environmental and economic	Catchment Detox, City Rain, Clim'way, EcoVille, Electro City, EnerCities, Futura, Plan It Green!	-
	Environmental and social	MiniMonos	-
	Environmental, economic and social	EcoPolicy, Green & Great, Oiligarchy, Oil God, Perfect-Ville, Pipe Trouble	-

most of these CMSs are single player. Exceptions of note are Perfect–Ville, Green & Great, Ecopolicy and Futura.

Some assessment results of the effectiveness of CMSs are available. The design of Futura was empirically evaluated through observational data on hundreds of users, showing its effectiveness in raising discussion and cooperation between players and, thus, in potentially improving the desired learning outcomes [32]. Other interesting results can be obtained from the quantitative and qualitative evaluation of EnerCities, which involved more than 800 students from five different countries [33]. The analysis concluded that players found the game fun and attractive, and that playing the game increased participants attitudes towards saving energy at home, for instance turning off TVs rather than using standby functions and taking shorter showers.

3.2 Interactive Fiction Games

In interactive fictions, the player proceeds through a world made of multiple connected scenarios, usually exchanging textual information with non–playable characters (NPCs). In this kind of games, the narrative is fundamental to the educational aspect. The comprehension of the background story is crucial for choosing the decisions that can lead to the fulfillment of objectives. Therefore, the educational contents are always embedded into the narrative.

A first example is *Precipice*. Player's objective is to improve the NPCs environmental awareness in order to avoid forthcoming disastrous consequences. By completing puzzles and conversations, the player can move between present and future assessing the effects of the chosen actions. In *Citizen Science*, players can learn the causes of the pollution of their local lake by traveling through time and

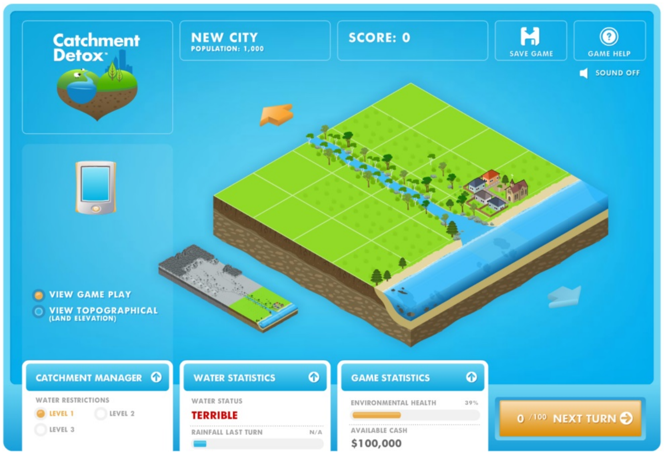

Fig. 1. CMS Catchment Detox

gathering information from NPCs. This knowledge can then be used to change the course of history. *Riverbed* is a fictional murder-mystery related with the social instability due to shortages of clean water.

Similarly to CMSs, interactive fiction games usually portray realistic scenarios to foster knowledge transfer between fictional and real world. For instance, Citizen Science depicts the Mendota Lake in USA, and the setting, story and characters archetypes in Riverbed are based on real cases, like the shrinking of Aral Sea and Colorado River.

All the interactive fiction games we found deal only with the environmental aspect of sustainability, are single player and their interaction acts are simple enough to be understood by a 7 years old child. Despite that, it may be argued that some games, such as Precipice and Riverbed, aim at engaging older audiences as well, since they portray darker atmospheres and "more adult" background stories (involving murders and catastrophic futuristic scenarios).

The only interactive fiction game for which we found a (partial) scientific assessment was Citizen Science. In-class observational analysis and small group interviews with children from 7 to 11 years old, indicated that players enjoyed the game and showed interest in absorbing further information about the educational topic [34].

3.3 Role-playing Games

Role-playing video games (RPG) involve the representation of a character into a fictional setting. The aim of these games is usually to complete a series of quests or reach the end of a central storyline. The main characteristics of RPGs are their narrative elements and the sense of immersion into the game story. Furthermore, RPGs require both exploration of and interaction with the virtual world where the story takes place, two of the elements at the basis of the experiential learning process [35].

A first example of this kind of games is *Ludwig*. In a futuristic Earth depleted of fossil fuels, the learner explores the environment to find a way to create alternative energy. Another example is *Desertification story*, where players deal with the resources scarcity of a village [36].

An interesting sub-category of RPGs is that of the massively multiplayer online RPGs (MMORPGs), where a very large number of players interact with one another within the game virtual world. MMORPGs usually demand cooperative problem solving and teamwork to achieve in-game goals. This characteristic is particularly interesting in the learning contexts, since, besides promoting collaboration, it facilitates social negotiation of meaning, i.e. the process in which learners test their own understandings against those of others [37].

Examples of MMORPGs are *Mini Monos* and *PowerUp*. In MiniMonos, children (of six and above) create monkey avatars that cooperate with others in carrying out real world activities (for example, setting up a school recycling program). Such activities impact the monkeys' happiness and the sustainability of their natural habitat [38]. PowerUp was a 2008 project from IBM, aimed at promoting engineering careers among students across the world. Focused on energy, the game objective was to generate clean energy and save the planet from ecological disaster. In order to facilitate collective decisions, players could meet and chat in an orientation center where "engineer" NPCs provide their experience and act as guides.

Qualitative evaluation data of Desertification story indicate that most players found the game interesting and understood its educational content [36]. Ludwig was tested both qualitatively (by 200 students and 8 teachers) and quantitatively (by 80 students). Results indicate that the game is able to impart knowledge to a classroom only when the teacher provides adequate support, thus suggesting that Ludwig is a valuable supplement for conventional instructional tools rather than a self-learning material [39].

3.4 Playful Activities

Several playful activities, such as quizzes and text sentences to be completed, have been proposed to teach sustainability related concepts. Children are the main target audience and often the only sustainability aspect addressed is the ecological one. The educational approach of these activities is based on direct instruction [7], presenting straightforward pieces of information and clear feedbacks on the answer correctness. Furthermore, most of these games provide supporting didactic material that can be used by parents or teachers for post-game discussion and reflection.

Examples are available in online portals like *PBS Kids*, *EPA*, *Discover Water* and *Games Planet Arcade*. *The Water Cycle* (Figure 2) is a game focused on teaching water cycle contents such as transpiration, consumption, flow, melting, and so on. More complex examples are *Heroes of Koskenniska*, *Alberto's Gravimente Toys*, *ecoCampus* and the *mobile Sustainability Serious Game (MSSG)*. Heroes of Koskenniska is a location tracking based game that requires players to navigate the North Karelian Biosphere Reserve in Finland and answer questions concerning the human impact in the surrounding environment [40]. Alberto's Gravimente Toys [41] is a game for children of the primary school that depicts several sustainability scenarios. In each of them, players have to collect and organize the different parts of a story. The last following examples are related with sustainable architecture. EcoCampus is an augmented-reality game for academic students where players can interactively explore different building redesign solutions and assess them under

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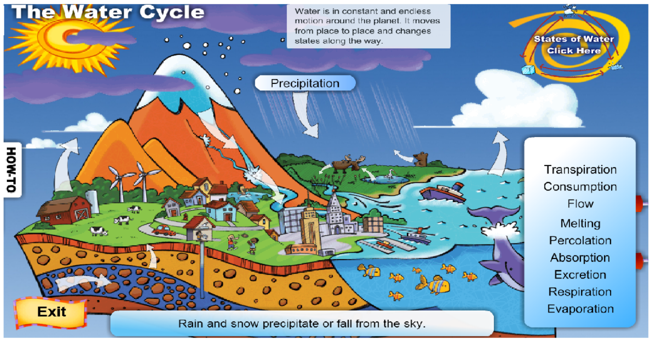

Fig. 2. Example of the Water Cycle game activity, in the portal Discover Water

the sustainability point of view [42]. MSSG is both a mobile and web game where university students are confronted, through a series of mini–games, with issues in designing sustainable public spaces [43].

In general, these playful activities are designed for a single user although some of them, such as Heroes of Koskenniska and Alberto's Gravimente Toys, encourage players to act collaboratively and exchange information with other peers playing the same game [40], [41]. The main target audience of these games is clearly that of the younger players, with few playful activities expressly designed with mature audience in mind (e.g., ecoCampus, which targets civil engineering and architecture students).

Some evaluation data, although mostly qualitative, are available for our example games. Authors of Heroes of Koskenniska reported a general user appreciation and a presumed increase of the number of reserve visitors during the evaluation period [40]. Alberto's Gravimente Toys testing showed that most players understood the learning contents [41] and that most of the children (85%) preferred to play the game collaborating with a friend to build the story. MSSG was evaluated by 33 computer science students through a questionnaire, which showed an improvement of the volunteers' perceived knowledge about the sustainability issues. A more solid evaluation was attempted for ecoCampus, with 108 students playing the AR game and two control groups of 65 and 23 students, which completed the same activities using, respectively, blank sheets of paper and a paper-based approximation of the game. The students playing the AR game were able to produce more creative designs in shorter time (with 28% less students reporting inadequate time to complete the activities), and had better learning outcomes when compared with students of the control groups [42].

3.5 Procedural Rhetoric Games

Procedural rhetoric is the practice of authoring arguments through interactive processes [17]. Rather than directly providing the desired information, procedural rhetoric games enable players to experience a particular claim or argument through their choices and interactions within a dynamic

Fig. 3. Procedural rhetoric game Pipe Trouble

game system [22][1]. Furthermore, these games introduce their arguments trying to represent real-world concepts and practices in a way that elicits lasting emotional responses or critical reflections in the player [17]. Examples of such games are the following.

Pipe Trouble (Figure 3) tackles the complex issues related to the deployment of gas pipelines and tries to stimulate learners' critical thinking about energy extraction. Players have to construct a pipeline balancing several conflicting requirements. Gas company representatives demand for the meeting of deadlines and budget constraints. At the same time, deployment should be careful enough to avoid destroying farmland and spoiling environment, with consequent rise of protests from the community. Besides that, players have to face obstacles, which include a group of eco-terrorists trying to bomb the pipeline.

Oiligarchy and *Oil god* have similar arguments: the politics behind oil industry generate unsustainable negative consequences to the environment. In both games, the player has to increase oil extraction profits by drilling exploitation wells, corrupting politicians, stopping alternative energy sources and increasing the world oil addiction. While the game is played, player actions negatively affect the environment, resources start to deplete and, with the advance of time, objectives become out of reach.

In procedural rhetoric games, information communication relies on both feedback to users' actions and game mechanics. As examples of feedback, in Pipe Trouble company representatives progressively ask for actions in disagreement with environment law, while the visible degradation of the environment triggers the protests of the local communities. The strategy mechanics of Oiligarchy and Oil God involve resource management and political decisions and are

1. The definition of procedural rhetoric games appeared first in Ian Bogost book "Persuasive Games" [17], a term that in literature refers also to "interactive computing systems explicitly designed to change attitudes or behaviors" (Fogg, [44]). In this paper, in order to avoid misunderstandings, procedural rhetoric games are classified as educational games, since we believe their focus is in communicating a message to players, while games under Fogg's definition are included into the motivational games class.

aimed at fostering players' reflection over the consequences of their actions [28]. The time-limited scenarios and fast-paced gameplay of Pipe Trouble aim to recreate the urgency and pressure conditions that characterize several situations where environmental decisions need to be taken, which can result in choosing the non–optimal option.

The release of the procedural rhetoric games definitely influenced the game community. Oiligarchy was considered one of the defining examples of the overlap between interactive digital storytelling and political discussion [45]. Pipe Trouble achieved a historical milestone. After being in the center of controversy upon its launch in 2013, being speciously accused of glamorizing the bombing of gas pipelines, it became the first video game ever featured at the Cannes Film Festival [46]. In spite of such achievements, empirical test data were not available for any of these games.

Procedural rhetoric games usually (and clearly) embrace a holistic approach to the sustainability aspects. While none of the analyzed works directly state its target audience, it is clear that an older audience can reach a deeper understanding of the argument. As a further information, all these games are single player. This can be seen as a drawback of the current procedural rhetoric approaches, as multiplayer settings, where players assume different cooperative or competitive roles, are likely to bring further contributions to the rise of critical thinking on the game topics.

4 Motivational Games

Motivational games are based on the assumption that education towards sustainability should also be able to induce a social change in learners. This process involves several interconnected phenomena related to both people's daily life and their relation with others and the community. In order to contribute to such social changes, serious games should not be limited to a mere communication of new knowledge. Rather, they should leverage their educational component to help people modifying their attitude and beliefs, stimulate the adoption of specific behaviors (e.g., "routine" actions that are energy consumption aware) and foster motivation to change [47].

Analyzing the motivational games, we identified two main approaches, *eco feedback games* and *gamification approaches*, which are detailed in the following.

4.1 Eco Feedback Games

The most common goals of eco feedback games are persuading people to reduce CO2 emissions (*Eco Island*) and energy consumption (such as in *Climate Race*, *Energy Battle*, *LEY!*, *Power Agent*, *Power Explorer*), or to improve garbage recycling actions (*GAEA*). Thus, the main sustainable aspect targeted by these applications is the ecological one. All these games adopt a similar structure: they propose a set of activities and analyze data collected from users to provide a proper feedback to their actions (see Table 2).

The accomplishment of the proposed activities is verified by collecting (usually in an automatic way) different data. For instance Climate Race, Energy Battle, LEY!, Power Agent and Power Explorer collect energy consumption data from players' smart meter devices and GAEA tracks player's mobile phone location. In other cases, players have to insert manually meter measurements (Energy Battle) or check activities like turning down the air heater by one degree and taking a train instead of a car (Eco Island).

Eco-feedback games leverage two main elements to motivate players. The first is the feedback provided by the game, typically in the form of charts, textual information and tips on ways to be more efficient in achieving the game objectives (see Figure 4(a)). As an alternative, some games propose more "ludic" approaches. For instance, the objective of Eco Island is to save a virtual island from rising sea levels, which varies according to the more or less green activities taken by players (see Figure 4(b)). In Power Explorer, the level of energy consumption visually affects the health of the player character. The second relevant motivational element is that, in all these games, the proposed activities require cooperation and competition among multiple users, which are generally organized in teams. Several researchers agree that a combination of intra-group cooperation and inter-group competition offers advantages over pure cooperation or competition [20], [48]. Competition provides additional motivations, while cooperation enables the synergistic effect, i.e. players understand the interconnected impact of many individual actions, which is often unclear when they are analyzed individually [49]. Furthermore, in-game direct communication among players can improve argument comprehension and provide additional motivational and emotional support to individual users [47].

While several of these games have been scientifically evaluated, researchers' opinions about their effectiveness in generating the intended behavior changes are divided. Several results report an immediate positive outcome [50], [51], [52], [53], [54], [55]. For instance, [50] reports that electrical devices were less frequently left powered on before leaving for five minutes (-12.6%) and rather put in standby (+7.9%) or switched off (+1.7%); average energy savings during the game period were 24% for Energy Battle, 22% for Power Agent and 16% with Power Explorer. However, results on the preservation of these effects in the long term were inconclusive. In Power Agent [55], Eco Island [51] and Energy Battle [52], the players' levels of energy consumption returned to their initial values some weeks after the game ended. The only success case reported is Power Explorer, with a stable 14% reduction ten weeks after the game was played [54].

TABLE 2
Evaluation of eco feedback games

Proposed activity	Data collection	Serious games
Reduce energy consumption	Manual	Energy Battle
	Automatic	Climate Race, LEY!, Power Agent, Power Explorer
Reduce CO2 emissions	Manual	Eco Island
Household waste sorting	Automatic	GAEA

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(a) (b)

Fig. 4. Feedback on behavior change persuasive games; (a) explanatory approach in Climate Race, and (b) ludic approach in EcoIsland

4.2 Gamification

Another powerful approach to motivate players towards more sustainable actions is gamification, i.e. the use of game design elements in non-game contexts [25]. Similar to the Eco Feddback games, gamification approaches mostly focus on the ecological aspect of sustainability. Sections 4.2.1 to 4.2.3 present the most salient examples of this category.

4.2.1 *Employee Engagement in Eco-friendly Actions*

Some companies use gamified applications to motivate employees towards eco-friendly behaviors. These applications propose challenges that require reducing the consumption of some resource. Two prominent examples are *Eco.system* and *SuMo*.

Eco.system focus on motivating employees to reduce annual carbon footprint of the Scottish energy company SSE through changes on daily minor actions, such as using stairs instead of lifts, reducing document printing and switching off monitors overnight [56]. Eco.system uses two main motivators to engage players: a) a social network, where each participant enters his own environment-friendly actions, and b) a monetary prize, aimed at redistributing the yearly company savings originated from employee sustainable behaviors. SuMo [57] aims at engaging and motivating players in finding eco-friendly ways of traveling by using challenges, badges and leader boards. Evaluation in a company with over 8,000 employees during a period of one year showed that SuMo users reduced by a 10% their annual carbon footprint, while users of a control group, not using the app, increased their quota by 2.1% [58].

4.2.2 *Gamified Electronic Bills*

Gamification has been also used to encourage householders to reduce resource consumption. The proposed solutions rely on user-friendly electronic bills enriched with personalized feedback and gamified elements (such as leader-boards and neighborhood comparison).

Two examples are *OPower* and *Water Smart*, which target, respectively, energy and water consumption. Both tools were tested quantitatively. The OPower testing lasted five years and involved 88.000 families [59]. Results showed a 3.0% savings in comparison with the control group. In addition, the test indicated partial success into providing long-term lasting effects. Families that received the personalized

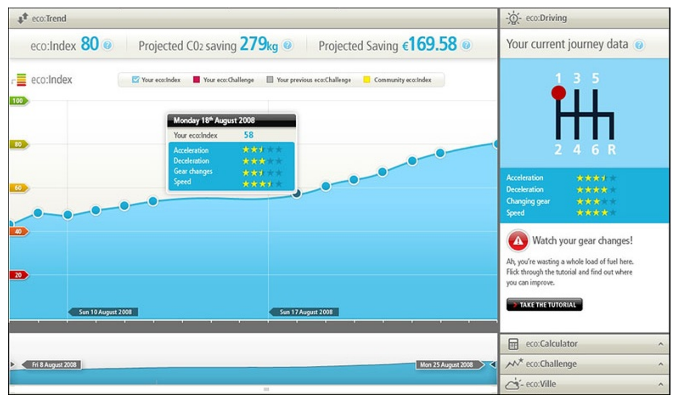

Fig. 5. Fiat eco:Drive interface

reports only during the first two years of the program, maintained in the following three years a 1.5% energy reduction with respect to the control group. Similarly, WaterSmart involved 10.000 homes for a period of one year resulting in a 4.6% to 6.6% decrease in water use between the treatment and the control group [60].

4.2.3 *Efficient Driving*

Recently, several cars have exploited telemetry data to provide gamified cues for drivers. One of the earliest examples is the *Toyota Prius Hybrid telemetry system*, which allowed drivers to control their fuel efficiency [21]. Thereafter, the gamified car telemetry evolved into more complex applications, such as *Fiat eco:Drive*, *Honda Eco score*, and *Ford Smartgauge with EcoGuide*. These systems track drivers history, display user–friendly dashboards and informative feedback about their driving efficiency (see Figure 5), and position them in a worldwide rank [56].

Qualitative evaluation of Toyota Prius Hybrid telemetry system involved 34 drivers during six weeks, founding that drivers instantaneously changed their driving behavior according to system feedback [21]. In addition, a quantitative study about more than 5.500 Fiat eco:Drive users over a 30 day period showed an average 6% fuel reduction [61].

5 Design Frameworks for SSGs

As we have seen in the previous Sections, a number of SSGs were designed to approach different issues, from both an educational and a motivational point of view. However, while it is widely acknowledged that serious games provide an engaging, motivating and entertaining environment, these characteristics do not necessarily result in a meaningful learning experience. For this reason, several researchers highlighted the need to base the design and development of serious games on sound theoretical frameworks that encompass theories from both pedagogy and game design fields, with the aim to provide effective links between game mechanics and learning elements [62]. In other words, the integration of these two perspectives aims at exploiting game design elements to engage player in the learning activities and, at the same time, increasing the effectiveness of the game as a learning tool (which, in turn, requires grounding the design choices on a sound pedagogical framework).

Several methodological frameworks (some of which are reviewed in [63]) have been defined for (general) digital learning game design. However, sustainability learning requires to deal with complex systems and involves multiple dimensions and stakeholders. In the first place, this fact rules out some pedagogical approaches and, consequently, the design frameworks that are based on them. Second, it rises the need of specific tools to deal with multiple interrelated domains represented under several perspectives.

As a further comment, different types of SSGs (educational and motivational) have different peculiarities, which makes it difficult to define a unique methodological framework embracing all of them. In the following, for each category we first introduce some reference models proposed in the literature. In general, these models are structured in terms of *key concepts* and *design guidelines*. The key concepts summarize the common aspects of educational or motivational games, and the design guidelines are intended to provide clear instructions to designers and developers on how to adopt each specific concept (Table 3).

Then, we discuss to which extent the design guidelines are embraced by the identified SSGs. We believe that this discussion can be of interest for at least four reasons. First, it helps to enlighten the practical applications of the proposed guidelines. Second, it enables the identification of those guidelines that were not extensively applied and are, therefore, candidates for further exploration. Third, it allows to link the described SSGs with a sound theoretical design framework even if not explicitly done during the game design phase (which, in turn, could as well provide an a posteriori indication of the soundness of the design choices). Finally, it is (hopefully) an interesting material that designers can consult when planning to develop a sustainability game.

5.1 Educational Games

To the best of our knowledge, the only design framework expressly developed for educational SSGs is the one described in [64]. In their work, Fabricatore and Lopez first analyzed the content of 30 games to identify possible enablers of sustainability learning. Then, they devised a design model based on both their results and on studies related to learning about complex systems [68].

Another interesting reference for educational games is the *Guidelines for Excellence* (GFE), a compilation of opinions from researchers, theorists, and practitioners related to what effectively works in the development of sustainability learning materials [69]. In particular, the model of Fabricatore and Lopez has several elements in common with the GFE, which indicates its alignment with a sound reference in the production of learning materials for sustainability.

In the following we introduce the four key concepts defined by Fabricatore and Lopez along with their relations with GFE guidelines.

Contextualization. Both [64] and [68] underline the relevance of contextualization to foster an in-depth awareness of the sustainability issues and encourage knowledge transfer between virtual and real world. According to Fabricatore and Lopez, designers should have a multi–faceted approach. They should contextualize the *game thematic* by considering simultaneously all aspects (social, economical and ecological) and conflicting values (e.g. economical growth vs ecological justice) of the sustainability issues. Then, they should also *contextualize the player* by offering real-life roles (e.g. farmers, citizens, mayors) and representing the multiple views involved (cultures, races and genders).

Player empowerment. Players should be allowed to exert full control on the game system and act as freely as possible, in order to be more engaged in the experience [68]. Player empowerment relates to the sense of players self-efficacy described in GFE [68], i.e. the learners perception of their ability to influence the outcome of a situation. Fabricatore and Lopez suggest two design guidelines to foster player empowerment: a) present different roles that players can select, each with its own skill sets, and b) offer multiple victory states and different paths to achieve them.

Social interactions. Meaningful social interactions among players help to promote knowledge production [70] and enhance creative thinking and interpersonal communication. These are two relevant characteristics that should be approached when learning about complex systems [68]. According to [64], social interactions can be improved with a) the introduction of mechanics that demand multiple players to communicate and cooperate within the game world, and b) the extension of the communication out of the game spaces, e.g., exploiting social networks.

Adaptivity is a term that encompasses two elements. First, the progressive introduction of interactions and game mechanics according to players' individual needs; second, the players proactive and responsive adaptation to unanticipated scenarios or non-player planned disruptions in game dynamics [64]. This concept has no correspondences in GFE, since it is not directly related to the educational contents of the game.

5.1.1 An Evaluation of Educational Games

One immediate question is: to which extent the analyzed educational games embody these design principles?

As introduced in Section 3, most of the games stress *thematic contextualization* through the emulation of real-life scenarios/actions and the representation of different scales, both in local to global dimension and in short to long time

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TABLE 3
Design guidelines for sustainability games

Game class	Key Concepts	Design Guidelines	Examples
Educational	Contextualization	Define game thematic contemplating simultaneously all aspects and conflicting values of sustainability issues	In an enterprise management game, players should aim at sustainable enterprise development, balancing the profit generation and its impact on environment, social community and global economy [64]
		Contextualize the player (role and actions)	In a multiplayer game, each player can choose a different role (representative of the oil company, a politician and a native) and interact with other players to reach her/his goals mediating contrasting needs.
	Players empowerment	Employ multiple roles with different skill sets	In a CMS, the mayor takes decisions related to the construction of houses, factories, public transportation and leisure areas; the ministry of energy shall develop the energy matrix based on renewable and/or depletable resources.
		Offer multiple victory states	In a CMS, user can play as a farmer (developing and implementing efficient cultivation strategies to ensure sufficient crops while preserving water reserves) or an entrepreneur (maximizing profit while adopting fair-trade strategies and creating sufficient wealth for the town) [64]
	Social Interactions	Adopt mechanisms to harness communication and cooperation	In a village, players have to collect and preserve the available water against enemies trying to waste it. In order to reach their objective, players have to choose and implement common strategies to distract them
		Expand the communication outside the game space (e.g to social networks)	Embed a web–based game in social media to allow players posting their scores, thus enhancing gameplay experience and creating an element of competition [33]
	Adaptivity	Progressively present mechanics and interactions	Design a first level where basic actions and slow moving enemies (i.e., monsters polluting the environment) are introduced. As players improve, more complex actions and challenging enemies are introduced
		Introduce non-player planned disruptions in game dynamics	In a CMS, a natural disaster, like an hurricane or an earthquake, causes extensive damages to the city requiring players to handle the new situation
Motivational	Players' individuality	Allow players to set their own goals	Enable players to select their own in game targets (e.g., the level of CO2 emissions to achieve and maintain [51])
		Tailor content and feedback to the players' characteristics	In a game motivating energy saving, provide different advises for different player contexts (e.g. a person living alone in the city center, or a large family living in the suburbs [65])
		Design different challenges, considering different player types	Provide both cooperative settings to attract "socializer" players and individualized rewards to appeal to "achievers" [66]
		Tolerate player failures	Design a game where different methods to reach an intermediate goal can be repeatedly experimented; a failure determined by a choice triggers a discovery process revealing that a particular method does not work
		Offer multiple levels of difficulty for each individual	Adjust the level of difficulty either manually (e.g., including a "gamemaster" mode) or automatically (e.g., by profiling users according to in–game analytics [67]); grant players the possibility to select their own difficulty level
	Multiplayer activities	Propose inter-group competition and intra-group cooperation	Enable groups of players to compete in trash recycling activities [53]
		Enable social motivation (e.g, by expanding the game space to social networks)	Each player is in charge of the sustainable development of a fictional city, and players can use the game web-site facilities and social media to share their status, visit other players' cities and rank them

spans. Additionally, a significant number of games consider all the different aspects of sustainability (environmental, social and economic). On the other hand, most of the works do not take into account *player contextualization*. Few games (e.g., Ecopolicy and Green & Great) allow players to assume different policy–maker roles, and only the procedural rhetoric games hint at the different social and cultural elements involved in the depicted scenario. However, their perspective is somewhat limited since it merely offers an "external" view over the different facets of the problem. For instance, Oiligarchy depicts how players' actions of oil exploitation impact on the lives of natives but learners do not have the possibility to play the role of natives. Thus, they cannot directly experience the social implications of other players' decisions. Based on these observations, we believe that social contextualization should be better explored in order to improve the learning outcomes of educational SSGs.

Another key concept that should receive more attention is, in our opinion, *player empowerment*. Apart from Perfect–Ville, which emphasizes the empowerment concept by allowing players to redefine game rules and contents, few other games introduce design elements aimed at effectively supporting it. Some games grant higher degrees of freedom during both navigation and interaction within the game environment. For example, Ludwig offers several non–mandatory side missions that require player active exploration of the scenario to be discovered. Other games offer the possibility to assume different roles with different skill sets (e.g., in Futura each player is responsible for a specific resource, like food, shelter and energy). In addition, some games offer multiple winning paths. As an example, in Ecopolicy players can take different approaches to govern a country maintaining its sustainability and no single winning strategy exists.

The lack of *Social interactions* among players is one of the major drawbacks of current designs, since most of the analyzed games are single player. Furthermore, few games offer ways to extend the communication out of the game space, mainly by simply sharing results and challenging friends through social networks (EnerCities, Plan It Green). On the contrary, when this social interaction is available, empirical evaluation shows its relevance to enhance knowledge acquisition in sustainability topics [32], [41].

Adaptivity is another key element that has been largely overlooked in the current educational games. To some extent, all of them present in a progressive manner their actions and mechanics to players. However, only the procedural rhetoric games induce non-player planned disruptions that require players to adapt to new conditions. Moreover, none of the analyzed games makes use of adaptive game mechanisms, capable of offering players different gameplay experiences based on their actions within the game.

Concluding, an evaluation of current SSGs based on the key concepts of the Fabricatore and Lopez model shows that much work has to be done in the future to fully exploit the capabilities of educational SSGs. Thematic contextualization is the only concept extensively applied to current designs and greater consideration should be given to the representation of social issues and to the introduction of game mechanics and technical tools capable of empowering players and improving interaction and communication among them. Finally, we think that a viable solution to fully benefit from adaptivity, could be the exploitation of in–game analytics, an approach that has demonstrated its effectiveness in the development of adaptive digital games [67].

5.2 Motivational Games

Several authors approached the definition of theoretical frameworks for motivational games. For instance, Weiser et al. (2015), and Huber and Hilty (2015) proposed guidelines based, respectively, on motivational and gamification theories [20], [48]. In another work, Antle et al. (2014) suggested a set of guidelines based on the analysis of 10 sustainability games under the lenses of the *emergent dialogue*, a theoretical model developed for creating and running policy workshops around sustainability issues [22].

These three works have some interesting similarities, which can be summarized into the two following key concepts: *players' individuality* and *multiplayer activities*.

Players' individuality. Addressing players' individuality in the game design requires taking into account two elements. First, the heterogeneous characteristics of the players. Players can be categorized into different types (defined in [66] as killers, achievers, socializers and explorers) and have different expertise (classified in [71] as novice, competent, proficient, expert and master). Designers should include game mechanics and elements capable of proposing different challenges and providing the appropriate level of difficulty for each individual. In doing so, they should also take into account all the societal, cultural and demographic aspects that can affect learners' decisions [48] (e.g. regulations, restrictions, location of living, non-availability of alternatives, and so on).

The second element to be considered is the players' *autonomy*. Designers should enable players to choose freely their own goals and the way to achieve them. In addition, games should also give players the autonomy to fail if desired [22], [48], since a game that tolerates failures allows players to rehearse different behaviors and to explore interactively their cause-effect relationships.

Multiplayer activities. Group experiences provide more possibilities for engagement (for instance, by offering intergroup competition/intra-group collaboration [20], [48]) and allow the representation of sustainable impact of both individual and group actions. In addition, even single player games should include some social interaction elements aimed at introducing other players into the proposed activities in order to induce competition (e.g., through normative comparisons of individual achievements) and enable social motivation (e.g., using mechanisms to support discussion about contents and exchange of experience and suggestions).

5.2.1 An Evaluation of Motivational Games

An analysis of the motivational games described in Section 4 results in somewhat different findings for the two key concepts previously defined.

Most of the works analyzed are based on *multiplayer activities*. Game evaluations confirm, as a general result, that this element is relevant in engaging players [50], [51], [53], [55] and improving the comprehension of the interpersonal and social relations linked to the sustainability field [72]. When implemented, the combination of intra-group cooperation and inter-group competitions seems indeed to be an intrinsic motivator (GAEA [53], Energy Battle [52]). Several games offer social interactions providing players with the opportunity to share experiences and suggestions (such as the Facebook Connect feature of GAEA, and the social network of Eco.system). The use of leader boards and normative comparisons is also typical of most of the gamification approaches.

Despite this, we think that there is still a need for a deeper understanding of multiplayer activities. For instance, it could be interesting, in future research, to tackle the following issues: how to design multiplayer activities aimed not only at achieving but also at maintaining the intended behavior change, and how to effectively engage different audiences in cooperative or competitive scenarios.

Concerning *players' individuality*, some games offer players the freedom to select their own goals in the game. For instance, Eco Island enables players to select their own target level of CO2 emissions (e.g., 10% less than the national average emissions). Other games allow players deciding which actions to take and when to perform them. For example, in Eco.System players are free to undertake their preferred actions to reduce CO2 emissions. Another option is to deliver personalized information and messages to the player according to his profile. In Opower, the game provides different advises related to home energy consumption for a person living alone in the city center and for a large family living in the suburbs [21].

Researchers have explored as well the use of different game mechanics to provide higher engagement for different type of players. In Eco Island, the multiplayer cooperative setting aims at attracting "socializer" players, but it also individualizes the contributions and associated rewards, a mechanic that is appealing for "achievers", i.e. players that

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prefer concrete measurements of succeeding in the game [66].

However, we were not able to find any game providing explicit support to two of the relevant aspects related to players' individuality, namely the presence of multiple levels of difficulty and the tolerance to player failure. We believe that both these elements are relevant in the design of a motivational game and worth to be explored in future research.

6 Discussion and Open Areas of Research

The papers surveyed in the previous Sections show that, despite the interesting results obtained, fully understanding how to develop effective SSGs requires further work. This is because either the background theory has not been fully explored, or the research findings are controversial. Therefore, in this Section we briefly discuss some open problems and potential areas of research.

Research question 1: Which methodological frameworks are most suited to drive SSG design?

SSGs must provide an experience in which entertainment and instruction are seamlessly integrated. To this end, well-designed games need to be grounded on learning theories, game design practices and instructional strategies that allow researchers to manipulate key variables and determine which factors have the greatest effect on learner motivation and achievement.

Among the design models and frameworks specifically addressing the sustainability learning issues (see Section 5), some were used in practice and their preliminary evaluation seems to indicate the effectiveness of their guidelines [73], [74], [75], [76]. On the contrary, other frameworks were proposed [63], [77], [78], [79] but not extensively used or they were assessed by the same researchers proposing them [80] and, thus, the evidence of their relevance has yet to be demonstrated.

In our view, a common trait of these approaches is the relatively lower emphasis put on the entertainment dimension with respect to the educational one. Entertainment is a relevant element, since engaging the player creates the ideal situation for learning to happen [77]. However, how to reach this objective is a long debated question among experts.

For decades now, researchers have attempted to offer adequate guidelines on how to produce "enjoyable" educational games. The initial focus of these studies was on technological aspects, such as game interface design, interaction devices and usability issues [81]. Recently, there has been a shift towards a broader view over the player-game relationship, usually referred to as *player experience* (PX). PX builds upon the aforementioned technological elements to encompass the domain of the player's experiences while interacting with the game. In other words, a game is made to be *experienced* by the player and the thinking, feeling and effect on the individual all need to be taken into account in the design process [82].

Several authors have introduced design models for educational games based on a PX perspective. In general, these studies identify characteristics aimed at enhancing PX, such as the introduction of different player models (novice, experienced and so on), the definition of clear goals and immediate feedback, the representation of real-life scenarios and the capability of providing player *adaptivity* [83], [84], [85]. It is interesting to highlight the direct link of these elements with the guidelines of Fabricatore and Lopez for the design of educational SSGs (Section 5.1). In particular, these elements could certainly bring benefits with respect to the key concepts not yet adequately addressed in educational SSGs, such as player contextualization (partially considered in procedural rethoric games only) and empowerment (which is fully exploited only in Perfect–Ville).

Concerning motivational games, the scenario seems a little less established and the current frameworks for gamification design [86] lack concrete strategies to approach directly PX. Marache-Francisco and Brangier started to tackle this issue in [87]. They established a grounding categorization based on prominent aspects of PX–driven gamification design. In particular, they highlight the relevance of motivational elements (i.e., taking into account users' emotions, harnessing sense of accomplishment and social acceptance), which found correspondences with the key concepts of players' individuality and multiplayer activities identified in Section 5.2.

Concluding, we believe that more research should be devoted to a) validate the practical application of design models and frameworks available in the literature in order to clearly identify their strengths, limitations and potential improvements, and b) define and assess novel theoretical frameworks for SSGs, which possibly fully integrate a PX perspective in their models.

Research question 2: Which technological tools can be used to improve learner immersion?

Several authors have highlighted the relevance of player *immersion* to achieve the desired learning outcomes in serious games [77], [88]. Fully immersed players reach an adequate level of engagement to trigger deep cognitive processing and to motivate players to invest psychologically in the absorption of the targeted academic contents [77].

Currently, both industry and scientific research investigate how innovative interaction paradigms (e.g. virtual and augmented reality, interactive surfaces, tangible devices) can enhance player immersion. However, the area of SSGs largely overlooked the use of advanced and immersive interaction technologies. Some interesting initial results about the applicability of novel interaction devices, especially in terms of harnessing players' creativity and collaboration, showed the effectiveness of tangible interaction [32], [41], [76] and augmented reality [42], [73]. Despite this, our view is that further investigation on this issue is required. For instance, fully immersive and highly realistic 3D virtual worlds can provide significant benefits in the development of deeply engaging experiential learning environments and, consequently, help to enhance knowledge transfer from virtual to real world. In addition, the integration of alternative methods of interaction, such as full and partial body motion capture, gesture recognition and wearable devices may enhance immersion in digital gaming, supporting cognitive processes, and mediating affective and social communication [89], [90], [91].

Research question 3: Since interaction among various players is a relevant factor in sustainability learning, which design elements and tools can foster cooperative/competitive behaviors?

Collaborative serious games are an effective way of supporting group learning. However, such games in themselves do not necessarily lead to an increase of collective knowledge production. Therefore, their development requires, again, taking into account both the theoretical ground for cooperative learning and the game design perspectives.

While motivational SSGs span all possible interaction patterns, with a preference for multiplayer ones, when the objective is to inform the players, the literature shows that most approaches are single player and the few multiplayer games available often lack competitive patterns. One possible explanation is the limited resources typically available for the development of educational games, which hinders the further addition of a collaborative dimension.

One way to tackle this issue could be to exploit design elements and technological tools that can foster such cooperative/competitive behaviors. An example is the work of Antle [32], which states that creating configurations in which each participant has a specific role, a different set of information and actions and can monitor other players' expressions, can hamper learner communication and negotiation. Other relevant suggestions can be found in the work of Sheridan & Williams, 2011 [92], which discussed elements that influence the creation of competitive learning environments. Examples are the absence of individual winners or losers, the creation of situations of intra-group collaboration and inter-group competition, the possibility of social comparison of competences and the immersion of players, as a means of stretching their expected potential.

We believe again that augmented and virtual reality technologies can provide a major contribution towards the development of effective collaborative games. In this regard, AR provides support for a multi-user, natural, face-to-face interaction by seamlessly blending real and virtual environments and integrating tangible and gestural interactions. On the other hand, VR enables the development of shared environments that guarantee an effective communication and interaction between different users and with the virtual objects.

Given the relevance of this topic and the initial (although limited) results of our research [73], [76], we think this is an area worth being explored to acquire a better understanding of which elements are necessary or suitable to effectively foster user collaboration and cooperation in SSGs.

Research question 4: To which extent are sustainability games effective?

Most researchers argue that serious games can be valuable tools to foster education towards sustainability and act as drivers of social, behavioral and attitude change in players. One interesting question is to what extent the empirical research results support these claims.

In Sections 3 and 4, we reported some evaluation data, which can be synthesized as follows. Most of the educational games evaluated were merely analyzed under a qualitative perspective. Despite positive results in terms of immersion and enjoyment, the greater part of the studies present vague conclusions, e.g. stating that players found the games fun, enjoyable, and informative [34], [40], [41]. A greater amount of quantitative data are available for motivational games, since their outcomes can be directly measured in terms of real-world variables (e.g. the amount of consumed resources). These findings are not enough to answer our research question, which sorely requires a deeper and critical analysis of the literature.

A good reference to shed some light on this issue is the recent study of Soekarjo and Oostendorp (2015). This paper reviews fifteen works that evaluate (qualitatively and/or quantitatively) the effectiveness of SSGs with respect to three outcome measures: changes in attitude, knowledge and behavior [93]. Results were mostly inconclusive. For each of the outcomes considered, the majority of the works found a significant positive outcome immediately after playing the game, some of them did not find any notable effect and no clear trends on the long-term continuation of these effects were obtained.

Soekarjo and Oostendorp (2015) suggest that one of the main limitations of these evaluations is the lack of a proper control condition. Most of the studies use pre and post-test measurements to evaluate changes in knowledge and attitude, but only some of them employ a control condition. Furthermore, in the majority of the cases this control condition is a "no info" condition, i.e. participants fill in a questionnaire twice without receiving any previous information. The results obtained in such experimental settings are often contradicted when a different control condition is applied. For instance, in [94] participants were divided into an experimental group (playing the game) and a control group (which received information about the topic discussed in the game in the form of a narrative story). The results showed no significant changes in attitudes between members of the two groups. Another example is the game EnerCities, which was evaluated qualitatively [33], showing lower energy consumption for people that played the game (experimental group) compared to those who did not (control group). In [93] the game was re-evaluated using an informative control condition, where the control group attended a slide presentation with similar information to that presented in the game. The results did not show any significant statistical difference in terms of attitude and knowledge change between the two groups. Both works [93], [94] seem to suggest that the game contents are more relevant than the game itself to achieve the desired outcomes. However, these results are again inconclusive for several reasons (e.g., the limited panel size [93], [94], or the lack of supplemental post-game material [93] that could have influenced previous results [33]).

In conclusion, current experimental results on the effectiveness of SSGs seem to be partial, and further work has to be done to develop a better understanding of tasks, activities, skills and operations that SSGs can offer in order to a) achieve the desired learning outcomes, while still being entertaining, and b) guarantee long-term lasting effects. In particular, more efforts should be spent in analyzing both the effectiveness of these games with respect to other communication media and their long-term lasting effects.

In our opinion, a relevant contribution to this issue would be the introduction of Game Learning Analytics

(GLA) to enhance learning and assessment. GLA refers to the integration in SGs of Learning Analytics approaches, aimed at capturing and analyzing players' interactions with the learning content, with the purpose of better understanding (and improving) the learning process [95], [96]. This information can be used during game play (e.g., to adapt and personalize the learning experience or to help instructors direct the learning process) and/or after the game session (e.g., to assess the learning outcomes). Despite their potential benefits, current SSGs largely overlooked the use of GLA. The only work we found [97] analyzed a single game, a fact that reduces the general validity of its results.

Appendix A
Literature review protocol

In this paper, we perform a literature review to document the current state–of–the–art within the SSG area, and identify possible areas where further research is needed. The purpose of this review is to understand the SSG design principles and the efficacy of this type of approach in communicating the desired educational content to learners or in influencing players' habits and behaviors. The following guiding questions were developed to help focus the extraction of information:

- RQ1: which SGs have been developed in the context of sustainability?
- RQ2: which approaches have been taken in SSGs to address the sustainability issues?
- RQ3: which design decisions guided the development of different SSGs, and how did they affect the resulting games?
- RQ4: which SSGs have been evaluated and how? What are the results of these evaluations?

The search process, carried out mainly between January and March 2017, started with an automated approach targeting three scientific paper databases, namely Scopus[2], ACM digital library and IEEE Explore portal. For each database, we carried out a search with the terms "sustainability AND games" limiting the results to papers published before January 2017. After this step, the 593 papers found (265 from Scopus, 183 from ACM and 145 from IEEE) were post–processed in order to remove repeated entries and exclude talks, panel discussions and book series titles, resulting in a total of 474 entries. The remaining papers were selected by reading over their title and abstract, and classified as either relevant or irrelevant, according to the following criteria:

- Does the study appear to detail/make use of any digital interactive technology?
- Does the study relate with any of the sustainable development aspects (social, economical, environmental)?

If the answer to any of these questions was no, then the study was excluded. After this step, each of the 90 accepted papers was read completely by at least one reviewer, who also assessed its quality on a five–point scale, and then its references were analyzed according to the aforementioned screening process. Since this work deals with digital games, which are not necessarily described in scientific publications, we also searched for unpublished material in both dedicated websites and online portals (e.g., Games For Change, Persuasive Games, Games For Sustainability, Learning For Sustainability).

In order to capture the characteristics of the problems and solutions proposed in these papers, we introduced a taxonomy of SSGs, whose initial version was defined based on the authors expertise. According to our findings, this taxonomy was further refined into the final one introduced in Section 2. Then, all authors categorized the relevant games according to this taxonomy and any disagreement was solved by discussion.

Finally, as a last step, we searched for references related to the open problems and potential areas of research identified during our analysis.

2. research limited to "computer science" as subject area

Appendix B
List of sustainability games (alphabetic order)

1) Alberto's Gravimente Toys (Ferraz et al., 2010)
2) Catchment Detox, ABC Science, http://ab.co/2m2LaJI
3) Citizen Science, University of Wisconsin, http://bit.ly/2mSBBfR
4) City Rain, Ovolo Corporation Inc., http://bit.ly/2mlfeCO
5) Climate Race (Simon et al., 2012)
6) Clim'way, ADEME, http://climway.cap-sciences.net
7) Desertification story (Zualkernan et al., 2009)
8) Discover Water, Project WET Foundation, http://www.discoverwater.org/
9) ecoCampus (Ayer et al., 2016)
10) EcoPolicy, Dr. Frederic Vester, http://bit.ly/2lGLBMu
11) EcoVille, ADEME, http://bit.ly/1jpdHj4
12) Eco Island (Shiraishi et al., 2009)
13) Eco.system (Owen, 2013)
14) ElectroCity, Genesis Energy, http://www.electrocity.co.nz/
15) EnerCities, Paladin Studio, www.enercities.eu/
16) Energy Battle (Geelen et al., 20112)
17) EPA games suite, US Environmental Protection Agency, http://bit.ly/2mi8ANn
18) Fiat eco:Drive, Fiat, http://bit.ly/29qrqxf
19) Ford SmartGauge, Ford, http://ford.to/2lH4MSP
20) Futura (Antle et al., 2011)
21) GAEA (Centieiro et al., 2011)
22) Games Planet Arcade, US Department of Commerce, http://games.noaa.gov/
23) Green & Great, Centre for Systems Solutions, http://bit.ly/2lH4But
24) Heroes of Koskenniska (Laine et al., 2010)
25) Honda Eco score, Honda, http://bit.ly/Y5TzPA
26) LEY! (Madeira et al., 2011)
27) Ludwig, ovos realtime3D, www.playludwig.com/
28) MiniMonos, Clark-Reynolds Company, http://bit.ly/2mlqPSI
29) MSSG (Mobile Sustainability Serious Game, Lameras et al., 2014)
30) Oil God, Persuasive Games, http://bit.ly/2mNEu24
31) Oiligarchy, Molle Industria, http://bit.ly/1kk9SlI
32) Opower, Oracle, https://opower.com/

33) PBS Kids games suite, PBS Kids, http://to.pbs.org/1pUy9Rx
34) Perfect-Ville (Yiannotsou et al., 2014)
35) Plan it Green, National Geographic, http://media.planitgreenlive.com/
36) Pipe Trouble, Pop Sandbox Productions, http://bit.ly/2m2s0VX
37) Power Agent (Gustafsson, Katzelf and Bang, 2009)
38) PowerExplorer (Gustafsson et al., 2009)
39) PowerUp, IBM, www.poweruphegame.org/
40) Precipice, Global EESE and Centre for Digital Media, http://bit.ly/2micINn
41) Riverbed, Mary Wharmby, www.riverbedgame.com/
42) SuMo, CloudApps, http://bit.ly/2nJAAaW
43) Super Energy Apocalypse (Doucet and Srinivasan, 2010)
44) Toyota Prius Telemetry system, Toyota, (Walz and Deterding, 2015)
45) WaterSmart, www.watersmart.com/

REFERENCES

[1] I. Burton, "Report on reports: Our common future: The world commission on environment and development," *Environment: Science and Policy for Sustainable Development*, vol. 29, no. 5, pp. 25–29, 1987.
[2] L. B. Sohn, "Stockholm declaration on the human environment, the," *Harvarf Int'l. Law Journal*, vol. 14, no. 3, pp. 423–515, 1973.
[3] C. Fabricatore and X. López, "Sustainability learning through gaming: An exploratory study." *Electronic Journal of e-learning*, vol. 10, no. 2, pp. 209–222, 2012.
[4] U. N. General Assembly, "The 2030 agenda for sustainable development," United Nations, Tech. Rep., 2015.
[5] J. M. Harris, "Sustainability and sustainable development," *International Society for Ecological Economics*, vol. 1, no. 1, pp. 1–12, 2003.
[6] D. Tilbury, "Rising to the challenge: Education for sustainability in australia," *Australian Journal of Environmental Education*, vol. 20, no. 02, pp. 103–114, 2004.
[7] G. L. Adams and S. Engelmann, *Research on Direct Instruction: 25 Years beyond DISTAR.* ERIC, 1996.
[8] M. J. Jacobson and U. Wilensky, "Complex systems in education: Scientific and educational importance and implications for the learning sciences," *Journal of the Learning Sciences*, vol. 15, no. 1, pp. 11–34, 2006.
[9] A. Gray, "Constructivist teaching and learning," Saskatchewan School Boards Association Research Centre, Tech. Rep. 97-07, 1997.
[10] D. Coakley and R. Garvey, "The great and the green: Sustainable development in serious games," in *9th European Conf. Games Based Learning (ECGBL2015)*, 2015, p. 135.
[11] B. Sawyer and D. Rejeski, "Serious games: Improving public policy through game-based learning and simulation," 2002.
[12] D. R. Michael and S. L. Chen, *Serious games: Games that educate, train, and inform*. Muska & Lipman/Premier-Trade, 2005.
[13] R. Dörner, S. Göbel, W. Effelsberg, and J. Wiemeyer, *Serious Games: Foundations, Concepts and Practice*. Springer, 2016.
[14] M. Ma, A. Oikonomou, and L. C. Jain, *Serious games and edutainment applications*. Springer, 2011.
[15] D. Djaouti, J. Alvarez, J.-P. Jessel, and O. Rampnoux, "Origins of serious games," in *Serious games and edutainment applications*. Springer, 2011, pp. 25–43.
[16] J. M. Vervoort *et al.*, "Stepping into futures: Exploring the potential of interactive media for participatory scenarios on social-ecological systems," *Futures*, vol. 42, no. 6, pp. 604 – 616, 2010, special issue: futures for multiple civilizations.
[17] I. Bogost, *Persuasive games: The expressive power of videogames*. MIT Press, 2007.
[18] K. Katsaliaki and N. Mustafee, "Edutainment for sustainable development: A survey of games in the field," *Simulation & Gaming*, vol. 46, no. 6, pp. 647–672, 2015.
[19] G. Liarakou *et al.*, "Evaluation of serious games, as a tool for education for sustainable development," *European Journal of Open, Distance and E-learning*, vol. 15, no. 2, pp. 96–110, 2012.
[20] M. Z. Huber and L. M. Hilty, "Gamification and sustainable consumption: overcoming the limitations of persuasive technologies," in *ICT Innovations for Sustainability*. Springer, 2015, pp. 367–385.
[21] S. P. Walz and S. Deterding, *The Gameful World: Approaches, Issues, Applications*. Mit Press, 2015.
[22] A. N. Antle *et al.*, "Games for change: Looking at models of persuasion through the lens of design," in *Playful User Interfaces*. Springer, 2014, pp. 163–184.
[23] P. Tragazikis and M. Meimaris, "Engaging kids with the concept of sustainability using a commercial video game–a case study," in *Transactions on edutainment III*. Springer, 2009, pp. 1–12.
[24] J. Hamari, J. Koivisto, and T. Pakkanen, "Do persuasive technologies persuade?-a review of empirical studies," in *Persuasive Technology*. Springer, 2014, pp. 118–136.
[25] S. Deterding *et al.*, "From game design elements to gamefulness: defining gamification," in *Proc. 15th International Academic MindTrek Conference*, 2011, pp. 9–15.
[26] D. Djaouti, J. Alvarez, and J.-P. Jessel, "Classifying serious games: The g/p/s model," in *Handbook of research on improving learning and motivation through educational games: Multidisciplinary approaches*. IGI Global Hershey, PA, 2011, pp. 118–136.
[27] ESRB. (2017) The esrb rating system. [Online]. Available: www.esrb.org
[28] T. Fullerton, *Game design workshop: a playcentric approach to creating innovative games*. CRC Press, 2014.
[29] N. Yiannoutsou, C. Kynigos, and M. Daskolia, "Constructionist designs in game modding: The case of learning about sustainability," *Proceedings of Constructionism*, pp. 19–23, 2014.
[30] M. Daskolia and C. Kynigos, "Tinkering creatively with sustainability," *Proceedings of Constructionism*, pp. 194–203, 2012.
[31] L. Doucet and V. Srinivasan, "Designing entertaining educational games using procedural rhetoric: a case study," in *Proc. 5th ACM SIGGRAPH Symposium on Video Games*. ACM, 2010, pp. 5–10.
[32] A. N. Antle, J. Tanenbaum, A. Bevans, K. Seaborn, and S. Wang, "Balancing act: enabling public engagement with sustainability issues through a multi-touch tabletop collaborative game," in *Human-Computer Interaction (INTERACT 2011)*, 2011, pp. 194–211.
[33] E. Knol and P. W. De Vries, "Enercities-a serious game to stimulate sustainability and energy conservation: Preliminary results," *eLearning Papers*, no. 25, 2011. [Online]. Available: http://bit.ly/2myrLQq
[34] A. B. Meagan K. Rothschild. (2013) Citizen science: civic engagement that is more than a game. [Online]. Available: http://bit.ly/2jk3Hjx
[35] M. D. Dickey, "Game design and learning: A conjectural analysis of how massively multiple online role-playing games (mmorpgs) foster intrinsic motivation," *Educational Technology Research and Development*, vol. 55, no. 3, pp. 253–273, 2007.
[36] I. A. Zualkernan *et al.*, "A role-playing game-based learning platform for environmental awareness," in *9th IEEE Int'l. Conf. Advanced Learning Technologies (ICALT 2009)*, 2009, pp. 78–80.
[37] M. D. Wagner, *Massively Multiplayer Online Role-playing Games as Constructivist Learning Environments in K–12 Education: A Delphi Study*. ProQuest, 2008.
[38] MiniMonos, "Mini monos," 2017. [Online]. Available: http://bit.ly/2iJhbqa
[39] T. Wernbacher *et al.*, "Learning by playing: Can serious games be fun?" in *6th European Conf. Games Based Learning*, 2012, p. 533.
[40] T. H. Laine, C. I. Sedano, E. Sutinen, and M. Joy, "Viable and portable architecture for pervasive learning spaces," in *Proc. 9th Int'l. Conf. Mobile and Ubiquitous Multimedia*. ACM, 2010, p. 1.
[41] M. Ferraz *et al.*, "The alberto's gravimente toys: children's fiction on technological design," in *Proc. 7th Int'l. Conf. Advances in Computer Entertainment Technology*. ACM, 2010, pp. 7–10.
[42] S. K. Ayer, J. I. Messner, and C. J. Anumba, "Augmented reality gaming in sustainable design education," *Journal of Architectural Engineering*, vol. 22, no. 1, p. 04015012, 2016.
[43] P. Lameras, P. Petridis, and I. Dunwell, "Raising awareness on sustainability issues through a mobile game," in *Interactive Mobile Communication Technologies and Learning (IMCL), 2014 International Conference on*. IEEE, 2014, pp. 217–221.
[44] B. J. Fogg, "Persuasive technology: using computers to change what we think and do," *Ubiquity*, vol. 2002, no. December, p. 5, 2002.
[45] G. Ferri, "Satire, propaganda, play, storytelling. notes on critical interactive digital narratives," in *Interactive Storytelling*. Springer, 2013, pp. 174–179.

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TABLE 4
Synoptic table highlighting for each of the reviewed game (i) the target audience (EC: early childhood, Y: youngsters, T: teen, M: mature), (ii) the interaction pattern (SP: single player, CO-OP: cooperative multiplayer, COMP; competitive multiplayer), (iii) the sustainability aspects addressed (En: environmental, Ec: economic, S: social) and (iv) the key design concepts partially or fully implemented (C: contextualization, PE: player empowerment, SI: social interactions, A: adaptivity, PI: players individuality, MA: multiplayer activities).

Game	Target audience	Interaction pattern	Sustainability aspect	Key design concepts implemented					
				C	PE	SI	A	PI	MA
Educational									
Construction and Management Simulation									
Catchement Detox	Y	SP	EnEc	X	X		X	-	-
City Rain	Y	SP	EnEc	X	X		X	-	-
Clim'way	Y	SP	EnEc	X				-	-
EcoPolicy	M	CO-OP	EnEcS	X	X	X	X	-	-
EcoVille	Y	SP	EnEc	X	X		X	-	-
ElectroCity	Y	SP	EnEc	X	X			-	-
EnerCities	Y	SP	EnEc	X	X	X		-	-
Futura	Y	CO-OP	EnEc	X	X	X	X	-	-
Green & Great	M	COMP	EnEcS	X	X	X		-	-
Perfect-Ville	Y	CO-OP	EnEcS	X	X	X		-	-
Plan it Green	T	SP	EnEc	X	X	X		-	-
Super Energy Apocalipse	T	SP	En	X	X			-	-
Interactive Fiction Games									
Citizen Science	Y	SP	En	X				-	-
Precipe	Y	SP	En	X				-	-
Riverbed	Y	SP	En	X				-	-
Role Playing Games									
Desertification story	Y	SP	En	X				-	-
Ludwig	T	SP	En	X	X			-	-
Mini Monos	EC	CO-OP	EnEcS	X		X		-	-
PowerUp	T	CO-OP	En	X		X		-	-
Playful Activities									
Alberto's Gravimente Toys	EC	SP	En			X		-	-
Discover Water	EC	SP	En					-	-
ecoCampus	M	SP	En					-	-
EPA	EC	SP	En					-	-
Games Planet Arcade	EC	SP	En					-	-
Heroes of Koskenniska	Y	SP	En			X		-	-
MSSG	M	SP	En					-	-
PBS Kids	EC	SP	En					-	-
Procedural Rethoric Games									
Oil God	T	SP	EnEcS	X			X	-	-
Oiligarchy	T	SP	EnEcS	X			X	-	-
Pipe Trouble	T	SP	EnEcS	X	X		X	-	-
Motivational									
Eco feedback games									
Climate Race	Y	CO-OP	En	-	-	-	-	X	X
Eco Island	Y	CO-OP/COMP	En	-	-	-	-	X	X
Energy Battle	Y	CO-OP/COMP	En	-	-	-	-		X
GAEA	Y	CO-OP/COMP	En	-	-	-	-	X	X
LEY!	Y	CO-OP/COMP	En	-	-	-	-		X
Power Agent	Y	CO-OP/COMP	En	-	-	-	-		X
Power Explorer	Y	CO-OP	En	-	-	-	-		X
Gamification									
Eco.system	M	COMP	En	-	-	-	-	X	X
Fiat eco:Drive	M	COMP	En	-	-	-	-		X
Ford Smartgauge with EcoGuide	M	COMP	En	-	-	-	-		X
Honda Eco score	M	SP	En	-	-	-	-		
OPower	M	CO-OP/COMP	En	-	-	-	-	X	X
SuMo	M	COMP	En	-	-	-	-	X	X
Toyota Prius Hybrid telemetry system	M	SP	En	-	-	-	-		
Water Smart	M	CO-OP/COMP	En	-	-	-	-	X	X

[46] I. Hamilton. (2013) Controversial pipeline video game expands to iphone following positive independent review. [Online]. Available: http://bit.ly/2k10ng6

[47] C. Klimmt, "Serious games and social change," in *Serious Games: Mechanisms and Effects*. Routledge, 2009, pp. 248–270.

[48] P. Weiser *et al.*, "A taxonomy of motivational affordances for meaningful gamified and persuasive technologies," in *ICT for Sustainability (ICT4S)*, 2015, pp. 271–280.

[49] R. N. Madeira *et al.*, "Ley!: persuasive pervasive gaming on domestic energy consumption-awareness," in *Proc. 8th Int'l. Conf. Advances in Computer Entertainment Technology*. ACM, 2011, p. 72.

[50] J. Simon, M. Jahn, and A. Al-Akkad, "Saving energy at work: the design of a pervasive game for office spaces," in *Proc. 11th Int'l. Conf. on Mobile and Ubiquitous Multimedia*. ACM, 2012, p. 9.

[51] M. Shiraishi *et al.*, "Using individual, social and economic persuasion techniques to reduce co 2 emissions in a family setting," in *Proc. 4th Int'l. Conf. Persuasive Technology*. ACM, 2009, p. 13.

[52] D. Geelen, D. Keyson, S. Boess, and H. Brezet, "Exploring the use of a game to stimulate energy saving in households," *Journal of Design Research 14*, vol. 10, no. 1-2, pp. 102–120, 2012.

[53] P. Centieiro *et al.*, "A location-based multiplayer mobile game to encourage pro-environmental behaviours," in *Proc. 8th Int'l. Conf. Advances in Computer Entertainment Technology*. ACM, 2011, p. 31.

[54] A. Gustafsson *et al.*, "Power explorer: a casual game style for encouraging long term behavior change among teenagers," in *Proc. Int'l. Conf. Advances in Computer Enterntainment Technology*. ACM, 2009, pp. 182–189.

[55] A. Gustafsson, C. Katzeff, and M. Bang, "Evaluation of a pervasive game for domestic energy engagement among teenagers," *Computers in Entertainment (CIE)*, vol. 7, no. 4, p. 54, 2009.

[56] P. Owen, *How Gamification Can Help Your Business Engage in Sustainability*. Do Sustainability, 2013.

[57] CloudApps. (2017) Sumo employee engagement. [Online]. Available: http://bit.ly/2jkhyGd

[58] "Supercharge your sustainability: Using social, mobile & game mechanics to engage employees," CloudApps, white paper, 2017.

[59] B. Willhelm. (2014, Apr.) Home energy report program: 2013 impact evaluation, puget sound energy. [Online]. Available: http://bit.ly/2ixnmz7

[60] D. L. Mitchell, M. Cubed, and T. Chesnutt, "Evaluation of east bay municipal utility district's pilot of watersmart home water reports," California Water Foundation and East Bay Municipal Utility District, Tech. Rep., 2013.

[61] Fiat. (2010) Eco-driving uncovered: The benefits and challenges of eco-driving, based on the first study using real journey data. [Online]. Available: http://bit.ly/2mojKN1

[62] P. Lameras, S. Arnab, I. Dunwell, C. Stewart, S. Clarke, and P. Petridis, "Essential features of serious games design in higher education: Linking learning attributes to game mechanics," *British Journal of Educational Technology*, vol. 48, no. 4, pp. 972–994, 2017.

[63] A. D. dos Santos and P. Fraternali, "A comparison of methodological frameworks for digital learning game design," in *4th Int'l. Conf. Games and Learning Alliance*, 2015, pp. 111–120.

[64] C. Fabricatore and X. López, "A model to identify affordances for game-based sustainability learning," in *8th European Conf. on Games Based Learning (ECGBL2014)*, 2014, p. 99.

[65] OPower. (2015). [Online]. Available: http://www.opower.com/

[66] R. Bartle, "Hearts, clubs, diamonds, spades: Players who suit muds," *Journal of MUD research*, vol. 1, no. 1, p. 19, 1996.

[67] T.-H. Nguyen, Z. Chen, and M. El-Nasr. A K Peters/CRC Press, Apr 2015, ch. Analytics-Based AI Techniques for a Better Gaming Experience, pp. 481–500, 0.

[68] B. Davis and D. J. Sumara, *Complexity and education: Inquiries into learning, teaching, and research*. Psychology Press, 2006.

[69] D. Simmons *et al.*, *Environmental Education Materials: Guidelines for Excellence*. ERIC, 1996.

[70] L. Sauvé, "Environmental education between modernity and postmodernity: Searching for an integrating educational framework." *Canadian Journal of Environmental Education*, vol. 4, no. 1, pp. 9–35, 1999.

[71] S. E. Dreyfus and H. L. Dreyfus, "A five-stage model of the mental activities involved in directed skill acquisition," DTIC Document, Tech. Rep., 1980.

[72] L. Sauvé, "Environmental education and sustainable development: a further appraisal," *Canadian Journal of Environmental Education*, vol. 1, no. 1, pp. 7–34, 1996.

[73] A. D. dos Santos, F. Strada, and A. Bottino, "The design of an augmented reality collaborative game for sustainable development," in *5th Int'l. Conf. Games and Learning Alliance*, 2016, pp. 15–23.

[74] A. N. Antle *et al.*, "Youtopia: a collaborative, tangible, multi-touch, sustainability learning activity," in *Proc. 12th Int'l. Conf. Interaction Design and Children*. ACM, 2013, pp. 565–568.

[75] D. Bucher *et al.*, "Exploiting fitness apps for sustainable mobility-challenges deploying the goeco! app," in *ICT for Sustainability (ICT4S)*, 2016, pp. 89–98.

[76] A. D. dos Santos *et al.*, "Designing collaborative games for children education on sustainable development," in *8th Int'l Conf. Intelligent Technologies for Interactive Entertainment*, 2016, pp. 3–12.

[77] G. A. Gunter, R. F. Kenny, and E. H. Vick, "Taking educational games seriously: using the retain model to design endogenous fantasy into standalone educational games," *Educational Technology Research and Development*, vol. 56, no. 5-6, pp. 511–537, 2008.

[78] A. Amory, "Game object model version ii: a theoretical framework for educational game development," *Educational Technology Research and Development*, vol. 55, no. 1, pp. 51–77, 2007.

[79] F.-L. Fu and S.-C. Yu, "Three layered thinking model for designing web-based educational games," in *Advances in Web Based Learning-ICWL 2008*. Springer, 2008, pp. 265–274.

[80] A. N. Antle *et al.*, "Emergent dialogue: eliciting values during children's collaboration with a tabletop game for change," in *Proc. Conf. Interaction design and children*, 2014, pp. 37–46.

[81] L. Nacke, "From playability to a hierarchical game usability model," in *Proceedings of the 2009 Conference on Future Play on@ GDC Canada*. ACM, 2009, pp. 11–12.

[82] J. Wiemeyer, L. Nacke, C. Moser *et al.*, "Player experience," in *Serious Games*. Springer, 2016, pp. 243–271.

[83] L. Nacke, A. Drachen, and S. Göbel, "Methods for evaluating gameplay experience in a serious gaming context," *International Journal of Computer Science in Sport*, vol. 9, no. 2, pp. 1–12, 2010.

[84] K. Kiili, S. de Freitas, S. Arnab, and T. Lainema, "The design principles for flow experience in educational games," *Procedia Computer Science*, vol. 15, pp. 78–91, 2012.

[85] A. Ibrahim *et al.*, "Educational video game design based on educational playability: A comprehensive and integrated literature review," 2012.

[86] A. Mora, D. Riera, C. González, and J. Arnedo-Moreno, "Gamification: a systematic review of design frameworks," *Journal of Computing in Higher Education*, pp. 1–33, 2017.

[87] C. Marache-Francisco and E. Brangier, "The gamification experience: Uxd with gamification background," *Gamification: Concepts, Methodologies, Tools, and Applications*, p. 1, 2015.

[88] L. A. Annetta, "The i's have it: A framework for serious educational game design." *Review of General Psychology*, vol. 14, no. 2, p. 105, 2010.

[89] N. Bianchi-Berthouze, "Understanding the role of body movement in player engagement," *Human–Computer Interaction*, vol. 28, no. 1, pp. 40–75, 2013.

[90] F. Arafsha *et al.*, "Emojacket: Consumer centric wearable affective jacket to enhance emotional immersion," in *Int'l. Conf. Innovations in Information Technology (IIT)*. IEEE, 2012, pp. 350–355.

[91] S. S. Rautaray and A. Agrawal, "Vision based hand gesture recognition for human computer interaction: a survey," *Artificial Intelligence Review*, vol. 43, no. 1, pp. 1–54, 2015.

[92] S. Sheridan and P. Williams, "Developing individual goals, shared goals, and the goals of others: Dimensions of constructive competition in learning contexts," *Scandinavian Journal of Educational Research*, vol. 55, no. 2, pp. 145–164, 2011.

[93] M. Soekarjo and H. van Oostendorp, "Measuring effectiveness of persuasive games using an informative control condition," *International Journal of Serious Games*, vol. 2, no. 2, pp. 37–56, 2015.

[94] T. Lavender, "Homeless: It's no game - measuring the effectiveness of a persuasive videogame," Ph.D. dissertation, School of Interactive Arts & Technology, Simon Fraser University, 2008.

[95] M. Khalil and M. Ebner, "What is learning analytics about? A survey of different methods used in 2013-2015," *CoRR*, vol. abs/1606.02878, 2016. [Online]. Available: http://arxiv.org/abs/1606.02878

[96] L. Shoukry, S. Göbel, and R. Steinmetz, "Learning analytics and serious games: Trends and considerations," in *Proceedings of the 2014 ACM International Workshop on Serious Games*, ser. SeriousGames '14. New York, NY, USA: ACM, 2014, pp. 21–26.

[97] W. Westera, R. Nadolski, and H. Hummel, "Serious gaming analytics: what students log files tell us about gaming and learning," *International Journal of Serious Games*, vol. 1, no. 2, pp. 35–50, 2014.

Alysson Diniz dos Santos received the BSc and MSc degrees in computer science from Universidade Federal da Paraiba. He is currently a Professor at Universidade Federal do Ceara and PhD candidate at Politecnico di Torino. His research interests include educational games, collaborative learning, and human computer interaction.

Francesco Strada received the MSc degree in Digital Media from Politecnico di Torino. He is currently a research assistant at the Computer Graphics and Vision research group of the same university. His research is focused on virtual and augmented reality, human computer interfaces and serious games.

Andrea Bottino is currently Professor of Computer Science at the Dipartimento di Automatica e Informatica of the Politecnico di Torino and head of the Computer Graphics and Vision research group of the same university. He is a member of IEEE and author of several journal and conference papers. His current research interests include computer vision, machine learning, human computer interaction, computer graphics, virtual and augmented reality and virtual heritage.