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Educational collaborative games for sustainable development learning

By

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Declaration

I hereby declare that, the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

Alysson Diniz dos Santos
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"My work is a game, a very serious game".

M. C. Escher

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Abstract

In a world regularly menaced by environmental and humanitarian crises, addressing education for a sustainable future becomes a critical issue. However, sustainability learning is extremely challenging, since the instructional tools to use must be able to deal with the inherent complexities of the matter, which can be summarized by three main factors: a) the interdisciplinary domains related to sustainability issues, such as ecology, economics, politics and culture, b) the involvement of several social structures, such as individuals, families and communities, and c) the demand for collaborative skills, creativity, flexibility and critical reflection.

This thesis discusses educational games in the context of sustainability issues, by focusing on three main research questions:

- RQ1: which are the theoretical models that underlie educational games design;
- RQ2: which is the current state of the art of the developed sustainability games?
- RQ3: how to design educational games aiming to foster learning and collaboration in sustainability scenarios?

Concerning the first two research questions, this thesis aims at identifying, from a theoretical point of view, the elements that facilitate the achievement of the instructional goals in general educational games. To this end, it surveys the literature related to the design guidelines and evaluation tools for educational games. From this investigation, it is possible to identify (i) the lack of validation of current tools and (ii) the need to balance both educational and engagement elements into game design. Then the work analyzes the state of the art of sustainability serious games, by establishing a taxonomy related to the main purpose of the game, broadly dividing the various approaches into the categories of: (i) educative games, i.e. those

intended to teach, and (ii) persuasive games, i.e. those aimed at influencing players' habits or opinions towards more sustainable practices. The in-depth analysis of both groups allows: (i) the initial proposition of key aspects that should be considered in the design of a sustainability game, attempting to enhance its effectiveness, and (ii) the definition of open questions that demand further scientific investigation.

Then, the thesis tackles the last research question (from a more practical point of view) by detailing the design, development and evaluation of two sustainability games, *WaterOn!* and *Sustain*. In particular, since collaboration among users is a relevant dimension in sustainability learning, one of the research objectives of this work is to acquire a better understanding of users' collaboration in sustainability games and which tools, game mechanics, design and narrative elements are necessary/suitable to effectively foster such cooperation. As for the two collaborative games developed, each of them has different learning objectives, target audiences and interaction designs in order to analyze the effectiveness of sustainability learning from two distinct instructional approaches (identified in the theoretical part of this research). Sustain evaluation indicates its success in achieving both pedagogic and collaborative outcomes. Although WaterOn! lacks a similar evaluation, it allows conjectures about the adopted theoretical and practical tools, which also inspired the development of Sustain.

Concluding, this thesis identifies the relevant theoretical background and guidelines that underlie sustainability game design, with specific emphasis on the collaborative dimension of the learning process, and evaluate their effectiveness through the evaluation of games based on such guidelines. The positive results found in the assessment contributes to the current literature by supporting the effectiveness of educational games as an additional learning tool in the context of sustainability.

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Chapter 1

Introduction

We are living at a time of immense threats to the survival of many societies. Poverty, inequality, unemployment, epidemics, natural disasters, violent extremism, terrorism and related humanitarian crises menace to reverse much of the development progress made in recent decades. Moreover, natural resource depletion, environmental degradation, and climate change indicate the biological support systems of the planet is at risk. It is also, however, a time of great opportunity. Access to education has greatly increased, and the spread of information and communications technology has the potential to accelerate human awareness of the global environment, as does scientific and technological innovation. Such context enforces the importance of decisions considering *sustainable development* (or sustainability), *i.e.* the search of significant shifts in technologies, techniques or infrastructures, meeting today's demands, without compromising future generations needs [2].

Since the publication of the Stockholm Declaration on the Human Environment, in 1972 [3], there has been an increasing interest in supporting sustainable development [4]. 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 specifically critical to disseminate information and foster learning of sustainability issues [5].

However, this task is not trivial, since sustainability learning has specific requirements. First of all, sustainability is characterized by three dimensions, which are tightly coupled and often conflicting [6]:

- *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. The interplay of these multiple dimensions and conflicting perspectives gives origin to complex scenarios, whose dynamics cannot be predicted by merely examining the isolated behaviors of their individual parts [4]. Such complexity defies traditional 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].

Finally, sustainability scenarios demand the stimulation of *collaborative skills*, such as dialogue-based decision making, creativity, flexibility and critical reflection [8]. These skills facilitate the emergence of learning in sustainability complex scenarios, and are fundamental for the resolution of issues that involve economic and natural resources, ethics, and multiple contradictory points of view.

The recent research stresses the contribution of constructivist approaches towards learning about complex systems [9]. The basic assumption of constructivist teaching is that learners are the makers of meaning and knowledge while they try to make sense of their own experiences. However, supporting this approach requires the design and development of specific learning tools. A constructivist learning environment should create an experiential learning context, where students can directly observe and experience phenomena related to the system in analysis. This environment should also help to make the core concepts explicit to the learners, in order to facilitate them to unveil and understand the links between these observations and their underlying framework. Another relevant element, related to the social constructivism theory [10], is the need to create collaborative and cooperative learning activities, since they are able to encourage discussion and reflection, which, in turns, can help to generate novel and shared knowledge and deeper insights and understanding [11].

These characteristics make serious games (SGs), i.e. those that do not have entertainment as their primary purpose [12–16], ideal tools for the development of effective (social) constructivist learning approaches. This statement can be supported by several arguments:

First, games enable *gameplay*, i.e. the experience of a game set into motion through the participation of players [17]. Gameplay is a distinctive feature of games, which can engage learners in interactive and dynamic activities. Such engagement, in turn, provides three potential effects [18]: *cognitive* (reducing the cognitive workload and clarifying patterns of value and relationships), *behavioural* (being able to influence players' attitudes and behaviours [19]), and *affective* (being able to trigger instant emotional responses to displayed elements). The integration of these three aspects (possible through gameplay) is particularly important, since it favors processes of participation, inquiry and social learning that challenge existing unsustainable practices [20]. Therefore, games may go beyond the mere transmission of knowledge (pure cognitive effects), or the training of individuals and groups to behave in particular ways (pure behavioural effects), which is a concrete challenge for sustainable development education [21].

Second, SGs allow the creation of virtual environments, which simulate real scenarios and where learners can analyze the dynamics and interactions between the elements and actors involved. The phenomena occurring in the virtual environment can be analyzed in detail, under different perspectives and with the capability to highlight their characteristics. The gameplay, the input and output interaction devices contribute to create a sense of immersion and presence, which are relevant elements contributing to help players achieve the desired learning outcomes [22].

Finally, digital games allow the creation of situated and socially mediated learning contexts by enabling shared experiences (e.g., by providing multiplayer settings or allowing to share information and results through the social networks). This way, games leverage collaborative learning scenarios needed by sustainability learning.

In this context, the main objective of this thesis is to discuss educational games in the context of sustainability issues. In particular, this thesis approaches the following research questions:

- RQ1: Which are the theoretical models that underlie educational games design?
- RQ2: Which is the current state of the art of the developed sustainability games?
- RQ3: How to design educational games aiming to foster learning and collaboration in sustainability scenarios?

RQ1 refers to the theoretical base of educational games design. This is a long debated question among researchers and practitioners (it started, at least, 30 years ago [23]), mainly due to its complexity, involving multiple interrelated aspects (such as appropriate feedback, user interface, narrative, challenge design and flow [24]) and disciplines (like computer science, design, pedagogy and cognitive psychology). This question is mainly approached in Chapter 2, which details prominent models for the design and the evaluation of educational games, considering a twofold view: instructional and engagement aspects. Specifically, we focus on how to balance both educational and engagement elements into the game design, and on the eligible methodologies to evaluate educational games. Chapter 2 also analyzes the current tools and suggest possible improvements, intending to elicit mechanisms that facilitate the achievement of the instructional goals and harness immersion in educational games.

Concerning RQ2, although previous studies analyze sustainability games [25, 4, 26–29], there is still a lack of a comprehensive study that discusses the different ways to approach sustainability learning through serious games, specially focusing on the game design aspect. In this matter, Chapter 3 presents a state of the art, which classifies sustainability games in two groups, according with their purpose: educative games intending to teach, and persuasive games aimed at influencing players' habits or opinions towards more sustainable practices. The in-depth analysis of both groups of identified games resulted in two main results: (i) the initial proposition of key aspects that should be considered in the design of a sustainability game, attempting to enhance its effectiveness, and (ii) the establishment of open questions that demand further scientific investigation.

In order to investigate RQ3, we designed and developed two collaborative games – WaterOn! and Sustain (respectively detailed in Chapters 4 and 5) – based on the theoretical findings obtained from research questions 1 and 2. Each game has different learning objectives. WaterOn! addresses concepts of the water natural cycle, and Sustain focus at raising players' awareness of the multiple actors and domains involved in sustainability scenarios. This way, it was possible to explore contrasting instructional approaches (direct instruction in WaterOn! and social constructivism in Sustain) and their application on sustainability issues. To cope with the particularities of each instructional approach, the games have distinct target audiences (children in WaterOn!, mature in Sustain), and are based on different interaction solutions (tangible interaction in WaterOn! and augmented reality in Sustain). Both games have been evaluated with users, although only Sustain evaluation followed a rigorous scientific methodology, which allow the extraction of meaningful conclusions. The tests results indicated Sustain's success in harnessing collaboration among users and communicating the intended information.

Limits to this research were imposed from the beginning. Namely, we focus on digital games, rather than board games, since it was our aim to explore the relation of different interactive solutions (such as augmented reality and tangibles) and sustainability learning. In addition, this research focused on games that were specifically designed with sustainability learning in mind, what excludes commercial off-the-shelf games that could be adapted for learning in the classroom. We did so since our focus was on analyzing game design explicitly focusing on sustainability learning (and not mere extensions or adaptations of already existent games). Such limits were needed to favor a deep understanding of a narrow topic, rather than a shallow study of a broader area.

Intended outcomes of this study, on a theoretical level, are the identification of the existent approaches of sustainability games, and the discussion of key design concepts to enhance their effectiveness. In a scenario in which a plethora of games exist (with a significant amount of juxtaposition of approaches), such theoretical reasoning might help future developers in identifying interesting gaps and opportunities. On a practical level, WaterOn! and Sustain design are, to the best of our knowledge, the first application examples of the chosen theoretical models. This way, this thesis offers a practical example of models' usage, which may, again, be a useful reference for future developers.

The rest of the thesis is organized as follows. Initially there is the establishment of theoretical foundations. Thus, Chapter 2 presents the investigation of the theoretical background of educational games design, and Chapter 3 provides an overview of the state-of-the-art of sustainability games. Then, concerning the practical part, Chapters 4 and 5 present (respectively) the design and evaluation of the proposed games, WaterOn! and Sustain. Finally, Chapter 6 summarizes the contributions of this thesis, and discusses future possibilities.

Chapter 2

Designing educational games: the theoretical background

Educational games (EGs) must provide an experience in which entertainment and instruction are seamlessly integrated. This requires considering two main aspects during the design process:

First, well-designed EGs need to be *effectively* educational, i.e. they need to be more than repetitive practices pushed into gameplay experience [30]. This demands EGs to be grounded on solid learning theories (among others, Bloom's taxonomy of educational objectives [31], Piaget's schemes [32], Vygotsky zones of proximal development [33]), which allow researchers to manipulate key variables and determine which factors have the greatest effect on learner results [34]. To this end, several researchers [1, 35–39] detailed *theoretical models* (i.e., guidelines for EGs design) based on well-established learning theories.

Second, there seems to be a general consensus in the literature that EGs need to be entertaining and engaging as well [40, 41]. In other words, EGs should immerse players, delivering an experience in which their attention is fully turned to the desired content. This, in turn, creates the ideal situation for learning to happen [35]. Researchers tackled this aspect as well ([42–48]) by proposing theoretical guidelines on how to design and evaluate entertaining and engaging EGs.

In this Chapter we discuss theoretical models behind EGs design, first introducing those focused on the *pedagogic design* of the EG and, then, those related to the design and evaluation of the *player experience* (in terms of immersion, engagement and fun) provided by the EG. This twofold vision aims at addressing RQ1: *which are the theoretical models that underlie educational games design?*

We believe this discussion may be interesting for two main reasons. First, our review of the EGs design models can result in a valuable reference for other researchers and practitioners in the EG area, since it can inform the choice of a specific model, as well as the proposal of a brand new one. Second, as a result of our research, we also underline aspects that, according to our opinion, could benefit from further scientific investigation. Furthermore, we also underline the fact that this Chapter introduces the basis on top of which the approaches taken in the practical part of this PhD research (Chapters 4 and 5) have been built on.

2.1 Literature review protocol

In order to investigate the main research question (which are the theoretical models that underlie educational games design?), we searched the Google Scholar engine for the keywords "educational game design model", with outcomes sorted by relevance (Figure 2.1 summarizes the identification and selection procedures).

Results were limited between 2007 and 2014. This time span was defined based on a review of the literature about EGs design published in 2007 [49], which states that "researchers are beginning to theorize the cognitive processes that occur through video game play". If researchers were beginning to theorize in 2007, we deemed interesting to investigate what have been done by the time this PhD project started (2014).

In the following, papers were selected by reading title and abstract, in order to exclude those not explicitly focused on informing educational games design. In accordance with this criterion we selected the first three pages of result (total of 30 papers). As in the third page no paper was included, we decided to stop there. This process resulted in eight included papers, which were then fully read. At this step, one paper was excluded, since we could not retrieve the full paper. Then, from the references analysis of the seven included papers, we included four other studies. The final eleven papers included in this search are listed in Appendix A, and the results from their analysis are detailed in the following Sections 2.2 and 2.3.

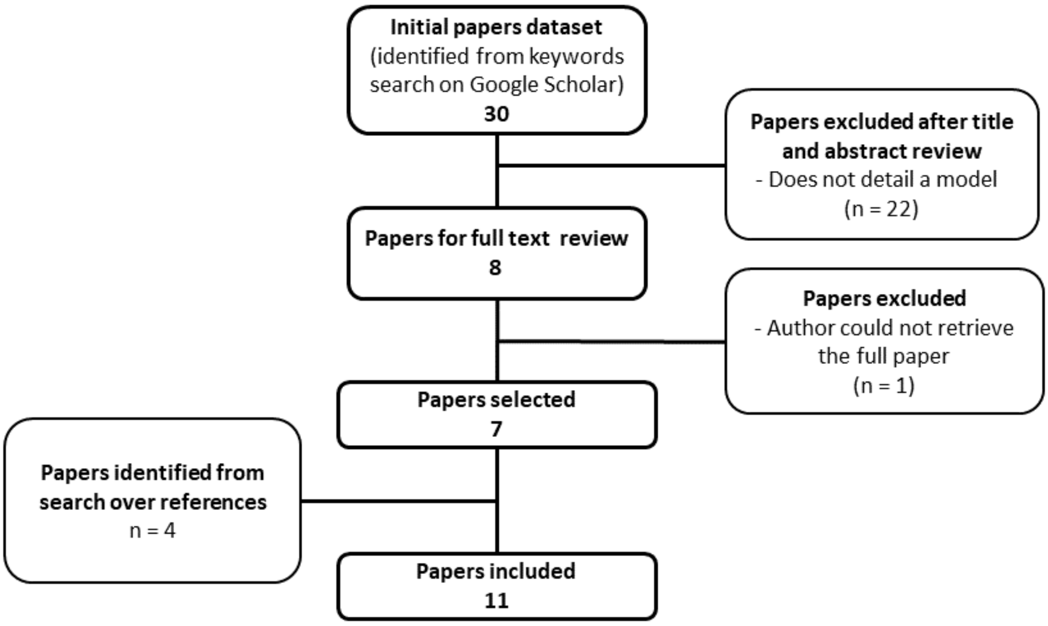


Fig. 2.1 Summary of papers selection process

We recognize that this Chapter does not present an extensive systematic review of the literature. Although we agree that a more extensive study could be indeed interesting, this part of the work had to cope with time constraints related to the organization of the PhD plan. Thus, the effort for a broader study had been allocated on reviewing the current state of the art in the specific subject of this PhD project, the sustainability serious games (Chapter 3). Despite that, it is our hope that the information presented here are an interesting reference, whose breadth is enough to embrace the most interesting approaches discussed and provide useful suggestions for the readers.

2.2 Theoretical models: designing educational games

The analysis of the collected papers (see previous Section 2.1), allows the identification of theoretical models to guide EGs design coupling learning theories and instructional strategies with traditional game design aspects [1, 35–39]. In general, such tools intend to improve EGs effectiveness through the establishment of sound and validated design methods.

2.2.1 Learning theories

In this section we briefly introduce the learning theories on which the design models detailed in Section 2.2.2 are grounded. For interested readers, details about these theories and their concepts are extensively documented by specialized authors (for instance in [50–52]).

Bloom's taxonomy of educational objectives states that targeted academic content needs to be introduced and reused in a hierarchical manner [31]. This is a popular pedagogical base for EG designers ([35, 36, 39]), due to its close alignment with the digital gaming activity itself. Indeed, in most games, to advance to the next level, the player is required to learn the rules of gameplay (and thus the associated learning objects) and how to apply them on the present level.

Piaget's schemes relate learning with adaptation, which is composed of assimilation and accommodation. Assimilation is the process of understanding world through existing schemes, whereas accommodation is the process of building new schemes [32]. Similar to the Bloom's taxonomy, the increasing complexity of challenges normally present in videogames, offer contents that should be assimilated and accommodated by the player.

Vygotsky zones of proximal development (ZPD) focus on the difference between a child's actual and potential levels of development [33]. A well-designed EG acts as a mentor, to move players from their actual to their potential development level [37].

The **Keller's ARCS** identifies four essential strategy components for motivating instruction [53]. At first, *attention* strategies should arouse and sustain curiosity and interest about the content or learning context. Then, *relevant* goals, clearly defined, and aligned with learner's interests should enhance motivation. In addition, students should be *confident* in the learning activity, i.e. challenge should be balanced to be neither too easy as to bore the leaner, or too difficult such that success seems impossible. Finally, the learning activity should provide *satisfaction*, which is possibly achieved through extrinsic and intrinsic reinforcement for effort.

The selection of a learning theory depends on what needs to be taught, how it is to be taught, and to whom it is being taught [35]. Therefore, the knowledge about the underlying pedagogical base is important for the designer to choose the methodological model adequate to his case.

2.2.2 Design models

Based on the learning theories, researchers derived theoretical models, i.e. design guidelines for educational games. In general, these models aim at developing a design paradigm in which educational effectiveness is integrated as a goal from the start of the design process and that sound educational practices are formally incorporated into EGs [54]. This Section details the theoretical models found during the literature review, namely: RETAIN, Is model, Game Object Model II, Three Layered Thinking model, Educational Game Design Framework, Adaptive Digital Game-Based Learning Framework and DGBL.

The **RETAIN** model is founded on Bloom's taxonomy, Piaget's schemes, Keller's ARCs model and Gagne's events of instruction [55] and is organized around six main aspects: relevance, embedding, transfer, adaptation, immersion and naturalization [35].

Relevance addresses three different aspects: *(i)* the learning materials should be relevant to learners, their needs and learning style; *(ii)* the instructional units should be relevant to one another, *i.e.*, instructional units should be introduced and set in context with previously learned materials; and *(iii)* the game has to be relevant to reality, which includes insights on how to use the fantasy, *i.e.* the fiction supported by the narrative, commonly present in games. A related aspect refers to appropriately *embedding* content into the game fantasy. The intent is to integrate the educational content in such a way as to make it intrinsic to the fantasy context of the game. Learning and gameplay should function together seamlessly.

Knowledge *transfer* and *adaptation* are tightly related. The first aspect refers to the ability to teach player-learners how to transfer knowledge from one situation to another, and can be achieved through recall stimulation. The second refers to knowledge acquisition and can be achieved through *assimilation* - interpreting events in terms of previous known ones - and *accommodation* - alteration or creation of new knowledge, expanding the player understanding.

Immersion is the creation of a belief in the enveloping fantasy of the digital environment. RETAIN authors see immersion as the suspension of disbelief, i.e., a state where the learner is immersed with deep mental involvement. This can (in part) be measured hierarchically from a simple interaction/reaction to being fully engaged to the context of the game. Adequate interactivity and a high level of engagement (provided by well-designed games) favor immersion.

Naturalization refers to automaticity or spontaneous knowledge, in which a learner uses the learned information habitually and consistently, monitors it, but does not have to devote significant mental resources to think about it. Games that are re-playable, *i.e.* the player enjoys playing repeated times, stimulate naturalization.

To simplify the model's use, the authors defined a table that classifies each of the five presented aspects in four levels (from 0 to 3). Each level has its set of requirements for the game to be considered at that level in a specific aspect. In a typical example, a game would be: level 1 in relevance, level 2 in embedding, level 2 in transfer, level 0 in adaptation, level 3 in immersion, and level 2 in naturalization. In addition, the authors classified the importance of each aspect, by the definition of a weighing scale. The table coupled with the weighting scale can be used to orient the development of an EG and to evaluate the effectiveness of an already-developed one. While in the literature RETAIN has been mainly used as an evaluation tool [56], in the following Chapter 4, we report a detailed example which exemplify its use as a reference design model for the development of a mobile and collaborative sustainability serious games named WaterOn!.

The **Is model** [36] is based on a constructivist point of view, *i.e.* the players should learn by constructing new knowledge, connecting a new to a prior experience. The model consists of a hierarchy of six elements, organized from low to high importance: *identity, immersion, interactivity, increasing complexity, informed teaching, instructional*.

Identity refers to the ability of capturing player's attention and tricking him into believing he is a unique individual within the environment - through a selectable avatar, for example. With a strong sense of identity and presence a player can later on easily feel immersed and emotionally engaged with the game. *Immersion* is about having a heightened sense of presence in the environment, being engaged with the content and thus intrinsically motivated to succeed in the challenge of the game. The author argues that through high *interactivity*, adequate challenge level, appropriate feedback and user interface a game can harness immersion [36].

Adequate *increasing complexity* enhances the education provided by the game. Game challenges should fit the player increasing ability, aiming at a pleasurable frustration state - in which the player feels stimulated to try harder when facing a defeat. An EG has to provide good level design and reward system to support adequate increasing complexity. Regarding feedback, *informed teaching* approaches embedded assessments within EGs. An EG can use in-game data (server-side data, ID, time, location, patterns of use and interaction, chat-logs and other tools) to run a posteriori analysis on players' proficiency [36].

Being *instructional* is the aim of any EG. To achieve it, they should present the previous elements - identity, immersion, interactivity, increasing complexity and informed teaching. Furthermore, other aspects can enhance the instructional power of the EG. It should be adequately integrated to the curriculum, being re-playable and connected to traditional lab activities. The teacher should be responsible for creating scaffold-structuring interactions and developing instruction in small steps, based on tasks the learner is already capable of performing independently.

The author presents a game concept, which exemplify the EG design process. However, to the best of my knowledge, no game so far reported to use the Is model in its design.

The **Game Object Model II** (GOM-II) relates pedagogical dimensions of learning with game elements, based on the object oriented conceptual design paradigm [37]. The model is focused on the development of adventure educational games and is organized around five core concepts: *definition, narrative, gender, social collaboration and challenges-puzzles-quests*:

The *definition* of an EG refers to its learning potential. A well-defined EG should: *(i)* require the player to learn new strategies and skills and solve ever-more complex challenges or puzzles; *(ii)* identify and exploit complex relationships between simulated and real characters, and *(iii)* solve ethical dilemmas [37].

The *narrative* defines the fantasy of the game. A good narrative should allow players to actively construct their own meaning/understanding through the use of plot devices (*e.g.* back story and cut scenes). The *gender* considers the different perspectives between male and female players. In order to be gender-inclusive, the EG conflict design should include appropriate role models. The *social collaboration* concerns the social practice side of learning. An educational game should harness dialog, altruism, reciprocity, collective action and solidarity to support the development of a community of peers [37]. The *challenges-puzzles-quests* are the core of

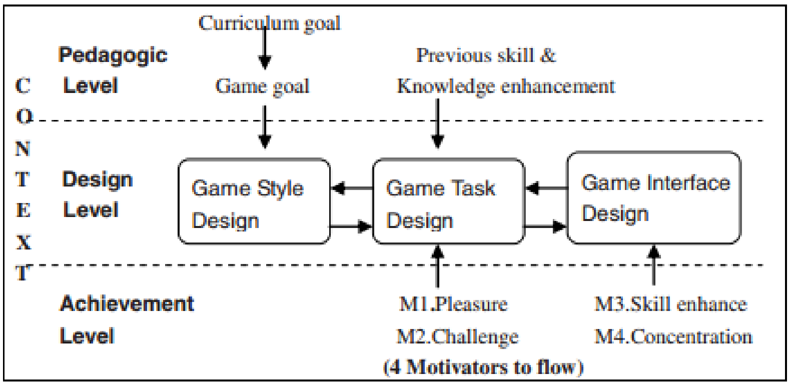


Fig. 2.2 Three Layered Thinking model overall organization [1]

the learning activities. Well-designed challenges generate tacit knowledge through knowledge exposition, conversations and reflection.

GOM-II is an evolution of the GOM model (successfully used to design the academic adventure game Zadahr [57]). GOM-II was developed based on insights acquired on the design of the educational adventure game γKhozi [37, 58].

The **Three Layered Thinking Model** (TLT) aims at supporting the design of web-based educational games, and stresses the importance of decreasing task complexity to adapt to limited budget environments. The model is structured in three levels (see Figure 2.2), in which the *pedagogic level* (knowledge production) and the *achievement level* (knowledge outcomes) influence the core *design level* [1].

The *pedagogic level* relates to the knowledge production targeted by the EG. On this level, the designer must transform curriculum into game goals, considering the previous skills of the player and the desired knowledge enhancement. The *achievement level* relates to the knowledge outcomes of the EG. On this level, the designer should aim at the four flow factors - skill, challenge, concentration and pleasure [59]

The *design level* is the core level, aimed to guarantee the requirements of the pedagogic level and to achieve the motivators of the achievement level. It includes designing the EG's: style, task and interface. The style design (*i.e.* the definition of game genre, number of players, camera style, *etc*) should match the game goals (defined on the pedagogic level). The task design of the EG (*i.e.* the design of levels, challenges and puzzles) should enhance players knowledge and skills through challenge provision. The tasks should consider the player previous skills and the desired knowledge enhancement (defined on pedagogic level) and also provide pleasure and challenge (motivators of achievement level) to the player. The game interface design should help the player keep concentrated in the game (another motivator of the achievement level).

The authors carried out the design and development of three games to empirically test the Three Layered Thinking Model. The games were applied on a group of 120 undergraduate students of a web-based course on introduction to software applications. The authors tested different game styles, tasks and interfaces to achieve different curriculum goals. They conducted surveys to assess the motivation of the games, isolating and weighting the four motivators (skill, challenge, concentration and pleasure). They also used log data to assess the time spent on the game and how frequently the students played the game. Results indicated that the produced games were successful in encouraging learners engagement [1].

The **Educational Game Design Framework** (EGDF) is focused on games for higher education, in which students need to self-learn specific subjects or materials, with integrated self-assessment modules. The model combines two main factors: game design and pedagogy [38].

In *game design*, the focus is on usability and multi-modality. The DLG design should consider the usability test items of effectiveness, efficiency and satisfaction, based on ISO 9241 [60] and on the heuristics of Pinelle [61]. The multi-modality component uses the multimedia aspect of the game to provide fun and engagement. In this aspect, the authors suggest the use of the heuristics of Malone [62] to generate challenge, fantasy, and curiosity in the game.

The *pedagogy* ensures that the DLG meets the learning outcomes. The authors suggest that the DLG subject selection should consider Bloom's taxonomy of learning outcomes [31] and motivation theory [63] to evaluate how the game affects students' motivation. The pedagogy should lead to appropriate learning content modeling, providing verifiable learning outcomes, in order to guarantee the achievement of learning goals.

No game developed with this model was found in the literature.

Similar to EGDF, the **Adaptive Digital Game-Based Learning Framework** (ADGBL) is also grounded on two major components, the learner and the game design [39].

The learner aspect should consider players': (i) cognitive development, adapting game design in accordance with players' age, (ii) psychological needs, based on Erik Erikson psychosocial theory [64], and (iii) learning behaviour, following the Slavin principles of behavioral learning [65].

The *game design* aspect consists of three elements:

- Multimodal is the element that manages the interaction between the learner and the game. Animations, interfaces, narrative and any other multimedia elements should be designed to extend the learning provided by the DLG. The authors suggest the adoption of the interaction cycle suggested by [66].
- Tasks should challenge the learners at the same time the help them to absorb learning content. Tasks should be designed with different levels in order to adapt to the different level of players. Also, the tasks should be presented in an increasing level, helping players to learn without being discouraged.
- Feedback should be provided just in time to the players. Clues and hints should be given directly or indirectly to learners and rewards should learners to evaluate their evolution in-game.

The authors do not indicate any game designed with the ADGBL model.

Finally, the **DGBL** model is focused on games for teaching History [67]. The model includes several aspects also present in previous models, such as: clear rules and instructions, immersive and enjoyable multimedia experiences, adequate challenge and instant feedback. However, the model also includes interesting guidelines focused on History subject, namely: (i) accuracy in background story's date, location and time, (ii) consideration for Country-specific curriculum needs, and (iii) opportunities for informal communication. Authors also describe the tasks that should be carried in a five-step process for game development: analysis, design, development, quality assurance, and implementation and evaluation.

We could not identify any game designed with the DGBL model.

2.3 Player experience: designing engaging educational games

In addition to the pedagogic design, for decades now, researchers attempted to offer adequate guidelines on how to produce "enjoyable" EGs [62]. Initially, these studies were focused on technological aspects, such as game interface design, interaction devices and usability issues [68]. Recently, there has been a shift towards providing a broader view over the player-game relation. Thus, going beyond the aforementioned technological aspects, current studies consider as well several elements related to the personal and individual gaming experience. These factors can be clustered in different levels [24]: *behavioral* (how player behave during interaction, *e.g.* whether they laugh, smile or frown), *physiological* (how the game affects the player physiological activity, *e.g.* measuring variation of heart rate and blood pressure during the game), and *psychological* (related to the subjective individual experience, the actions driven by intrinsic motivation, the feeling of presence and immersion, and so on). Such a broader view over the game interaction is usually referred to as *player experience*.

2.3.1 Definition

In order to structure a grounding terminology for this study, it is necessary to (i) (briefly) clarify the use in this work of the term player experience, since there seems to be some ambiguity in the literature [24], and (ii) describe its relations with other similar terms, like usability, playability, and game experience.

In human-computer interaction (HCI) field, *usability* is defined as "the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use" [69]. This definition led authors to derive mathematical bases for usability factors, *i.e.* measuring effectiveness in terms of completion rates and errors, efficiency from time on task, and satisfaction through standardized questionnaires [70].

In a similar way, researchers adopted the term *playability* (or *game usability*) as a proxy for usability in games. In other words, playability refers only to tangible elements at the technological level (such as the game interface, the input and output devices and the design choices affecting the gameplay), which are usually evaluated (again) through objective quantitative measurements [68].

However, there are elements missing in this picture. A game is made to be *experienced* by the player and the thinking, feeling and effect on the individual need to be considered as well. Therefore, player experience (PX) builds upon playability to encompass the domain of experiences made by the player while interacting with the game [71]. While some authors adopt the term *game experience* to denote this concept, we prefer to use PX since it highlights the central role of the player as the driver of the game design and evaluation.

PX has some similarities with *user experience* (UX), which studies how a person perceives and responds to the interaction with a system [72]. In our view, the main difference is that PX places higher attention in addressing the "emotion" dimension, which is central in describing and enhancing the interactive experience human enjoy at play (see also [73]).

2.3.2 Design models

The interplay between PX and game–based learning is characterized by an intricate collection of relationships among several factors, such as playability, player context, cognitive and emotional states, instructional design and learning theories. All these factors need to be well–balanced within the game design. To this end, several works in the literature introduce models for guiding EG design under a PX perspective. In the following, we discuss those extracted from our literature review, with explicit reference to the relationship between PX and effective educational content delivery.

Game Experience Model (GEM). The core idea behind the GEM is that, to achieve the learning objective of the game, designers should take in account the social, temporal and spatial contexts [44]. This means that a game designer should work towards two joint objectives. First, refine and test the game software and balance the game variables in order to provide an optimal playability and, second, improve the overall PX by including specific elements, such as: the introduction of different player models (*e.g.* novice, experienced) and the use of adaptive game mechanics.

Empirical evaluation of GEM [44] showed its effectiveness in delivering an overall satisfactory PX, and prompting learning.

Flow Model. [45] proposes a model to bring learners to the flow state, which is characterized by high focus, engagement, motivation, and immersion. Reaching this state guarantees that the player is completely engaged in the game activity, performing tasks effortlessly and distraction–free [59]. The model defines a set of factors (the *antecedents*) needed to guarantee the flow emergence.

Clear goals aim at ensuring player's focus on the learning tasks. Thus, educational contents should be embedded in several goals (a main one presented at the beginning of the game, and smaller ones in the following). Another aspect influencing player's focus is *immediate feedback* of goal progression and achievement. Feedback pace must be optimal: too frequently will break the flow state, whereas too rarely will make information absorption inadequate.

Playability and *sense of control* are two interconnected factors. The first refers to the balance between the progress of challenge difficulty and player's developed skills. This aims at keeping the player in the flow state and "away" from both anxiety (challenge is too complex) and boredom (challenge is too easy). Such balance instills as well a sense of control to the player, which might enhance PX and absorption of educational context.

An assessment of the Flow model has been attempted in [74]. In contrast with the hypothesis of [45], this work reported insignificant effect of flow with respect to the learning outcomes. However, since the author of [74] highlights some limitations of his work, these results are inconclusive and require further investigation.

EFM Model. Similar to the Flow model, [75] presents the EFM model attempting to create an effective learning environment through bringing players to flow state. Several aspects are similar to those presented by the Flow model, such as: the definition of clear goals with immediate feedback, and the adequate balance between skills and challenges. In addition to that, the EFM model still suggests that multi-choice plots might enhance players' sense of control and that suitable props should be provided to avoid players giving up when facing difficulties. Despite authors relate the development of an EG based on EFM model [76], the paper is in Chinese, what prevented us from analyzing it.

Playability Model. [43] details a set of design guidelines to foster the *educational playability* of an EG (*i.e.*, a game being entertaining and educative at the same time). These guidelines include elements introduced by other models, such as the concept of adaptation (GEM) and game goals, game control, and feedback (Flow). In addition, new concepts are introduced: (i) *ethics*: game contents should always be presented within an acceptable ethical framework; (ii) *realism*: the game should simulate real life scenarios, to facilitate content transfer between virtual and real worlds; (iii) *game reward*: the introduction of a reward system has positive effects on the player motivation and, as a consequence, on the learning outcomes; and (iv) *player knowledge*: players should be indirectly prompted to activate and use their prior knowledge, which should be enriched with new contents delivered throughout the game. A main drawback of this work is that neither [43] nor any work published afterwards detailed an actual use of the proposed design model.

2.3.3 Evaluation tools

While sound theoretical design models striving to enhance the integration between PX and instructional design are sorely needed, ensuring an effective and high–quality EG requires as well their joint evaluation. Such evaluation requires to combine several interrelated aspects: the game effectiveness in facilitating learning, its playability and the user engagement, fun and emotions. In the following, we discuss the tools that have been specifically proposed for the PX evaluation of EGs.

Heuristics. Heuristics are design guidelines that can serve as well as game evaluation tools. In evaluation mode, one or more double experts (*i.e.* usability specialists who ideally are also game players) analyze, according to the proposed guidelines, the features of the prototypical game and produce a list of usability problems that should be solved before the final game release.

The Playability Heuristic Evaluation for educational computer Game (PHEG) [46] guidelines are grouped along five dimensions (interface, educational element, content, playability and multimedia). PHEG based evaluation should involve (at least) one specialist in each dimension, to offer multiple views over PX. In order to validate their model, authors cross referenced the problems identified by PHEG, with the ones highlighted by a panel of 115 University students while reviewing different

EGs. In particular, the panel results indicated the effectiveness of PHEG in detecting flaws in the analyzed games [46], thus highlighting its efficacy as evaluation tool.

In another work, [47] introduces ten heuristics to evaluate PX in EGs, with focus on mobile devices. The guidelines refer to several aspects, such as: adequate use of technology, player's attention, learning content, in-game challenges and assistance during the interaction. To compile the guidelines, the researchers employed a qualitative method (audio recorded interviews) with participants playing StoryTimes, a game designed to teach multiplication to children [47]. The major drawback of the study is the lack of a sound evaluation of the proposed heuristics (StoryTimes was used exclusively to capture user feelings towards the interaction and not as the object of the evaluation).

Surveys. Pre and post-play surveys and interviews are probably the easiest and least expensive approach to PX assessment. Concerning them, we found in the literature only two questionnaires specifically conceived to analyze EGs: the EGameFlow and the Serious Game Experience Model.

EGameFlow [42] is a scale to measure learner's enjoyment in EGs that incorporates the learning dimension to the ones originally defined in GameFlow questionnaire (developed to analyze the flow concept in general video games [77]). The proposed scale contains 42 items spanning eight dimensions: concentration, goal clarity, feedback, challenge, control, immersion, social interaction and knowledge improvement. The data analysis demonstrated the statistical validity of EGameFlow (*i.e.* that the model is well–founded). However, since only four games of "low" complexity were analyzed, more research is needed to assess its general validity.

As highlighted in [48], one of the main drawbacks of the EGameFlow model is that it can only be applied to games with clearly defined learning outcomes. To tackle this issue, [48] proposed the *Serious Game Experience Model* (SGEM), which addresses games whose primary educational objective is more open/abstract. SGEM was tested in the evaluation of the game Poverty is not a Game (PING), whose aim is raising consciousness about poverty. SGEM is based on the Game Experience Questionnaire (GEQ), a tool used in the PX evaluation of several digital games [48]. Due to this, GEQ lacks an evaluation of the educational part of the game, which was addressed in SGEM by introducing a Perceived Learning module. The PING game was evaluated by 340 third and fourth grade students (aged 14-16 years). Although the collected data indicated the statistical validity of SGEM, authors expressed their concerns about the model generalization, since it was tested with only one game.

Behavioural and physiological evaluation. Another validation approach is based on the analysis of data collected during the game [78]. In particular, two methods are emerging: using analytics and players' physiological measures.

Game learning analytics (GLA) refers to the integration of learning analytics approaches in EGs, *i.e.* collecting and analyzing data about players and their contexts, for purposes of understanding and optimizing learning [78]. According to [79], the adoption of GLA demands several steps. At first, it should be established the intended use of the extracted information, which can be used during game play (*e.g.*, to provide an adaptive and personalized learning experience or to help instructors directing the learning process) and/or after the game session (*e.g.*, to assess the learning outcomes). Then, it is needed to choose and capture data, *i.e.* define meaningful data to be captured and how to collect them. Finally, since data can be captured from various devices (*e.g.* in case of multiplayer settings) and can be of different nature (*e.g.* logs of players activities and video recordings), strategies to aggregate data should be defined.

Although the entertainment game industry has been collecting data from users for many years, EGs have not yet taken full advantage of it [79]. Therefore, even considering the growing available literature available, we could not find sound theoretical models that have been thoroughly evaluated. For a more extensive discussion on this topic, the reader can refer to [78].

Physiological measures. Another objective technique is based on the measurement of physiological variables, which can be interpreted as indicators of player's cognitive and emotional states. In specific, for learning environments, attention, effort and excitement can be derived from posture, facial expressions, eye tracking, pupil diameter, skin conductance, heart rate, respiration and electro activity of derma and brain signals [79].

Several recent studies approached physiological assessment in the context of EGs. For instance, [80] found patterns in eye tracking data of students playing engineering design games (highest performing students looked at similar places for analogous amounts of time). In another example, [81] identified increased oxygenation and hemoglobin presence in certain areas of the cortex, while testers played learning games. In spite of the growing literature on the topic, there is still a need for models able to merge the computational complexities of physiological approaches with theories for learning. A broader discussion on this topic can be found in [82].

2.4 Discussion

The tools presented in previous Sections 2.2 and 2.3 indicate an active research community focused on offering a solid theoretical background for EG design and evaluation. However, there are some open areas that could benefit from further scientific investigation, concerning both design and evaluation tools.

2.4.1 Design tools

First, a limitation common to all the theoretical models presented in this Chapter, is the *lack of thorough validation* of the proposed tools. Despite the fact that all of them are based on sound theoretical research, they would still benefit from a solid scientific assessment of their effectiveness in supporting the learning process. On the opposite, few EGs were designed on the basis of the proposed guidelines and no updates for the analyzed models were presented in recent years. Moreover, most of the EGs we found were implemented by the same research teams that developed the models. These factors indicate a "fragile" user community of these design models, especially in comparison with the large amount of EGs developed and published in recent years. To overcome this issue, further research should focus on **the design of model-based EGs**. Only through empiric use (preferably by different research teams from the ones that developed the tools), the models would be adequately assessed (and possibly updated) and a community of users can appear. Although somewhat obvious, we think this is an important suggestion, which is aligned with other studies reporting little evidence of learning theory foundations in studies of game-assisted learning activities [83, 84]. We conjecture that one of the reasons for the few number of model-based games is the inherent complexity of developing an EG. Game development requires the contribution of different professional figures (e.g. programmers, UI, sound, animation designers and so on), which are involved in several tasks (e.g. game design, balance, programming, testing). Then, EG development should embrace as well the pedagogical aspect, which need to be carefully balanced among the design tasks and demands additional actors (instructional designer, teacher, and so on). All that in a scenario that (generally) involves strict budget constraints [85]. Summarizing, we believe that the aforementioned reasons create barriers, since time and budget constraints might not grant EG researchers the adequate resources to identify a suitable reference model for the design phase. In this sense, we hope that the work described in this Chapter might be a useful reference to aid EG designers in this choice.

As a further comment, it is also important to note that most of the described models approach learning from a broad perspective, without restrictions on game genres, platforms, and players' characteristics. However, learning is a complex and multi-faceted process, and players engage with particular games for a plethora of reasons (competition, collaboration, collecting prizes, stimulating creativity, and so on). Such wide view leads to the absence of detailed information on *how in practice the models' principles can be applied to game design*. Recent research has been trying to answer such issue. Some works focus on **how to map learning goals to game goals**. For example, [86] details the activity theory-based model for serious games (ATMSG [1]). The model suggests a three–level description of a serious game: (i) the *high-level*, which unveils the connection between the game concept and the high-level objectives of the game, (ii) the *intermediate level*, in which the game sequence is described into several actions from the points of view of game designer, player, and instructional designer, and (iii) the *low level*, in which game actions are described in terms of concrete mechanics and their instructional objective [87]. This way, ATMSG offers a step-by-step understanding on how every game action is related to the game pedagogical objective. Additionally, there seems to be a tendency towards **models tailored to specific domains and target audiences**. By narrowing the focus of the theoretical tools, authors intend to offer more practical and easily verifiable guidelines. For instance, [88] present the *conceptual engagement model*, aimed at engaging young students (7 to 16 years) in mathematics EGs. According to the authors, clarity of goal and thematic/visual appeal are triggers to the engagement, which is then maintained through challenges, creativity, social interactions, rewards and feedback. Authors discusses each of these characteristics, presenting examples on modern entertainment games. A similar example can be

[1] Being published in 2015, this work was not identified until we structured this Chapter's discussion (our literature review was limited to 2014). However, in this Section we describe the most important features of the model.

found in [89], where authors investigate the engagement of mobile games for teaching History to secondary students.

Finally, the described models are always *biased, either for the educational or for the PX aspect*. In our opinion, both PX and instructional design are necessary conditions for providing effective learning in an interactive and engaging way. Therefore, we believe that EG designs should carefully balance both aspects. Actually, this can be done by adopting and "merging" two models, one more focused on PX and another on instructional design. Clearly, our hope is the **emergence of a model where these two aspects are balanced**, a topic worth to be explored.

2.4.2 Evaluation tools

Concerning the identified evaluation tools, each of them has its own pros and cons. For instance, heuristic evaluation is based on accepted principles. Empirical results obtained in various studies show its effectiveness in identifying major and minor game problems before its actual release. However, heuristics only foresee the mere involvement of experts, thus neglecting to consider the end–users in the evaluation loop. As a consequence, this approach appears unable to fully capture and analyze player's emotions, which represent a relevant part of PX.

On the other hand, surveys are able to effectively capture subjective player preferences. Nevertheless, this method requires a sufficient number of respondents to be statistically significant, and may present discrepancies between objective and subjective user reactions (sometimes what players do is different from their claim on what they think they do). In addition, surveys heavily rely on player's memory and, therefore, information may be lost in the delay between action (gameplay) and recall (interview or questionnaire application).

In turn, behavioural and physiological evaluation allow data-driven analysis, which may help to clarify the complex mechanisms of learning while playing games. However, both approaches may increase assessment costs. Indeed, physiological assessment requires specific devices and controlled setups, and the (potentially) huge amount of recorded data might require the implementation of data mining approaches. In addition, data analysis in GLA might be troublesome, specially due to the (possible) heterogeneity of devices/sensors used to collect them. In a similar vein, physiological data are volatile, variable, and may be harsh to interpret.

Given their different characteristics, we believe that a more comprehensive assessment could be obtained by **combining the analyzed evaluation methods**, in order to simultaneously target playability (through heuristics), users' opinions (through surveys), behavioural and physiological data. While such multimodal approach could strengthen an effective PX assessment for EGs, it also creates barriers by increasing the complexity of the evaluation and, thus, a careful planning of such an experimental protocol should be considered.

Chapter 3

Sustainability serious games: the state of the art

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 sustainability serious games (SSGs) referenced in the "games for change" portal and in the two surveys [25] and [4] already sums up to 91.

In order to shed a light over this growing field, 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. Therefore, this Chapter focuses on the research question RQ2 defined in the Introduction (i.e., "which is the current state of the art of the developed sustainability games?"). 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. In particular, the objectives of the work described in this Chapter are the following:

- O1: detail the current state of the art of the various forms of digital gaming approaches to sustainability,
- O2: present possible (and suitable) design strategies for sustainability games,

- O3: summarize issues that may be approached by further research in the field.

Given the relevance of serious games for sustainability education, recent studies have started to clarify the link between sustainability and serious games. For instance, [25] examined 49 games and suggested that, in order to improve their learning outcomes, future sustainability games could profit from: (i) exploiting "out of the game" teaching and learning resources (e.g. texts, videos, software, and other materials that teachers can use to assist students to achieve their learning goals), and (ii) expanding social interaction, possibly adopting social networks. In another study, [26] analyzed 34 games. On one hand, they concluded that current SSGs have an adequate usability level and are consistent with the main pedagogical aspects of education for sustainable development. On the other hand, authors identified as well the need of improving the learners' construction of knowledge and negotiation of conflicting levels. [27] analyzed 11 games and observed that, although they are indeed engaging educational tools, most of the analyzed SSGs offer little support to help players' transferring what they learned in the game into real-life actions (thus, creating a gap between values and action). Finally, [4] analyzed 20 games focusing their investigation on how broadly these games "facilitate the development of sustainable mindsets". Authors identified several aspects that could be further explored in future SSGs, such as (i) the design of true multi-age games, (ii) the development of game settings based on an even integration of social, economic and environmental aspects of sustainability, (iii) the definition of mechanics that naturally require situated learning, and, as highlighted as well in [25], (iv) the design of a gameplay effectively leveraging on social interactions.

In general, the aforementioned studies offer interesting reflections about the application of SG to the sustainability context. However, we believe that researchers could benefit from a study driven by the analysis of relevant *game design aspects* that discusses as well the distinct ways to approach sustainability learning through serious games, such as the one carried out in this work. Such a review could add to the previous findings by analyzing different game purposes (educational or motivational, see Section 3.2), identifying the key design concepts that summarize common aspects of SSGs, and discussing the effectiveness of current SSGs in achieving their educational goals. Hopefully, such could also represent a useful reference to guide developers and, possibly, to identify aspect or elements in the state of the art where novel contributions are required. To this end, our research was driven by the following guiding questions:

- Q1: which recent serious games have been developed in the context of sustainability?
- Q2: which approaches have been taken in SSGs to address the sustainability issues?
- Q3: how designers intended to make the SSGs achieve the intended outcomes? Which features did they leverage on for this task?
- Q4: which SSGs have been evaluated and how? What are the results of these evaluations?

The first two questions (Q1 and Q2), which are related to objective O1, aim at identifying the current existing SSGs and their approach to tackle sustainability issues. This way they aim at drawing a representative picture of the state of the art based on the obtained findings. Questions Q3 and Q4 present the further details that enclose O1 and are also connected with the second objective O2. Understanding the main design decisions taken in current SSGs, their effect in the final game and the efficacy of such games (in terms of intended outcomes) is the building ground for "presenting possible design strategies for sustainability games" (O2). Finally, findings related to each of the questions, can contribute to summarize issues that may be approached by further research (O3).

The rest of this Chapter is organized as follows: Section 3.1 details the adopted literature review protocol (and answers Q1) and Section 3.2 presents the resulting taxonomy of SSGs (answering Q2). A detailed analysis of the different classes of SSGs is presented in Sections 3.3 and 3.4 (aimed at responding Q3 and Q4). Then, Section 3.5 discusses some design models explicitly defined for SSGs (aiming at O2) and, finally, Section 3.6 highlights open problems and possible areas of research (enclosing O3).

3.1 Literature review protocol

The search process (for an overview, see Figure 3.1), was mainly carried out between January and March 2017 and started with an automated approach targeting three scientific paper databases, namely Scopus[1], 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 and (again) pruned according to (more specific) criteria, in order to exclude works with a mere theoretical focus and others that simply integrates existing commercial off-the-shelf (COTS) games into the learning process:

- Does the paper detail the design and/or evaluation of a SSG?
- Does the study relate with a serious game (rather than a COTS one)?

This selection resulted in an initial list of 29 papers. Then, the references of these papers were analyzed according to the aforementioned screening process. As a result, 11 additional papers were included to the final list, which is available as Appendix B.

Furthermore, since this work deals with digital games, which are not necessarily described in scientific publications, we also searched for unpublished material, selected based on Google visibility. We (again) used the keywords “sustainability

[1] research limited to “computer science” as subject area

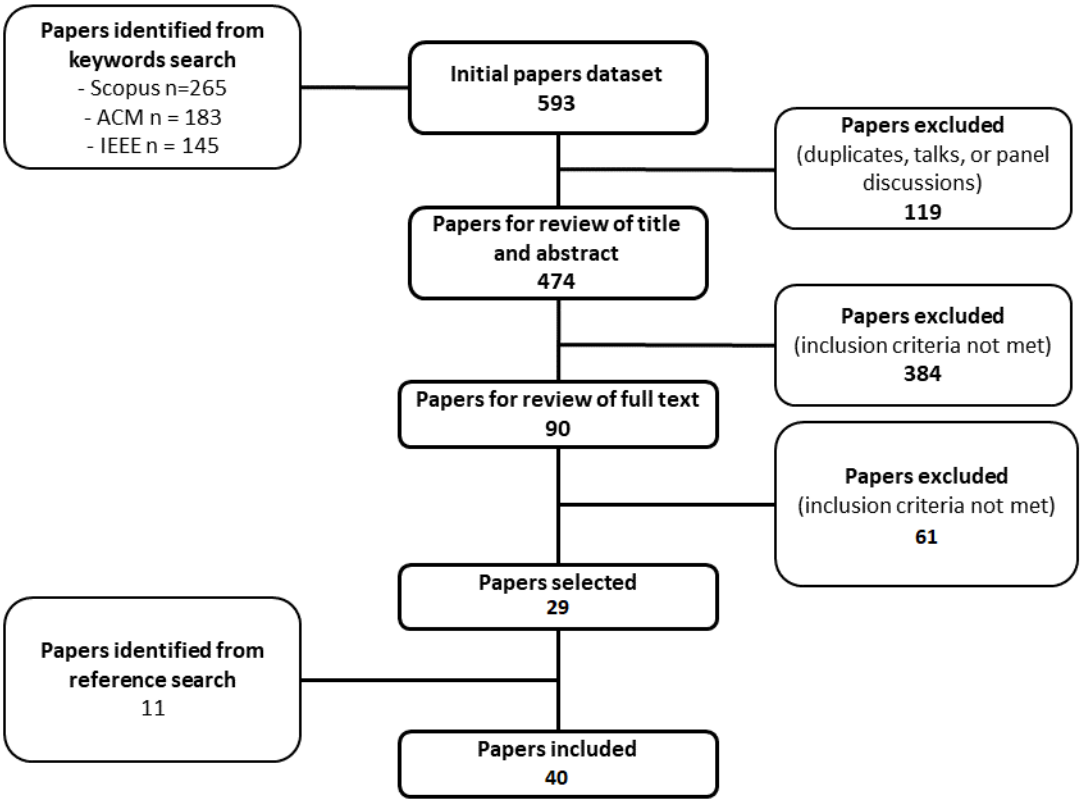


Fig. 3.1 Summary of papers selection process

AND games", and chose games directly appearing or being mentioned by third parties in the first three pages of the search results [2].

This mixed research process, which includes both scientific publications and unpublished SSGs, resulted in a total of 64 games to be analyzed (listed in Appendix C). These 64 games represent our answer to the guiding question Q1 (which recent serious games have been developed in the context of sustainability). Although we recognize that it is difficult to offer an extensive and "complete" list of sustainability games (new games emerge constantly, based on different hardware platforms and available on different sources), our hope is that the methodological approach chosen is rigorous enough to identify a number of works capable of providing a representative picture of the state of the art, on top of which we may base our discussion.

[2] This research was carried out in January of 2017. As visibility changes greatly over time, present results can be different.

3.2 A proposed taxonomy

After the identification of the relevant works, we needed to define the basic categories related to the main objectives that SSGs aim to achieve. To this aim, this study adopts a mixed approach, involving direct and indirect analysis.

Games available online (at the time this research was carried out) were directly examined, i.e. the researchers played these games. The time spent in analyzing each game varied according to their goals and dynamics. Not all the games were completed, since some of them simply repeated the same game dynamics across the different levels.

On the other hand, the games not available online were indirectly analyzed through "secondary research" (i.e. using existing data, collected for the purposes of prior studies [90]). The sources for such research were (i) scientific papers from the same authors of the games, (ii) official websites of the games, or (iii) books or scientific papers from third parties. Table 3.1 briefly reports the analysis method applied to each of the identified games.

Table 3.1 Games analysis methodology

Analysis	Games
Direct (18 games)	Catchment Detox, Citizen Science, CityRain, Clim'way, Discover Water, EcoVille, ElectroCity, EnerCities, EPA games suite, Games Planet Arcade, Oil God, Oiligarchy, PBS Kids, Plan it Green, Pipe Trouble, Precipice, Riverbed, Super Energy Apocalypse
Indirect (46 games)	Acttention, AgriVillage, Alberto's Gravimente Toys, Climate Race, Desertification Story, Dubuque water portal, Ducky, Eco Island, ecoCampus, EcoFactory, EcoPanel, EcoPolicy, Eco.system, Energy Battle, Energy Life, eVision, Fiat eco:Drive, Ford SmartGauge, Fishing with friends, Futura, GAEA, Ghost Hunter, Green & Great, Greenify, Heroes of Koskenniska, Honda Eco score, IdleWars, LandYOUs, LEY!, Life Tree, Ludwig, MiniMonos, Modern Mayor, Opower, Perfect-Ville, Power Agent, Power Explorer, PowerUp, Prometeruse Quiz, SuMo, Sustainability game, Toyota Prius telemetry system, Velix, Viaggia Rovereto, WaterSmart, We Spire

In order to guarantee that information from direct and indirect research was coherent with each other, the games' analysis (for both methods) was focused on obtaining the following information: target audience, interaction pattern, sustainability aspects approached. These informations represent the traversal categories to analyze the games, further detailed in the following Section 3.2.1. Finally, we also collected evaluation data, i.e. whether the games were valuated or not.

Then, based on this analysis, we organized the identified games in a taxonomy (see Table 3.2). The first level of this taxonomy divides games according to the two main *purposes* for which SSGs have been conceived, i.e. to inform players (*educational games* [27, 25]) or to motivate them to adopt environment friendly behaviors (*motivational games* [28, 29]). We believe these two purposes (educational and motivational) to represent the “approaches that have been taken in SSGs to address the sustainability issues” (Q2).

In the first class, i.e. sustainability educational games, we find works that try to communicate some information to the players. These games assume that, by providing knowledge about specific phenomena, it is possible to raise awareness in sustainability issues [91]. Sustainability educational games enable experimentation in simulated environments, useful for depicting possible catastrophic scenarios related to resource scarcity, poverty, global warming and so on [27]. Players are usually required to find creative solutions for the challenges to face, which demand critical thinking from the learners [92].

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 [93]. 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 are based on data sensed from the real world, such as energy consumption at home, participation in recycling programs, driving style and so on [29], 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 [94]).

In our taxonomy, the two main categories (educational and motivational) were further divided into sub-groups, whose main purpose was to gather together games providing similar challenges and player actions available to overcome them. The rationale of this choice is that defining challenges and player actions is a critical task in the design of a serious game [35, 95].

As for the educational games, we adopted the concept of "genre" expressed in [96] in order to group games with similar challenges and player actions. Among the list of possible genres identified in [96], we found SSGs examples for the following three: *construction and management simulation*, *interactive fiction* and *role-playing games* (Sections 3.3.1 to 3.3.3). In addition, we further added two genres for SSGs, i.e. games which present *simple game activities* focused on children (Section 3.3.4) and the *procedural rhetoric games* (Section 3.3.5), which are games based on the communication approach described in [19].

Concerning motivational games, the secondary classification aimed at establishing a parallelism with the concept of eco-feedback technology, i.e. technology that collects data from real-world behaviours (i.e. the player actions) and provides feedback with the goal of reducing environmental impact (i.e. the challenges) [97]. We thus identified the two following sub-groups: (i) the *eco-feedback games*, those that are directly identified as games by their authors, and (ii) *gamified applications*, i.e. applications that, although not directly identified as games, adopt some game design elements (as badges, points, leveling up, and so on) to motivate players. Eco-feedback games and gamified applications are presented, respectively, in Sections 3.4.1 and 3.4.2.

3.2.1 Other relevant classification dimensions

According to [98], there are two other useful dimensions that can characterize a serious game: a) *target audience* and b) *interaction pattern*.

The target audience (i.e., the audience who actually plays the game) classifies players according to their age. In this paper we adopt the North American Entertainment Software Rating Board (ESRB) age-based classification system [99], 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 [100]. In this dimension, we summarize the player patterns in the *single* and *multiplayer* classes. In turn, multiplayer games can be further divided into *cooperative* and *competitive* ones. We underline that additional

Table 3.2 Sub-groups of educational and motivational sustainability games

Educational (39 games)	Construction & management simulation	Catchment Detox, City Rain, Clim'way, EcoVille, ElectroCity, EnerCities, EcoPolicy, Futura, Green & Great, LandYOUs, Modern Mayor, Plan it Green, Perfect–Ville, Super Energy Apocalypse
	Interactive fiction	Citizen Science, Precipice, Riverbed
	Role playing games	AgriVillage, Desertification Story, Ludwig, MiniMonos, PowerUp
	Playful activities	Alberto's Gravimente Toys, ecoCampus, EcoFactory, Discover Water, EPA, eVision, Fishing with friends, Games Planet Arcade, Ghost Hunter, Heroes of Koskenniska, Life Tree, PBS Kids, Prometeruse Quiz, Sustainability game
	Procedural rhetoric	Pipe Trouble, Oiligarchy, Oil God
Motivational (25 games)	Eco-feedback	Acttention, Climate Race, Eco Island, EcoPanel, Energy Battle, Energy Life, GAEA, LEY!, Power Agent, Power Explorer
	Gamification	Dubuque water portal, Ducky, Eco.system, Fiat eco:Drive, Ford Smartgauge with EcoGuide, Greenify, Honda Eco score, IdleWars, OPower, SuMo, Toyota Prius telemetry, Velix, Viaggia Rovereto, Water Smart, We Spire

subdivisions of these patterns exist (see, for instance, [100]). However, we deemed it sufficient for our work since our main interest was analyzing *whether* multiple players interactions exist rather than on *how* these interactions happen (which might be the focus of future investigations). It is also important to notice that this category is not orthogonal, which means that games can be possibly listed as both collaborative and competitive at the same time.

Finally, the games can also be classified according with 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 (see Table 3.3). Such analysis is specifically relevant to sustainability games since they require to target different audiences, involving them in both individual and group activities related to different sustainability elements. Furthermore, these dimensions are hopefully useful to identify those combinations of audiences, patterns and sustainability aspects that have not been adequately explored in current SSGs (for further discussion, see Section 3.6).

Dimension		Educational	Motivational
Target Audience	Early childhood	Alberto Gravimente's Toys, Discover Water, EPA games suite, Games Planet Arcade, PBS Kids, MiniMonos	-
	Youngsters (7-12)	Catchment Detox, City Rain, Clim'way, Desertification story, EcoFactory, EcoVille, Electro City, EnerCities, eVision, Fishing With Friends, Futura, Heroes of Koskenniska, Ghost Hunter, Life Tree, MAID, Modern Mayor, Citizen Science, Perfect-Ville, Prometeruse Quiz	Climate Race, Ducky, EcoPanel, Eco Island, Energy Battle, Energy Life, GAEA, LEY!, Power Agent, Power Explorer
	Teen (13-16)	AgriVillage, Ludwig, Oiligarchy, Oil God, Plan It Green!, PowerUP, Super Energy Apocalypse, Precipice, Riverbed	Pipe Trouble
	Mature 17+	ecoCampus, EcoPolicy, Green & Great, LandYOUs, Sustainability game	Acttention, Eco.system, SuMo, Greenify, We Spire, IdleWars, Viaggia Rovereto, Toyota Prius Hybrid telemetry, Fiat eco:Drive, Honda Eco score, Ford SmartGauge with EcoGuide, OPower, Velix, Dubuque water portal, WaterSmart

Interaction Pattern	Single player	Alberto Gravimente's Toys, Catchment Detox, Citizen Science, City Rain, Clim'way, ecoCampus, Desertification story, Discover Water, EcoFactory, EcoVille, Electro City, EnerCities, EPA games suite, eVision, Games Planet Arcade, Ghost Hunter, Heroes of Koskenniska, LandYOUs, Life Tree, Ludwig, MAID, Modern Mayor, Oiligarchy, Oil God, PBS Kids, Pipe Trouble, Plan It Green!, Precipice, Riverbed, Super Energy Apocalypse, Sustainability Game	Toyota Prius Hybrid telemetry
	Cooperative multiplayer	Futura, EcoPolicy, MiniMonos, Perfect-Ville PowerUP	Acttention, Climate Race, Dubuque water portal, Ducky, EcoPanel, Eco Island, Energy Battle, Energy Life, GAEA, LEY!, Power Agent, Power Explorer, OPower, Velix, WaterSmart
	Competitive multiplayer	AgriVillage, Fishing With Friends, Green & Great	Acttention, Climate Race, Dubuque water portal, Ducky, EcoPanel, Eco Island, Energy Battle, Energy Life, GAEA, LEY!, Power Agent, Power Explorer, OPower, WaterSmart, Eco.system, SuMo, Greenify, IdleWars, We Spire, Viaggia Rovereto, Fiat eco:Drive, Honda Eco score, Ford SmartGauge with EcoGuide

Sustainability Aspects	Environmental	AgriVillage, Alberto Gravimente's Toys, Citizen Science, Desertification story, Discover Water, ecoCampus, EcoFactory, EPA games suite, eVision, Games Planet Arcade, Ghost Hunter, Heroes of Koskenniska, LandYOUs, Life Tree, Ludwig, MAID, Modern Mayor, PBS Kids, PowerUP, Precipice, Prometeruse Quiz, Riverbed, Super Energy Apocalypse, Sustainability Game	Acttention, Climate Race, Dubuque water portal, Ducky, EcoPanel, Eco Island, Eco.system, Energy Battle, Energy Life, Fiat eco:Drive, Greenify, Honda Eco score, IdleWars, Ford SmartGauge with Eco Guide, Toyota Prius Hybrid telemetry GAEA, LEY!, OPower, Power Agent, Power Explorer, SuMo, Velix, Viaggia Rovereto, WaterSmart, We Spire
	Env. and econ.	Catchment Detox, City Rain, Clim'way, EcoVille, Electro City, EnerCities, Fishing With Friends, Futura, Plan It Green!	-
	Env. and social	MiniMonos	-
	Env., econ. and social	EcoPolicy, Green & Great, Oiligarchy, Oil God, Perfect-Ville, Pipe Trouble	-

Table 3.3 Synopsis of the reviewed games for each classification dimension

3.3 Sustainability educational games

The literature review identified several sustainability educational games, with diverse pedagogic approaches. Therefore, in order to simplify the analysis, we grouped educational games according to their genre, and discussed the possible instructional approaches inside every genre. We identified the following five main categories: *construction and management simulation*, *interactive fiction*, *role-playing games*, *playful activities* and *procedural rhetoric games*.

In the following we detail the characteristic of each group, focusing on adding information helping to answer both Q3 (how do designers intended to inform players?) and Q4 (which games have been evaluated? How? Which were the results?).

3.3.1 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 CMS, like *City Rain*, *Clim'way*, *EcoVille*, *Futura*, *LandYOUs*, *Modern Mayor* and *Plan it Green* approach sustainable city planning, encompassing several interconnected aspects, such as water and energy management, pollution control, greenhouse gas emissions and trash recycling. 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 approach can be seen in *Perfect–Ville* [101, 102], a city planning game which 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 initial game rules and contents assumes that winning in Perfect–Ville requires to adopt a hedonic life-style based on a greedy and consumerist model. These (provocative) features aim at triggering critical discussion among participants. Then, before subsequent sessions, 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.

Others CMSs focus on specific issues. This is the case of *ElectroCity* and *EnerCities*, which deal with energy production. In these games, the 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. *Super Energy Apocalypse* proposes a different approach to the same problem. 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 [103]. Therefore, succeeding in the game requires players to find a sustainable balance between the production of energy and the environment pollution it causes. *Catchment Detox* (see Figure 3.2) tackles the water management issue. The game requires players to balance the food production rate with a sustainable water consumption. The game score combines economic success and the environment sustainability of the players' choices.

Finally, there is a group of purely managerial games, which are usually multiplayer. A first example is *Green & Great*, an advanced 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 CMS aims at fostering content transfer between game actions and real-world concepts [4], which is one of the objectives of experiential and constructivist teaching. To this end, most of the games emulate realistic scenarios. For instance, Futura depicts the Fraser River basin in Canada, Catchment Detox simulates the real water behavior in Australia's waterways, and ElectroCity portrays the energy production scenario in New Zealand. To improve this representation of reality, players can also assume policy-maker roles (mayor, presi-

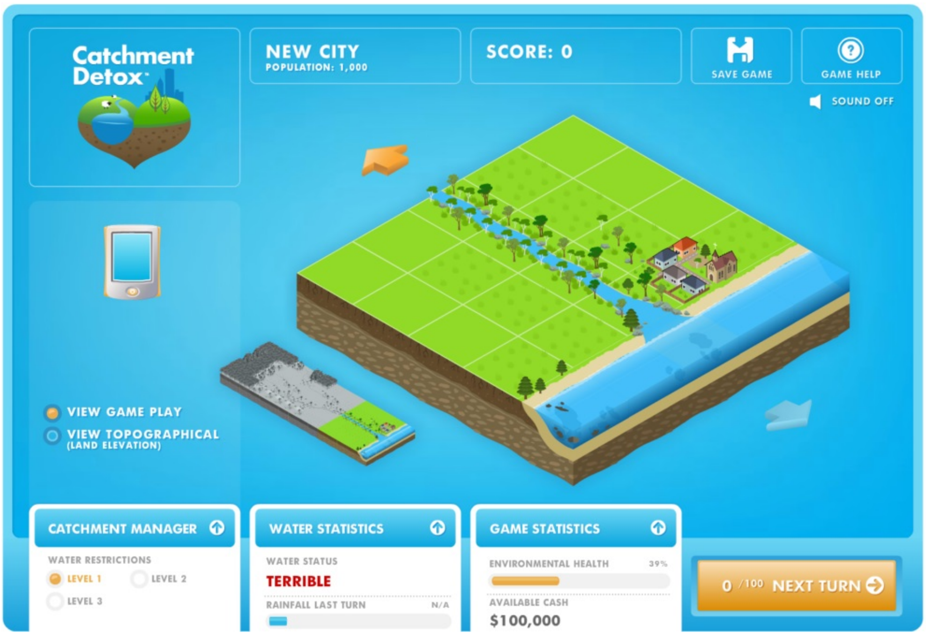


Fig. 3.2 CMS Catchment Detox

dent) that take real-life decisions (building structures, choosing a specific energetic matrix, managing resource consumption, and so on).

In general, the interaction acts of CMS games are simple enough to be understood by youngster audiences [104]. However, some games as Green & Great and Ecopolicy present more fine-grained managerial information, targeting mature audiences. It should also be noted that most of these CMS are single player. Exceptions of note are Green & Great and Ecopolicy, which provide web based multiplayer options, and Futura, which has been expressly designed to enable collaborative co-located learning. 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 [104]. Other interesting results on the effectiveness of CMSs can be obtained from [105], which performed both a quantitative and qualitative evaluation of EnerCities involving more than 800 students from 5 different countries. 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.

3.3.2 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). For instance, in *Precipice* the 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 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 CMS games, the interactive fiction games try to foster knowledge transfer between fictional and real world by portraying realistic scenarios. For instance, the lake depicted in Citizen Science is the Mendota lake in USA, and in Riverbed, the setting, history and characters archetypes are based on real cases, like the shrinking of the Aral Sea and of the Colorado River.

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 and usually presented through introductory screens and NPC dialogues.

All the interactive fiction games we found are single player, which is a common characteristic of games of this genre [96]. As for the audience, authors of Citizen Science claim that youngsters are their target. Although Precipice and Riverbed are based on interaction acts similar to those of Citizen Science, it may be argued that these two games have been envisioned with a slightly older audience in mind (teens), since they portray darker atmospheres and "more adult" background histories (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 [106].

3.3.3 Role-playing Games

Role-playing video games (RPG) involve the representation of a character into a highly developed 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 [107].

A first example of this kind of games is *Ludwig*, whose story is set in a futuristic earth depleted of fossil fuels. The learner controls a robot that explores the environment to find a way to create alternative energy. Another example is *Desertification story*, where players have to deal with the resources scarcity of a village [108]. Finally, in *AgriVillage* players have to face the environmental impacts of agriculture.

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, beside promoting collaboration, it facilitates social negotiation of meaning, i.e. the process in which learners test their own understandings against those of others [109].

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 [110]. 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 in an orientation center and chat with each other, and with "engineer" NPCs, who 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 [108]. 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, but only when adequate support is provided by the teacher. These findings seem to suggest that Ludwig is a valuable supplement for conventional instructional tools, rather than a self-learning material [111].

3.3.4 Playful Activities

Several playful activities, such as quizzes and text sentences to be completed, have been proposed to teach sustainability related concepts. In such games, generally children are the target audience, and often the only sustainability aspect addressed is the environmental one. Examples are *Prometeruse Quiz*, the *Sustainability game* and those available in online portals like *Discover Water* (see Fig. 3.3), *PBS Kids*, *EPA* and *Games Planet Arcade*. 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.

More complex examples are some location tracking based games, as *Heroes of Koskenniska*, *eVision* and *Ghost Hunter*. These games display information concerning the human impact in the environment surrounding players (which may be specific, as the North Karelian Biosphere Reserve in Heroes of Koskenniska, or general as in eVision and Ghost Hunter [112–114]).

Another interesting example is *Alberto's Gravimente Toys*, a game conceived for children of the primary school, which depicts several sustainability scenarios. In each of them, players have to collect and organize the different parts of a story. The game exploits as well Tangible User Interaction. For instance, players can rearrange the collected narrative chunks by squeezing an inflatable bat and play them in their present order by pressing a ball [115].

Finally, there are *ecoCampus* and *EcoFactory*. EcoCampus is an augmented-reality game for academic students where players can interactively explore different building redesign solutions and assess them under the sustainability point of view [116]. In its turn, EcoFactory aims at engaging youngsters in the sustainable manufacturing of a smart television.

Fig. 3.3 Example of a game activity, in the portal Discover Water

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 [115, 112]. As for the audience, the main target is clearly that of the younger players, with few playful activities expressly designed with mature audience in mind (e.g., ecoCampus, which is targeting 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 [112]. Alberto's Gravimente Toys testing showed that most players understood the learning contents and that most of the children (85%) preferred to play the game collaborating with a friend to build the story [115]. 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 [116].

3.3.5 Procedural Rhetoric Games

Procedural rhetoric is the practice of authoring arguments through interactive processes [19]. Rather than directly providing the desired information, procedural rhetoric games allow players to interact, observe, and reflect within a dynamic game system [91][3]. 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 [19].

Examples of sustainability-driven procedural rhetoric games are the following.

Pipe Trouble (Figure 3.4) 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 the profit of oil extraction by drilling exploitation wells, corrupting politicians, stopping alternative energy sources and increasing the world oil addiction. While the game is played, player actions negatively impact 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, company representatives progressively ask for actions in disagreement with environment law, while the visible degradation of the environment generate protests of the local communities. The strategy mechanics of Oiligarchy and Oil God, which involve resource management and political decisions, are aimed at fostering players reflection over the consequences of their actions [100]. In Pipe Trouble, the time-limited scenarios and fast-paced gameplay aim to recreate the urgency and pressure conditions

[3] The definition of procedural rhetoric games appeared first in Ian Bogost book "Persuasive Games" [19], a term that in literature refers also to "interactive computing systems explicitly designed to change attitudes or behaviors" (Fogg, [117]). 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.

Fig. 3.4 Procedural rhetoric game Pipe Trouble

that characterize several situations where environmental decisions need to be taken, which can thus result in choosing the non-optimal option.

The release of the procedural rhetoric games definitely impacted the game community. Oiligarchy was considered one of the defining examples of the overlap between interactive digital storytelling and political discussion [118]. 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 pipeline, it became the first video game ever featured at the Cannes Film Festival [119]. In spite of such achievements, empirical test data were not available for any of these games.

While none of the analyzed approaches 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 roles, either cooperative or competitive, are likely to bring further contributions to the rise of critical thinking on the game topics.

3.4 Sustainability motivational games

Motivational games assume that education towards sustainability should also be able to induce a social change in learners. This process involves several interconnected phenomena that are related to both people's daily life and their relationship 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 on 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 [120].

Analyzing the motivational games, we identified two main approaches, *eco feedback games* and *gamification approaches*, which are detailed in following Sections 3.4.1 and 3.4.2. Similar to what was done for educational games in previous Section 3.3, for each group of motivational games we report information related to the research questions previously introduced, focusing mainly on Q3 (how designers intended to motivate players) and Q4 (which games have been evaluated and with which results).

3.4.1 Eco Feedback Games

The most common goals of eco feedback games are persuading people to reduce CO2 emissions (*Eco Island*, *Ducky*) and energy consumption (such as in *Climate Race*, *Energy Battle*, *Energy Life*, *LEY!*, *Power Agent*, *Power Explorer*), or to improve garbage recycling actions (*Acttention*, *GAEA*) and promoting better eating habits (*EcoPanel*). 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 user to provide a proper feedback to their actions (see Table 3.4).

Data collection is used to verify the accomplishment of the proposed activities and is usually performed automatically. For instance, Climate Race, Energy Battle, Energy Life, LEY!, Power Agent and Power Explorer collect energy consumption data from players' smart meter devices, while Acttention and GAEA track player's mobile phone location. In other cases, players are asked to manually insert food consumption data (EcoPanel), meter measurements (Energy Battle) or check activities like turning down the air heater by one degree and taking a train instead of a car (Ducky and Eco Island).

Eco-feedback games leverage on two main elements to motivate players. The first is the feedback provided by the game, which is usually based on charts, textual information and tips on ways to be more efficient in achieving the game objectives (see Figure 3.5(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. In Power Explorer, the health of the player character is visually affected by the level of energy consumption. 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 [121, 28]. 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 [122]. Furthermore, in-game direct communication among players can improve argument comprehension and provide additional motivational and emotional support to individual users [120].

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 [123–128]. For instance, [123] 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, inconclusive results on the preservation of these effects in the long term were obtained. For instance, in Power Agent [128], Eco Island [124] and Energy Battle [125], 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 [127].

3.4.2 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 [94]. Similar to the eco feedback games, gamification approaches mostly focus on the ecological aspect of sustainability. In the following, we present the most salient examples of this category of applications.

Table 3.4 Evaluation of eco feedback games

Proposed Activity	Data Collection	Serious games
Promote better eating habits	Manual	EcoPanel
Reduce CO2 emissions	Manual	Ducky, Eco Island
Reduce energy consumption	Manual	Energy Battle
	Automatic	Climate Race, Energy Life, LEY!, Power Agent, Power Explorer
Household waste sorting	Automatic	Acttention, GAEA

(a) (b)

Fig. 3.5 Feedback on behavior change persuasive games; (a) explanatory approach in Climate Race, and (b) ludic approach in EcoIsland

Public Engagement in Eco-friendly Actions

Some gamified applications aim at motivating users towards eco-friendly behaviors. These applications propose challenges that can be accomplished by reducing the consumption of some resource. Prominent examples are Eco.system, IdleWars, Greenify, We Spire, SuMo and Viaggia Rovereto.

The Scottish energy company SSE employed *Eco.system*, a gamified application focused on motivating employees to reduce annual carbon footprint through changes on daily minor actions, such as using stairs instead of lifts, reducing document printing and switching off monitors overnight [129]. Eco.system uses two main motivators to engage the 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. Similar approaches are: *IdleWars*, used at the Centre for Sustainable Energy in the UK to reduce employees energy consumption [130], and the *We Spire* platform, which supports the creation of gamified sustainability engagement programs in companies [131]. However, public engagement through gamification is not restricted to companies. For instance, *Greenify* was used to motivate University students towards more sustainable practices in energy and food consumption [132].

Other applications aim at motivating players in finding eco-friendly ways of traveling. This is the case on *SuMo* [133] and *Viaggia Rovereto* [134], which use challenges, badges and leader boards to engage users. 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% [135].

Gamified Electronic Bills

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

Prominent examples are *OPower* and *Velix*, which target energy consumption, and *Water Smart* and the *Dubuque water portal*, which approach water consumption. OPower and Water Smart were more extensively tested. The OPower testing lasted five years and involved 88.000 families [136]. 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 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, Water Smart 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 [137].

Efficient Driving

Recently, several cars exploit telemetry data to provide gamified cues for drivers. One of the earliest examples is the *Toyota Prius Hybrid telemetry system*, which

Fig. 3.6 Fiat eco:Drive interface

allowed drivers to control their current fuel efficiency [29]. Thereafter, the gamified car telemetry evolved into more complex applications, such as *Fiat eco:Drive*, *Honda Eco score*, and *Ford Smartgauge with EcoGuide*. To motivate users, these systems track drivers' history, display user friendly dashboards and informative feedback about their driving efficiency (see Figure 3.6), and position them in a worldwide rank, according with a general score [129].

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 [29]. In addition, a quantitative study about more than 5.500 Fiat eco:Drive users over a 30-days period showed an average 6% fuel reduction [138].

3.5 Design guidelines for sustainability games

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, as discussed in Chapter 2, several researchers have highlighted the necessity to base the design and development of serious games on sound theoretical models that encompass theories from both pedagogy and game design fields. The integration of these two perspectives aims at exploiting game design elements to engage player in the learning activities and, at the same time, at increasing the effectiveness of the game as a learning tool (which, in turn, requires to ground the design choices on a sound pedagogical model).

Several methodological models (some of which are reviewed in Chapter 2) have been defined for (general) digital learning game design. However, most of these approaches are not suited for sustainability learning, due to its peculiar characteristics. As we stated in the Introduction, sustainability learning requires to deal with complex systems, which involve multiple dimensions and stakeholders. This fact defies traditional 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]) and, as a consequence, rises the need for specific tools capable of dealing with multiple interrelated domains represented under several perspectives.

As a further comment, different types of SSG (educational and motivational) have different peculiarities, which makes it difficult to define a unique methodological model 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*, which summarize the common aspects of educational or motivational games, and *design guidelines* associated to each of these key concepts. Table 3.5 summarizes the identified design guidelines, which represent the design strategies for sustainability games (the objective O2 previously defined).

In addition, we also 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 model 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.

3.5.1 Educational Games

To the best of our knowledge, the only design model expressly developed for educational SSGs is the Fabricatore and Lopez model (FLM) described in [139]. Their

Table 3.5 Design guidelines for sustainability games

Game class	Key Concepts	Design Guidelines
Educational	Contextualization	Define game thematic contemplating social, economical and environmental aspects
		Contextualize the player (role and actions)
	Player empowerment	Employ multiple roles with different skill sets
		Offer multiple victory states
	Social Interactions	Adopt mechanisms to harness interaction
		Expand the game space (e.g to social networks)
	Adaptivity	Progressively present mechanics and interactions
		Introduce non-player planned disruptions in game dynamics
Motivational	Players individuality	Allow players to set their own goals
		Tailor content and feedback
		Design different challenges, considering different player types
		Tolerate the players failures
		Offer multiple levels of dificulty
	Multiplayer activities	Propose inter-group competition and intra-group cooperation
		Expand the game space (e.g to social networks)

work first analyzed the content of 30 games to identify possible enablers of sustainability learning. Then, they devised the FLM design model based on both their results and on studies related to learning about complex systems [11].

Another interesting reference for educational games is the *Guidelines for Excellence* (GFE), a compilation (edited by the North American Association for Environmental Education) of opinions from researchers, theorists, and practitioners related to what effectively works in the development of sustainability learning materials [140]. In particular, the FLM model 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 FLM model along with their relations with GFE guidelines.

Contextualization. Both [139] and [11] 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 FLM, 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 [11]. Player empowerment is also related to the sense of players self-efficacy described in GFE, i.e. the perception of their own actions as drivers of changes in the game system, and responsibility for the consequences of their actions. FLM suggests 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 [141] and enhance creative thinking and interpersonal communication, two relevant characteristics that should be approached when learning about complex systems [11]. According to FLM, positive effects on the social interactions can be obtained 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 the social networks.

Adaptivity is a term that encompasses two elements (according to FLM). 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. We underline that this concept has no correspondences in GFE, since it is not directly related to the educational contents of the game.

A Discussion of Educational Games

Based on the direct and indirect analysis of educational games previously detailed (Section 3.2), we propose an integrative and critical discussion aimed at conveying a detailed view over possible trends and notable cases. In particular, one immediate question arises: to which extent the analyzed educational games embody the design principles presented in Section 3.5.1?

As introduced in Section 3.3, *thematic contextualization* is stressed in most of the games (namely, 64,1% of them). At different levels, CMS, interactive fiction, RPG and procedural rhetoric games deliver thematic contextualization through the emulation of real-life scenarios and actions, and the representation of different scales, both in local to global dimension and in short to long time spans.

On the contrary, only the 12,8% of the games consider *player contextualization*. 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 in tropical forests and in desert areas of Africa. Nonetheless, learners do not have the possibility to play the role of natives in the game and, thus, they cannot directly experience the social implications of other players' decisions. On the basis of these observations, we believe that social contextualization could be better explored in order to improve the learning outcomes of educational SSGs.

Another key concept that, in our opinion, should receive more attention, is *player empowerment*. Despite the fact that 48,7% of the games attempt in some way to consider this element, 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 player empowerment. In general, RPG 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. For instance, in Futura each player is responsible for a specific resource (food, shelter and energy) and cooperation is needed to accomplish the objectives, a strategy implemented to help players understand the relevance of the different roles. In addition, CMS games provide the availability of multiple winning paths. As an example, in Ecopolicy, while players are challenged to govern a country and maintain its sustainability, they can approach the different issues to face in several ways and no single winning strategy exists.

In spite of the relevance attributed for *Social interactions* in FLM, the majority of educational games are single player (79.4%). Furthermore, only three games (EnerCities, Modern Mayor and Plan It Green) offer ways to extend the communication out of the game space, mainly by simply sharing results and challenging friends through social networks. On the contrary, when this social interaction is available, empirical evaluation shows its relevance to enhance knowledge acquisition in sustainability topics [104, 115]. Summarizing, our results suggest that social interactions could be further leveraged by educational SSGs.

Adaptivity is another key element that we believe could benefit from further exploration. To some extent, all of the analyzed SSGs present in a progressive manner their actions and mechanics to player. However, only the procedural rhetoric games (7,7% of the 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, the discussion of current SSGs based on the key concepts of the FLM model, seems to suggest that some of the key concepts defined could benefit from further exploration in order to fully exploit the capabilities of educational

SSGs. Indeed, although thematic contextualization has been applied to current designs, greater consideration should be given to the representation of social issues, to the introduction of game mechanics and technical tools capable of stimulating co–located interactions and to the possibility of sharing and discussing game results in social networks. Also, in order to fully benefit from adaptivity, we think that a viable solution could be the exploitation of in–game analytics, an approach that has demonstrated its effectiveness in the development of adaptive digital games [142].

3.5.2 Motivational Games

The field of motivational technologies (i.e., a form of interactive technology designed to appeal to a user's intrinsic motivations, empowering them to achieve a desired habit or outcome and to activate lasting behavior change) have been largely explored by researchers in the last years. Furthermore, several authors approached the definition of theoretical models for designing motivational technologies [143–145].

However, when dealing specifically with motivational SSGs, the scenario seems less mature. Despite that, our survey the state of the art allowed us to identify three relevant theoretical works. In the first two, [121] and [28] proposed guidelines for SSGs based, respectively, on motivational and gamification theories. In the third work, [91] 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.

The three works ([121, 28, 91]) have some interesting similarities, which can be summarized into the two following key concepts: *players individuality* and *multiplayer activities*.

Player individuality. Addressing player individuality in the game design requires considering two elements. First, the heterogeneous characteristics of the players. Players can be categorized into different types (defined in [146] as killers, achievers, socializers and explorers) and have different expertise (classified in [147] 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 consider all the societal, cultural and demographic aspects that can affect learners' decisions [121] (e.g. regulations, restrictions, location of living, non-availability of alternatives, and so on).

The second element to be considered is the player *autonomy*. Designers should enable players to freely choose their own goals and the way to achieve them. In addition, games should also give players the autonomy to fail if desired [121, 91], since a game that tolerates failures allows players to virtually rehearse different behaviors and to interactively explore their cause-effect relationships.

Multiplayer activities. By enabling group experiences, cooperative and/or competitive, motivational games provide more possibilities for engagement (for instance, by offering inter-group competition/intra-group collaboration [121, 28]), 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. Examples are a) normative comparisons of individual achievements, which induce competition [28], and b) mechanisms supporting discussion about content and exchange of experience and suggestions, which enable social motivation [91].

A Discussion of Motivational Games

Following what was done for educational games, an analysis of the motivational games described in Section 3.4 results in somewhat different findings for the two key concepts previously defined.

From our personal observation, *multiplayer activities* seem to be well–explored in the context of motivational games. Game evaluations confirm, as a general result, that this element is relevant in engaging players [128, 126, 123, 124] and improving the comprehension of the interpersonal and social relations linked to the sustainability field [148]. When implemented, the combination of intra-group cooperation and inter-group competitions seems indeed to be an intrinsic motivator (GAEA [126], Energy Battle [125]). 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 *player 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 realize 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. For instance, the goal of Opower is to reduce home energy consumption and the game provides different advises for a person living alone in the city center and for a large family living in the suburban area [29].

Researchers have explored as well the use of different game mechanics to better engage 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 prefer concrete measurements of succeeding in the game [146].

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. Even admitting that this is not necessarily a gap in the state of the art (since demonstrating this statement would require a systematic review of the literature and the direct analysis of all games), we believe that both elements are relevant in the design of a motivational game and worth to be explored in future research.

3.6 Open research areas

The papers surveyed in the previous Sections show that, although interesting results have been obtained, fully understanding how to develop effective SSGs requires further work. This is either due to the fact that the background theory has not been fully explored in the context of sustainability games (which have their unique peculiarities), or that research findings are controversial. Therefore, in this Section we briefly discuss some open problems and potential areas of research (which is related to objective O3 previously defined).

Issue 1: Which methodological models are most suited to drive SSG design?

As introduced in Chapter 2, researchers proposed several theoretical models to base the design of effective educational games. Among those, some specifically addressing the sustainability learning issues (see Section 3.5) were used in practice and their preliminary evaluation seems to indicate the effectiveness of their guidelines [149–152]. However, in our view, these approaches put relatively lower emphasis on the entertainment dimension with respect to the educational one. A possible solution would be the integration with some of the proposed models for guiding the design of educational games under a PX perspective (see Section 2.3). 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* ([44, 45, 43]). It is interesting to highlight the direct link of these elements with the guidelines of FLM for the design of educational SSGs (Section 3.5.1). In particular, these elements could certainly bring benefits with respect to those key concepts that have not been fully addressed in educational SSGs, such as player contextualization (partially considered in procedural rhetoric games only) and empowerment (which is fully exploited only in Perfect–Ville).

Concerning PX and motivational games, the scenario seems a little less established and the current models for gamification design [153] lack concrete strategies to directly approach PX. [154] started to tackle this issue by establishing a grounding categorization based on prominent aspects of PX driven gamification design. In particular, the work highlights 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 player individuality and multiplayer activities identified in Section 3.5.2.

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

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

Several authors have highlighted the relevance of player *immersion* in serious games to achieve the desired learning outcomes [95, 35]. 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 [35].

Currently, both industry and scientific research investigate how innovative interaction paradigms (e.g. virtual and augmented reality environments, interactive surfaces, tangible devices) can enhance player immersion. Recent gaming platforms have introduced novel devices aimed at providing a more natural user interaction (NUI) such as the WiiMote, the Kinect and the PlayStation Move, and larger steps towards effective and fully immersive NUI gaming have been taken with the launch on the market of devices like the OculusRift, the Vive and the LeapMotion.

However, the use of advanced and immersive interaction technologies have been largely overlooked in the area of SSGs. Some interesting initial results about the applicabilities of novel interaction devices, especially in terms of harnessing players' creativity and collaboration, showed the effectiveness of tangible interaction [104, 115, 152] and augmented reality [116, 149]. 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 [155–157].

Issue 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, as saw in previous Section 3.5.1, only 20,6% of the analyzed educational games present a multiplayer (collaborative or competitive) mode. In addition, 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, for educational SSGs the literature shows that most approaches are single player and the few multiplayer games available often lack competitive patterns. One possible explanation is related to the limited resources typically available for the development of educational games (as discussed in Section 2.4.1), 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 [104], 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 [158], which discussed elements that influence the creation of competitive learning environments, such as: the absence of individual winners or losers, the possibility of social comparison of competences, the creation of situations of intra-group collaboration and inter-group competition and the immersion of players, as a means of stretching their expected potential.

We personally believe that, again, a major contribution towards the development of effective collaborative games can be provided by augmented and virtual reality technologies. In this regard, the advantage of AR technologies, where geometric elements and sounds are overlapped with the real world, is to provide tools that support 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, virtual reality 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 [152, 149], 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.

Issue 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 these claims are supported by empirical research results.

Stemming from the answers to Q4 (i.e. *which SSGs have been evaluated and how? What are the results of these evaluations?*), Sections 3.4 and 3.3 reported some evaluation data, which can be briefly 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 presents vague conclusions, e.g. stating that players found the games fun, enjoyable, and informative [106, 112, 115]. A greater amount of quantitative data is 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 [159]. 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. 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.

[159] still suggests 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 [160] 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 [105], showing lower energy consumption for people that played the game (experimental group) compared to those who did not (control group). In [159] 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. Summarizing, both works [160, 159] 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 [160, 159], or the lack of supplemental post-game material [159] that could have influenced previous results [105]).

Summarizing, current experimental results on evaluating the effectiveness of SSGs seem to be partial, and further work is required to develop a better understanding of the tasks, activities, skills and operations that SSGs can offer a) to achieve the desired learning outcomes, while still being entertaining, and b) to guarantee 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 of learning analytics approaches in serious games, aiming at capturing and analyzing players' interactions with the learning content, with the purpose of better understanding (and improving) the learning process [161, 162]. This information can be used during game play, e.g., to help instructors directing the learning process or to provide an adaptive and personalized learning experience, which is a key concept not fully considered yet in educational SSGs. Another option is to exploit analytic data after the game session, e.g., to assess the learning outcomes. Despite their potential benefits, current SSGs largely overlooked the use of GLA and the only work we found [163] analyzed a single game (thus, reducing the general validity of its results). That being said, we firmly believe that a viable solution to overcome the limit of the current research is to exploit, in future works, the potential of GLA in analyzing the effectiveness of serious games with respect to other communication media.

Chapter 4

WaterOn! a collaborative tangible game for teaching water cycle contents

Both the tools and concepts identified in Chapter 2, as well as the SSGs analyzed in Chapter 3, suggest that serious games offer unique possibilities for creating educational tools for sustainability. However, at the same time, there are evidences that the approaches developed so far often fail to fully leverage such potentialities [4]. Therefore, we believe that more research is needed, and the work described in this Chapter is a first step towards this direction. In particular, the approach we describe focuses on suggestions aroused from previous Chapters, which state that further research should:

- focus on the design of model-based EGs (Section 2.4.1);
- exploit technological tools and design elements that can foster cooperative behaviors (Section 3.6).

As for the first suggestion, this Chapter presents WaterOn!, a SSG whose design has been mainly based on the RETAIN model [35] (previously detailed in Section 2.2). To the best of our knowledge, WaterOn! is the first mobile game to be developed being based on this model, and (hopefully) could serve to exemplify its practical application for SSGs designers. Then, based on the results of our work, we also present open questions related to RETAIN, which might serve as well as an inspiration for possible updates of the model.

Concerning the second suggestion, WaterOn! employs several technological tools to favor cooperation: (i) mobile devices (which allow co-located players to move freely within the environment), (ii) a projected screen (offering a shared representation of the scenario, aimed at supporting players' discussion and coordinated actions), and (iii) tangible user interfaces (TUIs), i.e. the use of physical forms to interact with digital information [164], which have been showed to harness collaborative behaviors [165, 166]. As for the design elements aiming at the same objective, we complemented RETAIN guidelines with those of the tangible learning design framework (TLDF) [167], which is a theoretical model specifically aimed at informing TUI collaborative games. This way we intend to investigate the technological tools (mobile devices, shared screen, and TUIs) and design elements (TLDF) aimed at fostering cooperative behavior on an educative SSG.

It is also important to highlight that, due the limited tests that were carried out (see Section 4.5), our results are inconclusive for supporting the effectiveness of the proposed approach towards the promotion of cooperative behaviors. Despite that, we deemed interesting to report our conjectures in this Chapter, as they (i) inspired the development of Sustain (the second game presented in this thesis, Chapter 5), and (ii) they might, hopefully, stimulate other SSGs designers. Moreover, we stress that, to the best of our knowledge, this study represents the first combination of: mobile platform, TUI-based interaction, and the RETAIN guidelines in the development of a complete collaborative game.

4.1 WaterOn! game description

WaterOn! is a collaborative multiplayer game focused on teaching water cycle contents for 8-10 years old children. The game exploits multitouch interaction on mobile devices and a projected virtual environment in order to foster collaboration among co-located users. In addition, WaterOn! employs TUI interaction, which is proven to harness engagement for children in collaborative problem-solving activities [168], enable individual awareness and group communication [165], and reinforce the emotional impact of the game [169].

The game design and the instructional units have been centered around the target audience, i.e. 8-10 years old children. Two main reasons justify this target audience. First, studies show that there are still misconceptions in water education of school-age children [170]. Second, the chosen age-range also corresponds to the center of concrete operational stage of children (7-11 years old according to Piaget [32]). Therefore, the game mechanics have been defined considering that children at this age demonstrate logical and concrete reasoning and are more capable of taking part in cooperative activities, compared to their younger peers [32].

With reference to both the national curriculum standards alignment developed by the water.org foundation [171] and the educational materials available from Project Wet [172], the following three instructional units were defined:

1. identifying the three states of the water and the transitions between them;
2. describing the movement of water within the water cycle;
3. recognizing solar energy as main driver of water movements on earth.

Although the educational focus (teaching water cycle contents) might lead to the conclusion that WaterOn! is a science educational game rather than a SSG, we stress that education towards water is the basis for understanding other sustainability related concepts later introduced to elementary school children (e.g., the life-cycle of plants and animals, natural disorders, energy production and so on [173]). Water also involves multi-faceted issues (such as consumption, quality, supply and management), which impact all sustainability aspects (environmental, economic and social). As can be seen in Section 4.3.1, the background story of WaterOn! employs metaphors hinting the relations between water cycle and social aspect of sustainability. The game scenario is a human village that suffers from an unbalanced water cycle, the game treats water as a finite resource (wasting too much water leads to defeat), and the villains stem from an industry (depicting the negative impacts of human actions in the natural environment).

In comparison with other SSGs targeting children as main audience - such as CMSs and playful activities (see Sections 3.3.1 and 3.3.4) - WaterOn! stands out for offering a collaborative environment, which, although being important to understand sustainability issues, is present in only 12,8% of the educational SSGs analyzed in Chapter 3. Concerning collaboration and tangible interaction, [165] presents an extension of the Futura game (Section 3.3.1) that supports TUI based interaction. The analysis of the empiric results obtained indicate that, although the collaborative activity is more influenced by group dynamics than tool modality, the physicality of tangible tools facilitated individual ownership and announcement of tool use, which in turn supported group and tool awareness. In another work, specifically aimed at elementary school children, Youtopia presents a tangible and multi-touch tabletop-based solution [150]. Youtopia is a collaborative interactive activity for teaching concepts related to land use planning. Research findings indicate that the multi-player design encourage effective collaboration rather than simple parallel use of the available solutions [166]. Although these studies ([165, 150, 166]) present positive results, we believe there is still space for research on the correlation of tangibles, collaboration, and educational games for children audience. For example, [174] found that multi-input touchscreen interfaces do not always promote effective collaboration since children can be engaged with their own respective tasks with little consideration for others nearby. In this perspective, we think that WaterOn! might contribute to the discussion on cooperative SSG designs.

4.2 Theoretical background

Among the identified theoretical models (detailed in Chapter 2), we decided to base the design of WaterOn! on both the RETAIN (detailed in Section 2.2.2), and the tangible learning design framework (detailed in the following Section 4.2.2).

4.2.1 RETAIN

The reasons for choosing RETAIN were threefold: (i) it is both a design model and an evaluation tool; (ii) its theoretical bases are closely aligned with modern game design principles; and (iii) it is based on Piaget's theory of cognitive development [32] and, thus, well suited for a children game audience.

However, since the original design of the RETAIN rubric was built specifically for standalone console games, its use in the specific context of WaterOn! requires facing two issues: (i) being based on the Piaget's theory of cognitive development [32], it offers little or no emphasis to the collaborative part of the learning process; and (ii) being general, *i.e.* applicable to any kind of game, it does not present specific guidelines concerning tangibles design. To overcome these issues, we also consider the tangible learning design framework (TLDF) [167]. Being aimed at collaborative TUI games, this framework complements the guidelines of RETAIN.

4.2.2 Tangible learning design framework

According to the TLDF [167], the game design should consider four perspectives: info processing, embodied, collaborative and constructive.

Info processing perspective concerns employing demands that drive players' attention to the learning content, what can be achieved with: (i) TUIs design distributing information across modalities, and (ii) employing adequate mappings between physical objects and real-world entities.

TUIs design should also consider the *embodied* perspective, which refers to designing mental and body engagement with the world, in order to improve system usability. Under this perspective, tangibles should leverage image schema developed early in life (*e.g.* in - out, up - down, front - back, fast - slow and near - far).

The *collaborative* aspect of the game should guarantee that players negotiate and divide meanings, in order to create a shared conception of a problem. This can be achieved through (i) the creation of configurations in which players can monitor each other's activity and gaze, and (ii) the distribution of different roles, information and controls, among players in a way to foster negotiation. To the collaborative aspect we deem relevant to include additional guidelines for collaborative game designs outlined in [175], which can be summarized in three points: (i) the use of spatially separate but shareable individual territories and resources to facilitate negotiation and learning from others; (ii) the prevention of a single player to take over the game; and (iii) to avoid fast-paced interaction in order to facilitate reflection and self-regulation.

The TLDF still defines the *constructive* perspective, in order to guide the educational design of the game, but we considered this aspect already covered with RETAIN. Table 4.1 presents a synopsis of the TLDF guidelines.

Table 4.1 Abstract of the tangible learning design framework guidelines

Perspectives	Guidelines
Info processing	Distribute information across modalities
	Mappings between physical objects and real-world entities
Embodiment	Leverage image schema developed early in life
Collaborative	Allow players to monitor each other's activity
	Distribute different roles, informations and controls among players
	Use spatially separate but shareable individual territories and resources
	Prevent a single player from taking over the game
	Avoid fast-paced interaction

4.3 Game design

WaterOn! is meant to foster collaboration among children. Thus, in each level, it requires both communication and coordination between players to fulfill the objectives. In order to strengthen such cooperation, the game features a projected virtual environment (Fig. 4.1(a)). This screen shows the overall game scenario, where players are acting as individuals, and the game status, which is aimed at offering a shared understanding of what has been achieved and what has to be completed yet. Players interact with the game through a tablet, exploiting multitouch and allowing players to move inside the physical game environment. Each tablet displays a portion of the whole environment (Fig. 4.1(b)) and the system provides a direct feedback of players position on the projected scenario (Fig. 4.1(c)).

4.3.1 Level design

The first three levels of the game are aimed at teaching children the states of water and the fact that the transition between them occur when heat energy is added or lost. The story of these three levels is played around a bunch of villains trying to plunder water resources while players are the village dwellers fighting the enemies. In the first level, *melting*, the villains have frozen all the available water to incorporate the

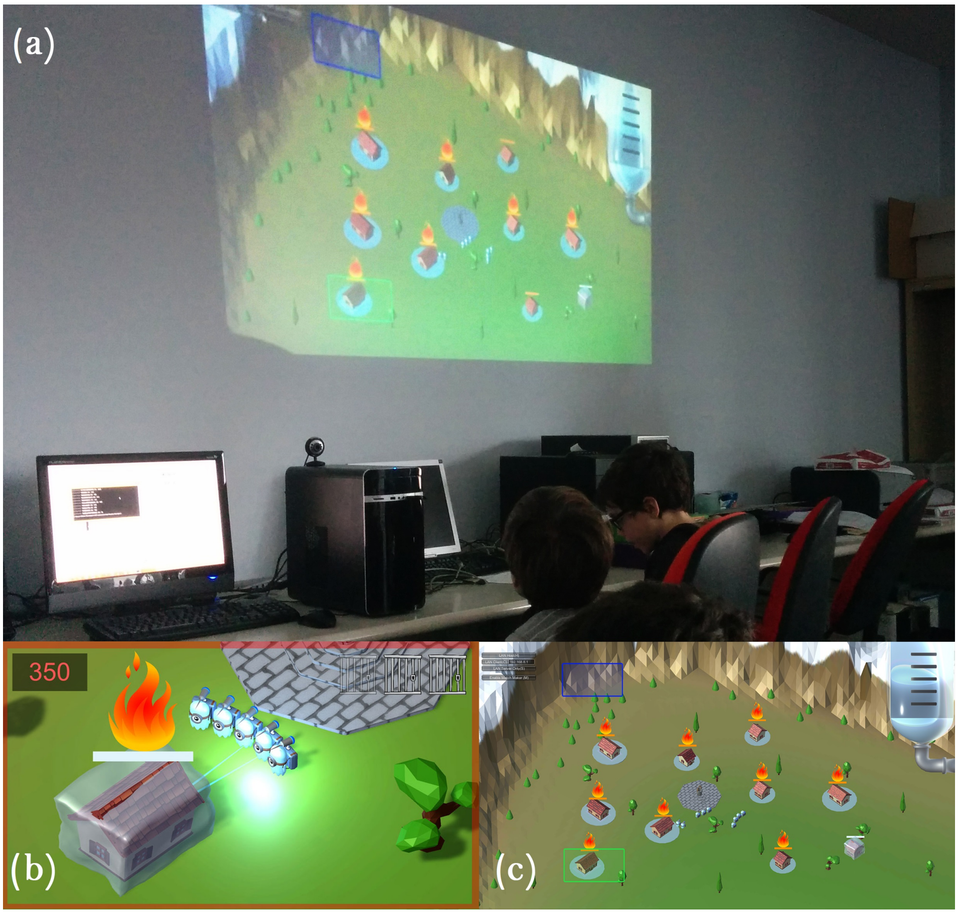


Fig. 4.1 (a) an image of the projected scenario; (b) view on the tablet screen; (c) feedback of player positions (the coloured boxes) on the main screen.

Fig. 4.2 Screenshots of *vaporization* (a) and *deposition* (b) levels.

village houses into giant ice cubes. Players have to melt the ice and fight against the enemies, which are trying to freeze again the water (Fig. 4.1). In the second level, *vaporization*, players have to blow up an air balloon, which is necessary to chase the (escaped) villain in chief, by transforming the collected water into steam. Players have to pour water into huge pots and to fuel the fire below them while enemies try to steal water from the pots (Fig. 4.2(a)). The last level, *deposition*, is preceded by an introductory scene showing that the air balloon has been attacked by enemies, which punched holes in it. The steam flowed out and condensed into clouds, while the air balloon crashed on a mountain top. The goal of the players is to move the clouds towards the mountain, cool them down to start snowing and create a snow ramp allowing to rescue the balloon passengers. Here the enemies use fans to hamper the cloud movements (Fig. 4.2(b)).

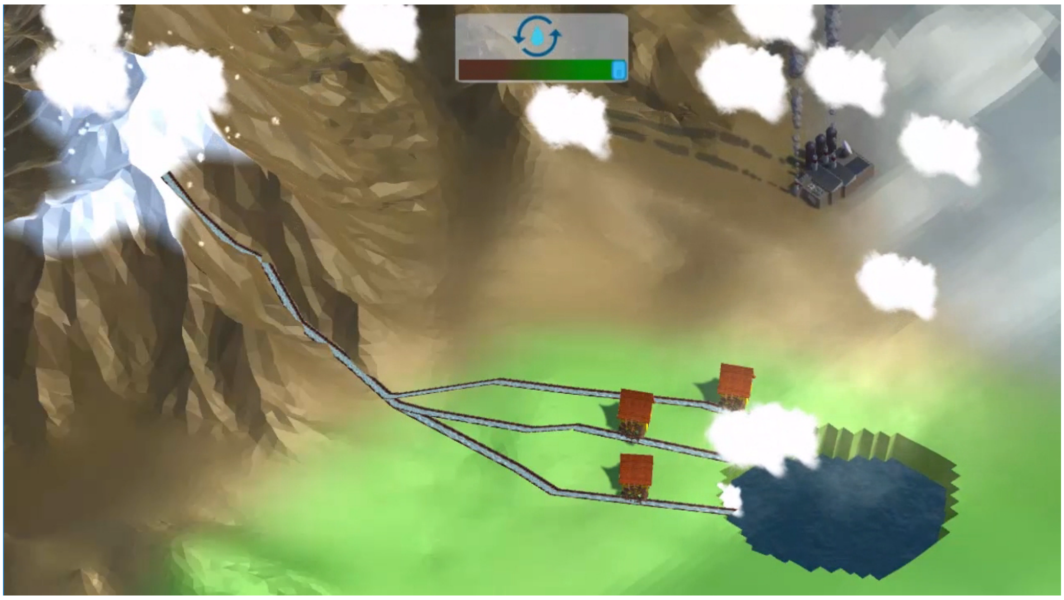


Fig. 4.3 Screenshots of the level *the cycle*.

In the first three levels, the lose condition is associated with the extinction of the shared resources (i.e. the water in the desired state). The aim of aggregating win-lose conditions to the communal resources is to stimulate negotiation and players learning from others [175]. Another feature aimed at fostering cooperation is the absence of individual failure or success in-game, since it is only possible to win or lose in group.

The fourth level (*the cycle*) concludes the game session, incorporating all the instruction elements and gameplay mechanics presented so far. In this level players face an evil factory, in which the villains are hidden. The scenario is an overview of the preceding game areas, with the water cycle perfectly balanced by players' actions in the previous levels: snowy mountains, flowing rivers and clouds being formed by water lake vaporization (see Figure 4.3). Then, the evil factory deranges the water cycle by shooting dikes (which stop the river flow), umbrellas (which block the clouds) and freezing weapons (which congeal clouds). Therefore, players have to reestablish the water cycle balance, using the tokens presented in first three levels: *freezing* and destroying the dikes, *blowing* the umbrellas away, and *heating* to self-destruction the freezing guns. Once that players manage to restore and maintain the water cycle, the evil factory collapses, and the game is finished.

4.3.2 Interaction design

Players can move around the environment using a map-based travel metaphor. As for the game interaction, players can use tangibles as tools to generate in-game actions. The available tangibles are the *heat token* (the heat source used to melt the ice in the first level and evaporate the water in the second; both have effect only when placed in the proper position), the *cold token* (required to cool down the clouds and generate the deposition effect) and the *blower token* (used to move clouds in the third level; the position where the marker is placed around the cloud in the tablet screen determines the wind direction and force).

To enrich the game mechanics, direct touch interaction is also available. Besides enabling navigation, player touches can activate specific actions in the game. For instance, in all levels, each player can tap on an enemy to imprison it for some seconds. Each player has a limited number of cages, which can be unlocked according to the points acquired by the player. The choice for a limited number of weapons is aimed at forcing a more “strategical" approach (i.e. requiring, again, collaboration). These touch interactions are not directly associated with the educational content of the game, but are meant to keep the player immersed by creating a more active gameplay and complexity progression among the levels.

4.4 Technical architecture

WaterOn! has been implemented into Unity 3D, a cross-platform game engine, which offers advanced lighting and rendering options, built-in support for spatialized audio, physics management, complex animations, multitasking, pipeline optimization and networking. Multiplayer collaborative interaction has been managed implementing a client-server architecture, where the server controls the primary screen and the clients are the players’ tablets.

In order to enable the use of tangibles with devices equipped with commercial capacitive touch screens, we developed custom passive markers characterized by unique patterns of conductive touch points that encode both their position and ID [176]. Our markers use four contact points per marker, where three of them define an orthogonal Cartesian reference system capable of providing position and orientation information, and the fourth one, the data point, defines the marker ID. We

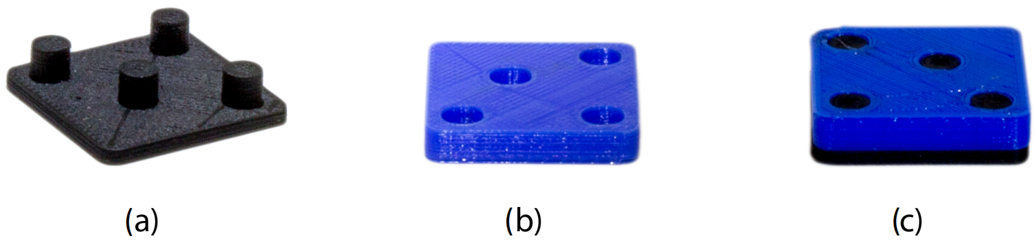


Fig. 4.4 The capacitive tangible (c) consists in a set of contact points (a) enclosed in a PLA shield (b).

experimentally found that the minimal size allowing a robust marker identification is 30 mm. With this size, the number of unique IDs that can be represented is 8, and a larger set of distinct markers can be obtained increasing the marker size. Since four touch points are required for a tangible, a maximum of two markers and two finger touches could be recognized at the same time on the tablets available for testing (NVidia Shield and Samsung Galaxy Tab were capable of handling 10 simultaneous touches). Markers are 3D-printed, using conductive graphene filaments to create the contact points, which are attached to a common base and then enclosed in a plastic PLA shield (Fig. 4.4).

4.5 Discussion

This Section discusses the influence of the chosen theoretical background in the design of WaterOn!. Such reflection intends to offer: (i) the first practical example of utilization of a theoretical tool (therefore being useful for future designers), and (ii) hints on what could be further explored/extended in both RETAIN and TLDF.

We underline that we actually tested our application with some volunteers (aged between 8 and 10). Although their number does not allow a systematic evaluation, we obtained positive feedbacks from our testers. Children expressed enjoyment and found challenging to progress in the game, which they commented was a factor increasing their fun. We observed that children rapidly find out they have to cooperate to successfully complete a level, although not instructed to do that. To this end, the shared scenario was effective in coordinating their efforts. Another positive finding was that all our testers enjoyed the use of tangibles as interaction tools.

4.5.1 WaterOn! and RETAIN

Relevance. The game mechanics (i.e., the use of simple interactions relying on previous knowledge on touchscreen devices and tangibles) were designed to match the developmental level of our target players. The learning objective is clearly defined (the three states of water and the transitions among them) and the game fantasy is intrinsically related to the educational goals, thus preventing the focus to shift away from the targeted contents. Instructional units are set in context with previous learned material (scaffolding) and learners and have direct links with the real lives of players.

Embedding: The educational content is endogenous to the fantasy context, i.e. the story and gameplay are tightly coupled with the information we want to communicate.

Transfer. The keys to progress in the game are mastering the instructional elements, which are introduced in a hierarchical manner, and using active problem-solving approaches. The introduction of the heat token (level 1, melting), the moving button (level 2, vaporization) and the blow token (level 3, deposition) creates a gameplay hierarchy (increase of difficulty), which accompanies the learning of instruction elements (water melting, vaporizing and depositing). Furthermore, the emulation of realistic scenarios intends to foster the transfer between the learned contents and real life. [35] suggests reinforcing this transfer by introducing post acquisition events (e.g. by exploiting accessory educational material or reviews), which is an interesting aspect to be investigated in a future work.

Adaptation. The content is sequenced in such a way as to require players to identify old schema and transfer it to new ways of thinking. Indeed, the first three game levels put forth the basis for adaptation, which will be necessary to win the game. To finish the level four, players have to extend the learned state transition concepts, in order to gain a clear understanding of the water cycle. Moreover, the repeated use of tokens stimulates the reuse of concepts learned in the previous levels.

Immersion. The use of tangibles and the progressive presentation of mechanics (i.e., the introduction of new mechanics in each level) intend to maintain the cognitive immersion of the players. The game plot, the shared environment and animations aim to harness belief creation. Nevertheless, the achievement of a "fully involvement to invest in the belief", as referred by [35], needs to be further investigated.

Naturalization. In the preliminary tests, our users always asked us to replay the game. Besides being a positive indication of their attitude towards the game, replaying helps content retention and improves the speed of cognitive response. This, in turns, leads to positive effects in terms of naturalization, i.e. making it easier to use the acquired knowledge in novel scenarios. Clearly, further analyses are required to confirm this conjecture.

4.5.2 WaterOn! and the Tangible learning design framework

Concerning the **info processing** aspect, we designed the blower token to be visually representative (through a paper stick attached to it) and to function as a fan (blowing unidirectionally). In our tests players readily understood its use and, therefore, the metaphor we used. In addition, the tokens interaction generates both visual, and audio feedback, thus exploring different sensory channels.

On the **embodiment** perspective, the two first presented tokens *evokes the hot-cold image schema* developed early in life. Moreover, the navigation system uses the map-based metaphor, much adopted in multitouch interaction. Our initial testers did not report usability difficulties, which indicate the success of WaterOn! embodiment strategies.

Several measures were taken considering the **collaborative** aspect.

First, *the use of spatially separate but shareable individual territories and resources* is at the base of the game design. The tablets offer single manipulation over a common territory and allow to increase the number of simultaneous players, since they do not need to share the physical space over the same screen. In order to avoid parallel (rather than collaborative) behaviour, the shared screen displays the common resources (associated to the win-lose condition) and the position of other players, allowing the *organization of strategies, based on teammates activities*.

In addition, WaterOn! *prevents a single player from taking over the game*, what is guaranteed mainly through game balancing. The quantity of enemies is adapted to the number of players and their power, when they act in group, overcome the capabilities of a single player. Therefore, the artificial intelligence acts to group enemies and prevent a player to win alone.

Finally, the game design *does not permit fast-paced interaction*. The tools controlled by the tangible tokens have a limited speed of action, and the number of items to be used with direct touches is also limited.

A possible issue might be why all WaterOn! players have the same role, information and controls (what opposes the guidelines of the TLDF). However, the design of the fourth level requires players to *coordinate a strategy to act with different tools*, what intends to overcome this issue and, once more, harness collaboration.

4.5.3 Open questions

As we stated in the introduction of this Section, although the RETAIN model has been previously used to evaluate serious games [35, 177], our work is the first attempt to use it explicitly during the design process. As a result, some questions arose during design experience:

How to make the player interested in keep learning about the topic after the game experience? This point was not discussed in [35]; however, we think it would be necessary to develop strategies capable of stimulating the children interest after the game sessions. One promising possibility is the involvement of a teacher backing WaterOn! application, and suggesting some pedagogic support material correlated to the fantasy of the game. A successful example of such approach can be found in [106], which, however, still demand further scientific validation. Another point related to the same question is how to accommodate knowledge transfer, one of the relevant element of the Gagne's Events of Instruction, which forms the base of the RETAIN theoretical background. While we supported retention by providing game situations that require players to use the information learned in other formats, we found difficult to (and still have no solutions on how to) ensure that these pieces of information are generalized enough to be used in different situations and naturalized (assimilated and made automatic or implicit [35]).

How to assess the full involvement to invest in the belief (i.e. the full immersion)? Although [35] link this requirement to the achievement of the highest level possible of content embedding, we found hard to detect which strategies can lead to this full immersion (which is, as stated in Section 2.2.2, the creation of a belief in the enveloping fantasy of the digital environment). We suggest that immersion aspect in RETAIN can be re-modeled taking it account as well the flow concept [59]. In our opinion, this also represents a possible link between RETAIN and models more focused on the PX aspect, such as the Flow or the EFM models (Section 2.3.2). Therefore, a possible option worth to be analyzed (and assessed) could be to merge these model (i.e., RETAIN and Flow or EFM) to obtain “a model in which pedagogic and PX aspects are balanced” (as suggested in Section 2.4.1).

Concerning the collaborative dimension, we found that the guidelines in [167, 175] were clearly defined and useful. However, we think they do not completely enclose the collaborative design of the game. For example, we witnessed that during the first level played by all our groups of testers, although the majority of the players understood the need to collaborate, some of them initially attempted to simply complete their personal goals. Although this problem was readily solved, one possible solution to avoid it from the very beginning could be the introduction of challenges requiring multiple actions from different players. While this approach was successfully tested with young adults [166], further investigation on its adequacy to a children audience is needed.

Chapter 5

Sustain, a collaborative augmented reality game for sustainable development

As stated in Introduction, serious games are promising approaches for the development of effective tools to disseminate information and foster learning towards environment and development issues (which is a complex task, demanding the management of multiple inter–related aspects and different perspectives on the subject). In order to investigate this assumption, this Chapter details the development and assessment of a serious game, called Sustain, aimed at:

- fostering collaboration and communication among co–located players, and
- raising awareness about the complexity related to managing sustainable development

Therefore, the learning outcomes for Sustain are not related to the learning of specific concepts (as in WaterOn!, for instance). Instead, players are expected to experience the trade-offs and understand the complexity involved in planning for a sustainable future. In other words, rather than providing direct instruction to players, Sustain aims at engaging them in a complex system representing an urban area environment, allowing active knowledge construction. This way, Sustain intends to offer an experiential learning environment, which is (as discussed in Introduction) one of the characteristics that makes games interesting tools for the development of effective learning approaches towards sustainability.

Sustain design is based on different theoretical models: the *educational* aspect follows the guidelines derived in Section 3.5.1, while the *collaborative* aspect is based on several design patterns (detailed in the following Section 5.1) that focus on promoting collaboration in serious games. To the best of our knowledge, this work is the first to merge the aforementioned theoretical backgrounds and also the first SSG that joins multiplayer collaboration with augmented reality interaction and construction and management mechanics.

Related works are the construction and management simulation games discussed in Section 3.3.1. Among these games, the closer to Sustain are EnerCities [105] and Futura [104], where players have to simultaneously handle several aspects (energy generation, housing, pollution...) in order to keep the sustainable development of an urban area. Qualitative and quantitative evaluation of both of these games highlight their effectiveness in offering enjoyable experiences and increasing awareness towards sustainability issues [104, 105]. As for the use of AR technologies in tackling sustainability learning, we also report that other works followed a similar approach. For instance, in 2013 McDonalds Germany released the mobile app *McMission*, in which visitors, by playing AR mini-games, receive information related to the societal and environmental projects in which the company is involved [178]. In spite of representing interesting approaches, Futura is the only one focusing on the collaborative dimension. A major difference between Futura and our approach is in the gameplay, which is fast-paced in Futura (a typical session lasts 3 minutes), while Sustain favors a slow-paced gameplay with turn-based mechanics and no time constraints.

Finally, linking the specific objectives of this investigation with the general ones of the dissertation, we first recall two of the questions aroused by Chapters 2 and 3.

- Which are the design models most suited to help sustainability serious games meeting their pedagogical goals?
- Since collaboration among users is a relevant dimension for learning, which are the design elements and the technological tools that can foster such cooperation?

Regarding the first question, we detail how Sustain design was informed by the chosen design model and, then, verify the achievement of the game's pedagogical goal. We expect this approach to be in line with the indication identified in Section 2.4.1, which stated the need for the design of educational games based on the existent models. A similar approach was taken concerning the second question, as we present the theoretical background behind the collaborative aspect of Sustain, and then discuss whether players successfully collaborated in an experiment. Hopefully, this discussion is of interest for game designers interested in informing their own future SSGs, both in pedagogic and in collaborative aspects. Furthermore, we hope Sustain to be of interest for the community of educators, since it is a collaborative experiential learning tool, which (to the best of our knowledge) presents a different approach in comparison with others SSGs.

5.1 Design guidelines for Sustain

As far as an educational serious game is concerned, its design and development should be based on sound theoretical models that encompass theories from both pedagogy and game design fields. As the pedagogical background related to this aim has been already introduced in Chapter 2, in this Section we will focus on the game design elements that were specifically guiding our development. These design guidelines were carefully selected after reviewing the literature related to the two main aspects considered in our research, i.e. collaborative learning and sustainability (or complex system) learning.

As for the collaborative dimension of the game, several features of Sustain were based on those from WaterOn!. For instance, the projected screen is aimed at offering a shared understanding of the scenario, and allows players to monitor each other's activities. Sustain also employs a slow-paced interaction, and prevents a single player from taking over the game (further details in the following Section 5.2). However, during the design and brief testing of WaterOn! we identified that these features "do not completely enclose the collaborative design of the game" (see Section 4.5.3). Therefore, for Sustain design we also employed several design patterns and key concepts derived from different models [179–182]. These design elements are briefly described in the following.

- *Complementarity.* The game should offer different roles that players can choose and each of them should be provided with specific actions and skills that are complementary with that of other roles [180]. This design pattern has two affordances. First, it helps a player to be more involved into one type of role and, second, it strengthens cooperation and communication among roles, which are necessary elements to effectively coordinate players complementary actions.
- *Shared goals.* This is a simple design pattern used by many cooperative games [180]. It consists in defining one or more common goals for all players, which, therefore, should be completed in group. Shared goals favor players' teaming up and finding creative solutions for the challenges to face. This design element is often used in conjunction with another one, the availability of *limited resources*, which should be carefully managed in order to reach the shared goals.
- *Trace payoffs back to their decisions.* Players must be provided with the possibility to reflect on the consequences of their actions [182]. This can be done, for instance, by introducing game breaks where summary information about the game status is provided. This key concept is particularly relevant since players should be put in the condition to experience expectation failure, which happens when they find out that the outcome of their actions is not as good as they expected, or even turned to be detrimental.
- *Gathering gates.* The game should provide points or situations in which players are forced to wait for others, since they might only continue together [181]. In spite of the possible drawback of faster players being annoyed while waiting for slower peers, the use of the gates guarantee that players receive sensitive information at the same time.

In addition to these collaborative-based design guidelines, several other elements were taken into account to help players achieve the planned educational objectives. These decisions were mostly based on the guidelines for educational games derived in Section 3.5.1. In the following we briefly summarize them.

First, in order to facilitate the transfer of game-based learning to real-world contexts, the designer should consider the *contextualization* of the game activities. This requires not only a *thematic contextualization*, i.e. the creation of a real–life like scenario that considers simultaneously all dimensions (economical, ecological and social) of the sustainability issues, but also a *player contextualization*, i.e. granting them the possibility to assume real–life roles, each with its own viewpoint over the problems discussed. This is aligned with Piaget's theory of cognitive development (previously presented in 2.2.1), since contextualized game activities allows players to build new schemes (accommodation), based on the comprehension of previous existing ones (assimilation).

Second, in order to be more engaged in the experience, the game should *empower* players, allowing them to exert full control on the game system and act as freely as possible. Two design guidelines might 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.

Finally, the game should promote meaningful *social* interactions among players, which help to promote knowledge production and enhance creative thinking and interpersonal communication. Social interactions can be improved with the introduction of mechanics that demand multiple players to communicate and cooperate within the game world.

5.2 Game description

Sustain is a city management game for three players. We actually believe that Sustain could engage a bigger number of players, as several stakeholders are involved in sustainability issues (for instance, politicians, educators, community representatives, and so on). However, considering the specificities of the needed setup (e.g. each player needs a tablet with enough computational power to depict real-time augmented reality scenario) and our available resources, we decided that three would be a valid value for our purposes.

In Sustain, players goal is to expand an urban area maintaining a sustainable balance between different elements, such as housing, production, resource exploitation (coal, oil, natural gas, renewable sources, and money), environmental pollution, quality of life, land development and population growth. The game rules aim at guaranteeing the relevance of sustainability practices, since a non-sustainable city causes unsatisfied citizens to leave, thus leading players to defeat.

As an educational game, Sustain might be played in formal learning environments, as part of a mediated teaching activity. However, as the educational goal is raising awareness about the complexity related to managing sustainable development (rather than teaching specific concepts), we believe that Sustain might also be played without any human mediation, and in different locations, as public venues, museums, and so on [1]. The only obstacle to play Sustain at home is its specific setup (demanding a computer as a server, and three tablets connected to the same network), which might difficult the game installation.

Sustain requires effective collaboration among players to fulfill the goals, and this collaboration is also crucial to achieve the educational purpose of the game, i.e. understand the complexity of managing a (sustainable) urban area. Concerning the target audience, as identified in previous Section 3.3.1, the interaction acts of CMS games are simple enough to be understood by youngsters. However, as cognitive capabilities still change until adulthood, in this study we considered a mature game audience, which is expected to understand the environmental impact of their decisions and to handle the mechanics of managing different interwoven elements. It seems promising a future investigation exploring Sustain impacts in younger audiences (which was not possible to be made in this thesis due to time constraints).

In the game, players can assume one of three roles: mayor, ministry of energy and ministry of agriculture. Each role has its own specific set of actions, which are progressively made available to the player as the game advances. The characteristics of these roles can be summarized as follows:

- The mayor can take decisions related to the construction of houses, factories, public transportation and leisure areas.
- The responsibility of the ministry of energy is to develop an energy matrix based on both renewable (wind and solar) and depletable resources (coal, gas or nuclear fusion). He is also responsible for the waste disposal of the urban area.
- The ministry of agriculture defines the government policy on agriculture, forests and food production and he is also responsible of leading educational

[1] In Sustain current development stage, the experiments employed tutorial sessions with players, in order to clarify eventual UI questions before actual game sessions (see Section 5.3.1).

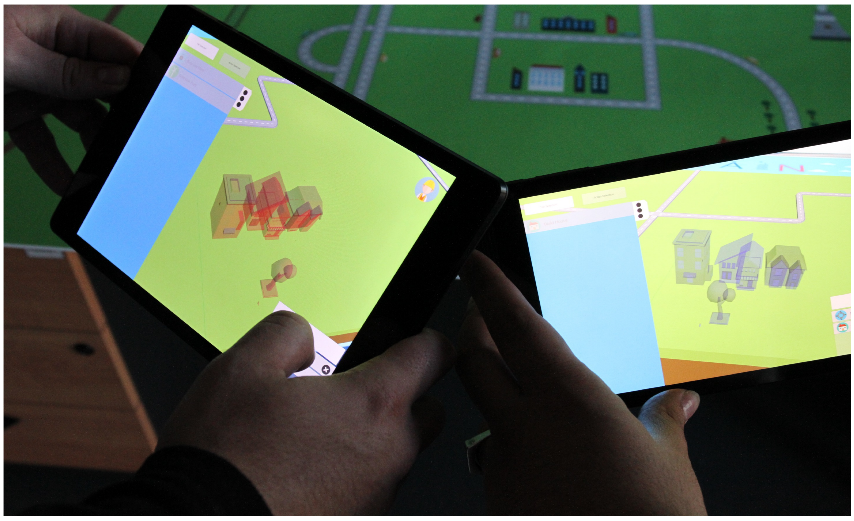


Fig. 5.1 Sustain different views allowed by AR. Blue indicates that the player can interact with that construction.

campaigns to raise public awareness about healthy eating and increase consumption of healthy foods.

These roles were chosen for mainly two reasons: first, to offer contextualization, as they relate directly with real-life policy makers, and second because they allow the establishment of mutual dependences among players (i.e. actions from three players are required to develop the city in a sustainable way). Finally, we also tried to balance the roles to be attractive to game audience, in order to foster game re-playability (players could, for instance, be willing to re-play with different characters).

Visualization and interaction with the game scenario exploit marker-based Augmented Reality (AR) on mobile devices (tablets). The rationale of leveraging on AR is that it allows the customization of players' view, according to their specific role. For example, every construction that a specific player builds is depicted in blue to himself, indicating that he can interact with it, and in red to others, meaning the opposite. This way, at any moment, each player may identify exactly with which constructions he/she may interact (see Figure 5.1). This way Sustain intends to enhance the representation of different points of view over the city, a feature that is a concrete challenge to face in sustainability games [4]. Despite working as a proof of concept, we believe that AR could be further explored in Sustain. Concerning this matter, the following Chapter 6 suggests indications for future investigations.

The marker used to register the augmented view is a large image representing a sketched urban area and its suburbs, printed on a A0 paper (84.1 × 118.9 cm) and fixed on a table. These dimensions intend to offer adequate space to accommodate three players, which are then free to move inside the physical game environment. Furthermore, the marker size allows a robust and stable marker tracking from various distances and viewing angles. Beside the tablets, Sustain features as well a projected virtual environment. This screen shows the overview of the current development state of the urban area, a summary of the tentative player actions, and the current game status. Figure 5.2(A) shows an overview of a game session, with the three players and their tablets, the AR marker, the projected scenario and the camera used to record the interaction (for evaluation purposes). Figure 5.2(B) displays a closer look on the projected virtual environment.

The game scenario is divided in two interrelated areas, the city and the farm. Each area is composed by a grid of 4 × 4 blocks. Players interact with these areas through the tablet interface, selecting actions (at the left of the screen, see Figure 5.3(A)). Each action is associated with a cost (in terms of funds) and is characterized by a specific effect on several internal game variables, such as transportation, food, energy, pollution, leisure, housing and working places (further details on Sustain variables in the following Section 5.2.1). These (positive or negative) effects are made readily available to the player through the game interface (see Figure 5.3(B)). In this way, she/he can analyze the expected outcomes of her/his decision and possibly discuss them with her/his peers to find a common agreement on the game politics.

Table 5.1 presents all actions available for players in each turn. Actions of turn 1 are intended to create the basic infrastructure for the city to receive the first incoming citizens. At this turn players should provide city with housing, working places, energy and food. Also, at the first turn, the energy minister is already confronted with an important decision: a coal plant generates more energy than an eolic plant, but at a higher environmental cost. Actions of turns 2 and 3 complete the city infrastructure by adding the support to the variables transportation and leisure. Turn 4 introduces green actions, i.e. actions capable of increasing the environmental health of the city. Finally, at turn 6, for the mayor and the energy minister are introduced actions of high impact, i.e. actions that produce great gains but at a high environmental cost. In general, we designed the actions aiming at enhancing player engagement, by offering progression of challenges (actions are progressively presented) and, whenever possible, making players face sustainability-relevant decisions.

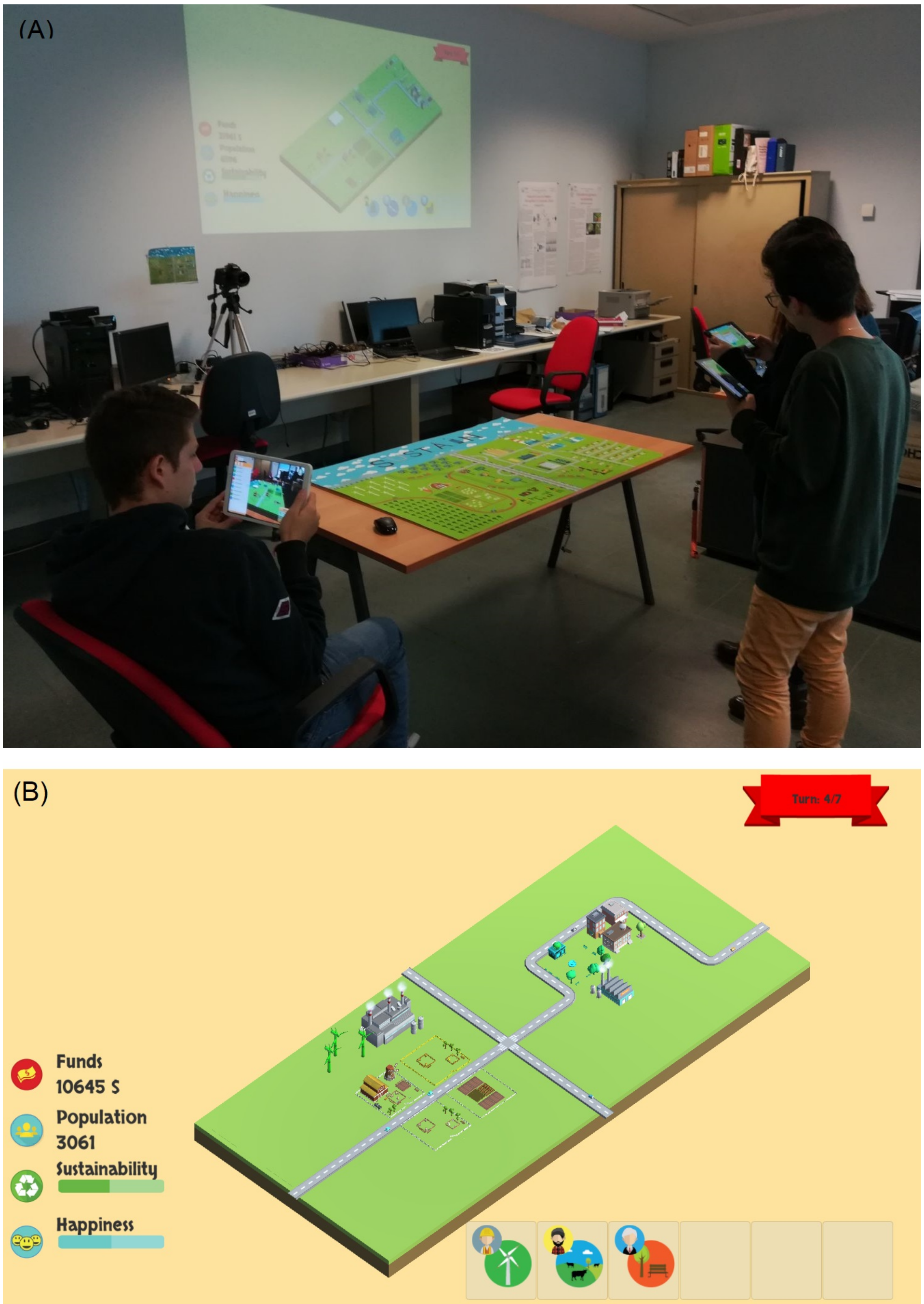
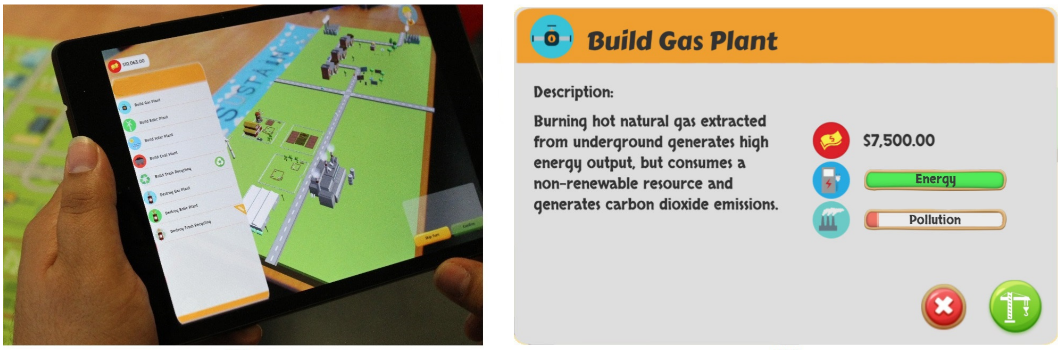


Fig. 5.2 Sustain game settings. (A) An overview showing the three players, the AR marker and the projected scenario. (B) A detail of the projected scenario, displaying the available funds, population number, sustainability and happiness levels (bottom left), and the number of turns (top right).



(A) (B)

Fig. 5.3 The player view.

The game is played on 7 turns. It was the minimum amount of turns that we deemed enough to represent all the actions that we had designed. As the interaction with Sustain is made (generally) standing and holding a tablet, and players have no established time limit to discuss, we wanted to avoid too long game sessions, which could fatigue the players.

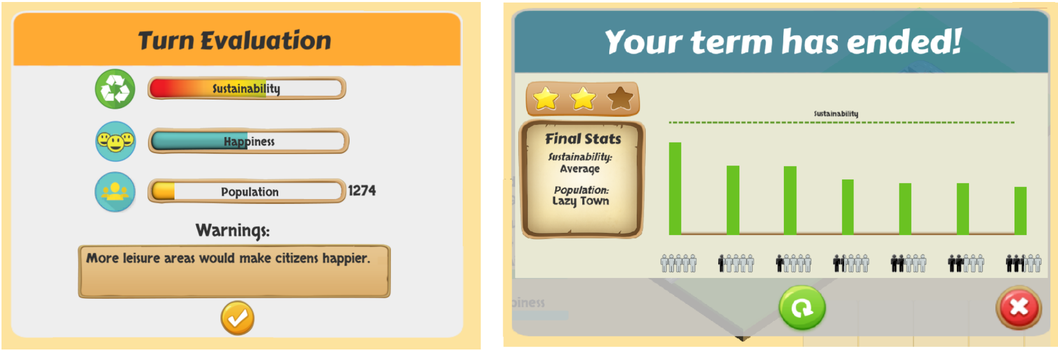
In each turn, players can take collectively six actions (with a maximum of two actions per player). Imposing a limit for the number of actions was made to enhance collaboration: in situations where several actions are needed, players should have to articulate themselves to choose the most relevant ones. Limited actions also prevent one player to "take over" the game, which is was a requirement identified during WaterOn! design. This way, one cannot just execute random actions until the group funds are finished. As selecting and executing actions are the main interaction acts between players and Sustain, we did not want to allow only one action per turn, to avoid players frustration (caused by too limited interaction). Therefore, the choice for two actions per player (and, consequently, six actions per turn). This way, players can also freely decide whether they want to take zero, one or two actions. The only constraint for picking a certain action is the availability of funds to implement it, which is a common resource that players should carefully manage. During the turn, players have the possibility to modify their choices, withdrawing a suggested action and possibly opting for a different one. The turns have no time limit and they end when the three players agree on completing their action selection process.

Once the turn is finished, the game is paused, each players' action is executed, and its aftermath is evaluated in a joint debriefing session. This is the moment when players focus on the shared screen, which displays:

Turn	Player	Action	Variable affected	Area
1	Mayor	build houses	housing	city
		build factories	working places	city
	Energy	build gas plant	energy	farm
		build eolic plant	energy	farm
	Agriculture	plant field	food	farm
		construct pasture	food	farm
2	Mayor	build roads	transportation	city
	Energy	apply solar panels	energy	city, farm
	Agriculture	build farms	food, working places	farm
3	Mayor	build leisure area	leisure	city
	Energy	build coal plant	energy	farm
	Agriculture	advertise healthy food habits	food	city
4	Energy	build thrash recycling facility	-	city,farm
	Agriculture	plant forest	-	farm
6	Mayor	build airport	leisure	city
	Energy	build nuclear plant	energy	farm
	Agriculture	build small farmers' markets	food	city

Table 5.1 Sustain actions (turns 5 and 7 do not present new actions).

- the influence of players' actions on the city current status; this status is characterized by three external variables (i.e., *sustainability*, *happiness* and *population number*), whose value is a function of the game internal variables and it is controlled by a fuzzy logic system, whose purpose is to introduce a certain degree of uncertainty in the game sessions
- a set of tips, generated by an internal artificial intelligence module, aimed at issuing warnings about critical status or at providing clues for improving the game variables during the following turns (see Figure 5.4(A)).



(A) (B)

Fig. 5.4 Feedbacks displayed in the projected scenario. (A) Turn evaluation, depicting levels of sustainability and happiness, population number, and hints for the next turn; and (B) end game evaluation, which summarizes the per turn value of the game variables (sustainability and population) and displays a star rating of the overall score.

This debriefing session is aimed at opening and fostering a critical discussion about the current development politics, thus offering players a chance to redefine or improve them.

After the seven game turns have been played, the win or lose condition is computed on the basis of the actual number of dwellers. Figure 5.4(B) shows the end game screen, which summarizes the results of each turn and provides a star rating of the overall score.

5.2.1 Artificial intelligence and sustainability dynamics

Sustain artificial intelligence module is aimed at simulating sustainability-relevant dynamics. It manages the whole game overall operation (i.e. the variations on sustainability and happiness levels, and the arrival of citizens every turn) and the feedback presented to players at every debrief session, through a fuzzy logic based control. The fuzzy logic introduces uncertainty to the game sessions and, being based on linguistic terms and rules (which are similar to human reasoning), are easy to model, develop and debug [183].

The Sustain AI module it is composed by: seven internal variables (transportation, food, energy, pollution, leisure, housing and working places), and three external ones (environmental sustainability, citizens' happiness and incoming citizens). All variables (internal and external ones) were defined through triangular or trapezoidal membership functions (for further details on fuzzy logic definitions see [184]), which are simple to calculate [183], and still enough to represent our intended behaviour.

The internal variables are those whose values are directly changed by player in-game actions. Six of these (transportation, food, energy, leisure, housing and working places) are defined as a rate according with the current population (see Figure 5.5 (A)). Thus, for instance, if energy is currently 0,5 it means that the city is generating energy enough to only half of the population, while the value 2 would mean that the city can generate energy to receive twice the current population. In its turn, the variable pollution (see Figure 5.5 (B)) is defined by the subtraction between: (i) the environment capacity of pollution absorption (which may be increased by the actions *plant forests* and *build thrash recycling facility*), and (ii) the sum of all pollution impacts of user actions. The values for pollution are based on the Air Quality Index defined by the United States Environmental Protection Agency [185]. Additional variables (such as water management, security and education) were identified in brainstorms realized inside the design team, and while reviewing CMS games detailed in Section 3.3.1. However, these variables would add significant complexity to the development of Sustain. Water management is the aim in more specific games, as Catchment Detox, and education and security are multifaceted aspects that we did not want to reduce through simple actions as “build police station” or “build school”. Therefore, considering the small design team and also the time constraint to the development of this project, we deemed the chosen variables enough to depict an initial overview of the city needs.

The three external variables are those which player does not have a direct control: environmental sustainability, citizens’ happiness and incoming citizens. The external variables are the outputs which inform the player (as can be seen in see Figure 5.4(A)) and their values are defined by a composition of several internal ones. These external variables enable Sustain to offer a feedback involving different aspects related to sustainable development: environmental (through the variable environmental sustainability) and social (through population happiness).

As can be seen in Figure 5.6, the external variables present a hierarchical correlation: environmental sustainability is composed by transportation, food, energy and pollution, while citizens’ happiness comprises environmental sustainability plus leisure, and the incoming citizens’ is formed by citizens’ happiness, housing and working places. This way, the number of citizens that arrive to the city in every round

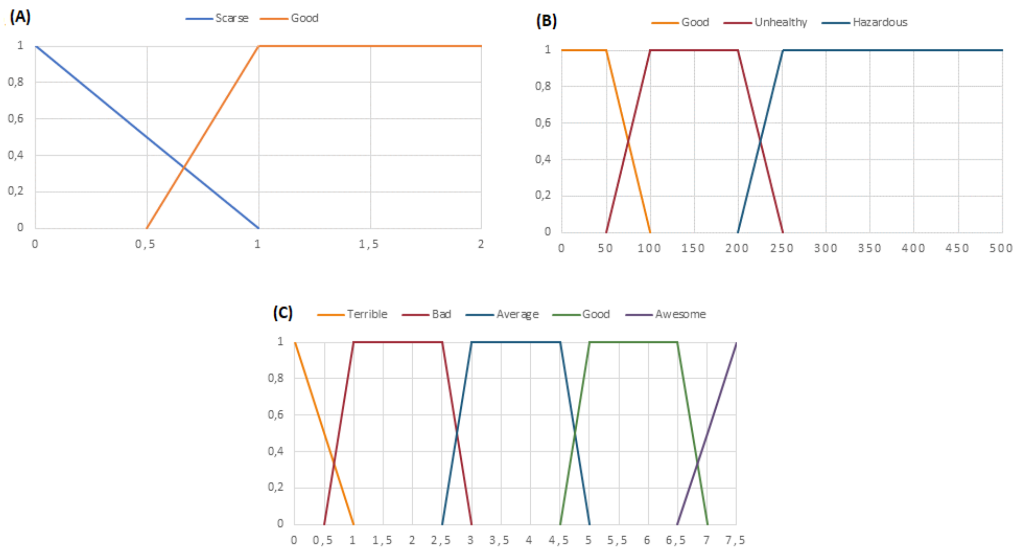


Fig. 5.5 Membership functions of Sustain variables. (A) internal variables transportation, food, energy, leisure, housing and working places; (B) internal variable pollution; (C) external variables environmental sustainability, citizens' happiness and incoming citizens

– what ultimately defines whether the players achieved the proposed objective or not – is a function of all the variables of the system. With this approach we intended to attach the main game goal (evolving the city) with the care for all the game variables.

The correlations among external and internal variables are expressed in the form of 41 fuzzy rules, which are documented in Appendix D. These rules were designed to highlight the importance of the variable pollution, as it summarizes the negative impacts to the environment. First, when pollution is in *hazardous* level, sustainability is necessarily in the level *terrible*. Moreover, only with pollution in *good* level, it is possible to have sustainability in levels *good* or *awesome*. This way we intended to stress the importance of players balancing the needs of the city (in terms of transportation, food, energy, leisure, housing and working places) but without forgetting the environmental protection.

5.2.2 Sustain and the design guidelines

Keeping as reference the key concepts introduced in Section 5.1, we defined the following basic design strategies to support collaborative learning in Sustain.

- *Favor the development of social skills*

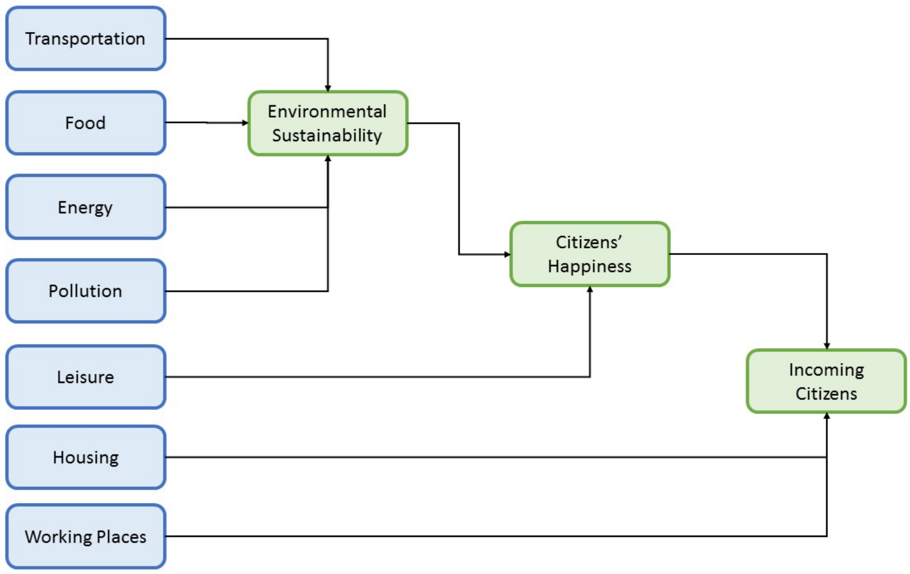


Fig. 5.6 Sustain variables organization under fuzzy-logic AI module. Blue represents internal variables, while green stands for external ones.

Since *social interactivity* among players is fundamental to both collaborative and pedagogic goals of Sustain, we considered several design elements aimed at promoting it. First, the game setting is designed to enhance the co–located experience, as the physical space is defined to accommodate the players and enable their freedom of movement. We deemed this important, as co–located gameplay might improve the level of communication between players and the sociability between unacquainted individuals [186]. In addition, the management of *shared and limited resources*, whose scarcity can lead to the impossibility of advancing in the game, might stimulate discussion to find a collective agreement about the relevance of the actions that could be chosen at a specific moment. Finally, the *complementarity* of players' roles is aimed at establishing mutual dependencies among them, which may favor collaboration and exchange of information aimed at reaching a common success.

- *Players should be allowed to reflect on the consequences of their actions*

Enabling processes of co-construction of knowledge and creating spaces for reflection and group discussion are other relevant factors that help achieve the learning outcomes of Sustain. This requires first to enable players to take informed decisions (rather than randomly picking actions) and, then, to allow them to observe the outcomes of their actions and to collectively reflect on them. These issues have been tackled in the following ways.

We implemented two mechanics aimed at helping players to take informed decisions. First, players can decide which actions to take with no time constraints and with the possibility to undo their choices, possibly as a consequence of their discussions and interactions with peers. Second, for each action selectable, players are informed (through the user interface) about its positive and negative effects on the game status variables (e.g. housing, energy generation and pollution). These pieces of information are both textual and visual.

In order to ensure a collective discussion on the actions' outcome, Sustain employs debriefing sessions that are presented after a *gathering gate*, i.e. the end of each turn. This guarantees that all players receive the common information at the same time. During these sessions, the projected screen offers players a shared understanding of what has been achieved and how far they are from the objective. This allows them to *trace payoffs back to their decisions* and facilitate discussion and decision-making processes. Furthermore, visually displaying the aftermath of players' actions aims as well to deliver what Sweetser calls third order emergence [187], *i.e.* the possibility to observe on a global scale the effects of dynamics happening at a local scale.

The subdivision of the game in turns allows as well to take into consideration another relevant design concept, i.e. *adaptivity*. When a new turn starts, players have to adapt to the novel situation created by their previous choices. Furthermore, the introduction of novel actions that can be performed, force the players to mentally adapt to the new features available.

- *Contextualize the gameplay and the game players*

Thematic contextualization is stressed in the game through the emulation of real–life scenarios and actions, and game rules guarantee that non-sustainable practices lead to defeat. *Players' contextualization* is achieved by allowing them to assume different policy—maker roles. Furthermore, the AR–based game platform offers slightly customized views for each player in order to highlight the different points of view over the same problem, which (as we stressed before) is a critical issue in sustainability scenarios. Additionally, AR is reported to increase immersion in educational environments [188] and may also enhance social interactivity in collaborative interactions [189], all factors that can contribute to the pedagogic success of the game [139]. Finally, besides offering different roles, the game *empower* players by allowing them to freely take their decision and explore alternative ways to fulfill their common tasks.

- *Players must feel their importance in the experience*

If players do not feel their relevance in the game, they are not motivated enough to collaborate with others or to improve their performance. As a consequence, they are unlikely to learn anything from the experience. The guidelines we implemented for supporting player empowerment were also aimed at both highlighting players importance and keeping them engaged in the gameplay. To this end, we also carefully tried to balance the actions available for each turn and each player, in order to provide them in every moment of the game with a list of significant and relevant choices to pick.

- *Players must learn through a ludic experience*

Sustain is designed to facilitate players to directly experience the complexity and difficulty of balancing environmental and human needs in sustainable development. This way Sustain is balanced to be challenging. It should be difficult to win the first time. Losing the game advances the learning outcomes since players directly experience the difficulty of balancing environment and population (which remains true even if players only play once). Players win once they begin to understand the complexity of the problem and develop strategies to address it. This design strategy is in line with experiential learning in which players learn from a concrete experience, and then test out their ideas through their continued experience of playing the game. The result is a multiplayer game that resembles stakeholder driven urban planning and enables opportunities for experiential learning whether players win or lose.

5.2.3 Implementation details

Concerning the technical aspect, Sustain (similarly to WaterOn!) has been implemented into Unity 3D, a cross-platform game engine. Multiplayer collaborative interaction has been managed implementing a client-server architecture, in which the server handles the simulation state and controls the projected screen and the clients are the players' tablets. Finally, we used as AR engine Vuforia, a software library that can be integrated into Unity, thus supporting the game deployment on different mobile platforms (Android, iOS and Windows Phone).

Given the small size of the development team, we approached the design and implementation following the SCRUM agile methodology [190] and adopting an iterative process, which included several cycles of:

- conceptualization, which included brainstorms and discussions around the key design aspects aimed at guaranteeing both the informative and engaging aspects of Sustain;
- prototyping, where the design choices were implemented into playable prototypes (in the first iterations) and complete game prototypes (as soon as all the main functionalities could be merged together);
- playtesting, which involved internal teams, target audience, experienced players and usability experts;
- evaluation, where the results of the playtest were critically reviewed in order to provide feedback to the design and implementation phases.

This iterative process allowed not only the rapid identification of errors and design flaws, but also the improvement of our original idea and of the usability and user experience within the deployed version.

5.3 Evaluation

The evaluation of Sustain aimed at answering the following research questions: (i) is the game capable of obtaining the expected learning outcomes and (ii) does Sustain represent an effective tool to support and foster collaboration among users? In order to investigate these questions, this Section presents the adopted methodology for the experiments, and the following Section 5.4 presents and discusses its results.

5.3.1 Experimental methodology

We collected data from 57 participants, which were a convenience sample from Italian and Brazilian tertiary students of psychology, computer engineering and architecture. In the following we detail the instruments and the procedure adopted in the tests.

Instruments

Data was collected through 3 instruments:

First, we used pre-test/post-test questionnaires aimed at evaluating players achievement of Sustain educational goal. The pre and post tests had both questions where players were requested to write the answers and others whose responses were based in 5 point-Likert scales (which is the minimum number for scales to be reliable [191]). The pre-test also had an initial section to gather participants name and playing habits.

Second, during the game we collected game analytics (GA), i.e. in–game data related to the players' and game activities in terms of play and debrief time, game variable values, UI interactions, number of analyzed, confirmed and withdrawn actions and so on. These data were compiled in a report for their analysis during the assessment phase. As previously discussed in Section 3.6, GA is a promising technique, which, however, is still not extensively applied in SSGs. Therefore, we believe that the discussion generated from GA applied in Sustain might be an interesting contribution to the community of SSGs developers and researchers.

Finally, the game sessions were also video recorded for later analysis. The video annotation process followed the model proposed in [179] that defines six Cooperative Performance Metrics (CPMs) to evaluate the effectiveness of collaborative games, where each CPM relates to a set of specific observable in–game events. These CPMs are the outcome from an iterative process involving several reviews of game researchers and game designers working in relevant companies, as Electronic Arts and Square Enix. The CPMs were validated for two independent researchers, and were also applied in practice in several studies [179, 192, 193]. For these aforementioned reasons we deemed the CPMs a comprehensive and rigorous methodology for the reliable coding of qualitative data from video.

We highlight that, due to various problems during the acquisition of the experimental data (bugs in the GA recording or corrupted videos), 3 out of the 19 groups had to be ruled out from the GA and video analysis.

Procedure

We invited the participants to come in groups of three, which generally consisted of students from the same subject who knew one another, but had not previously worked together. Testers gave their informed consent and compiled the pre-test questionnaire.

Before playing the game, we started a "training session" where volunteers received information related to the game context, the various roles they can assume and step–by–step instructions on how to use the application interface. These instructions were delivered through a "live" tutorial based on the first two game turns. No explicit indications to discuss the selection of their actions or suggestions to establish common development policies were given to players during this phase. This initial training step was aimed at guaranteeing the comprehension of the basic game mechanics and UI interactions in order to avoid, as much as possible, any possible bias in the results due to problems related to the in–game management of these elements.

Then, each group played Sustain once. While they were playing one researcher silently watched their interaction, and talked only when players asked for information about the game usage (e.g. rules and interface). A second researcher was responsible for the technical infrastructure (i.e. internet and video recording of the play sessions).

Finally, we asked players to compile a post–test questionnaire (similar to the pre–test one) in order to analyze how the game experience influenced the comprehension of the main challenges related to sustainable development.

Threats to validity

The experiment utilizes a convenience sample and, therefore, may not be generalizable. We also recognize that the number of samples are relatively low and represent a specific subset (i.e. University students) of our target audience (i.e. mature). Even if we try to mix students from different areas (psychology, computer engineering and architecture), we likely miss certain types of users (e.g. workers, households and so on). These factors limit our ability to generalize our results. However, for the purposes of initially studying our design, and identifying important factors, we hope that the sample and the adopted methodology were adequate.

5.4 Results and Discussion

This Section presents the experiment results and the associated discussion. First, Section 5.4.1 presents the GA findings and our conjectures about Sustain game experience. Then, Sections 5.4.2 and 5.4.3 analyze (respectively) pre/post tests and video recordings experimental data in order to formulate suitable answers about the game's capability of obtaining the expected learning outcomes and its effectiveness as a tool to support collaboration among users.

5.4.1 Game analytics findings

At first, GA findings allowed the investigation of a problem concerning Sustain game experience: the players focus on their in-game activities. By unfocused players we mean those randomly picking actions (not assessing their impact), rather than carefully selecting them, in agreement with others. Such unfocused players would unlikely obtain any desired learning, and would most probably hamper the collaboration with peers.

Our general impression is that gamers were actually focused on their in–game activities. We think that there are at least three GA evidences that allows to support our impression, which are based on: (i) the average number of action descriptions analyzed by players during each turn, (ii) the average number of times players analyzed the values of the game variables and (iii) the average number of withdrawn actions (summarized in Table 5.2).

The number of action descriptions analyzed is interesting because it provides an indication whether players were carefully comparing the different options before making their decisions or simply picking a random option. To extract this information, we analyzed the analytic data collected during the session, by first pruning all action and variable description view events whose duration was less than 2 seconds, a length which we deemed insufficient for a careful inspection of the information displayed on screen. The number of discarded events was less than 1% of the total, which we considered as an indication of the fact that accessing this information was made for the purpose of effectively analyzing it. Another thing we examined was the distribution of actions analyzed over the possible choices offered. What we can observe is that, at the beginning of a new turn, players tended to analyze all the new options offered for each turn, which were clearly highlighted in the user interface. We also verified that the number of times a player inspects repeatedly the same action in a turn are minimal (less than 2% of the events), which can be interpreted as an indication of the fact that the information displayed was clear and sufficiently compact to avoid a cognitive overload, i.e., players could remember easily the effect of each action on the system variables, which is the information needed to select suitable actions according to the development policies chosen by the individual or the group.

The analysis of the current values of the system variables is strictly related to the action selection issue. We recall that the information about the system variable values is first presented to the user during the debrief session at the end of each turn, where the aftermath of the selected actions is recapped and their effects on the environment are illustrated, together with hints issuing warning on critical variable status or providing clues for improving results in the next turn. Then, after the first turn, this information is also accessible to players, any time they like, directly from the devices (which explains the zero values of this item in Table 5.2 and for the first round). As it can be seen, this feature has been frequently exploited by players, with an average number of 0.7 views per player and turn.

In conclusion, it can be seen that the average number of action descriptions analyzed by players during each turn was about 120% of the available ones. We think that, combined with the previous result of 0.7 system variable views per turn and player, this is a positive indication of the fact that volunteers were carefully comparing the different options before making their decisions.

We also think that another interesting indicator of the careful selection of actions is the number of withdrawn actions averaged per turn over all the sessions (4.1[2]). Withdrawing an action usually means that the player found a better option or she/he

[2]This information was, again, obtained from the game analytic data collected during the game sessions.

opted for an alternative after discussion with her/his peers. Another option is that the player withdrew an action immediately due to an input mistake. In order to disambiguate the two cases, we (arbitrarily) labeled as mistakes those withdrawals happening less than 10 seconds after the action was chosen. The percentage of mistakes (13%, or 4 over 29) allows us to confirm with some confidence the first hypothesis (i.e., that the action was withdrew since a valid alternative was found).

Table 5.2 Summary (per turn and role) of actions available and average number (over all groups) of actions selected, variable check and action withdrawal.

Turn	*Role*	*Actions available*	*Action description views*	*Variable check*	*Withdrew actions*
1	Agriculture	2	4,0	0,0	0,1
1	Energy	2	3,5	0,0	0,1
1	Mayor	2	2,7	0,0	0,1
2	Agriculture	3	3,3	1,1	0,1
2	Energy	3	6,2	1,4	0,1
2	Mayor	3	3,7	1,3	0,1
3	Agriculture	4	5,6	0,3	0,2
3	Energy	4	5,9	0,6	0,0
3	Mayor	4	3,1	0,1	0,3
4	Agriculture	5	3,4	0,3	0,0
4	Energy	5	4,7	0,6	0,1
4	Mayor	4	2,7	0,4	0,1
5	Agriculture	5	4,4	0,6	0,0
5	Energy	5	5,3	0,8	0,0
5	Mayor	5	2,3	0,3	0,0
6	Agriculture	6	5,6	0,9	0,0
6	Energy	6	6,6	0,8	0,1
6	Mayor	5	4,0	0,7	0,4
7	Agriculture	6	11,0	0,8	0,1
7	Energy	6	7,3	0,9	0,0
7	Mayor	5	6,0	0,8	0,2

Gameplay issues

The in–depth analysis of GA allowed us to identify as well some problems in our implementation. Although we carefully tried to balance the available actions among roles (in terms of number of options and associated costs), when we analyzed the distribution of turn skipped among the roles we found a relevant unbalance. The role who took this decision most frequently is the ministry of energy (64%), followed by the ministry of agriculture (28%) and the mayor (8%). When reviewing the video recording, we noticed that in the second and third round, the ministry of energy is often faced with a difficult situation since his/hers actions have an average cost higher than that of other players. Thus, he/she is either in the impossibility to perform his/hers preferred action or, acting in accordance with peers, decides to preserve the available resources in order to grant in the next round a wider set of playable options for all roles. As for the skip rate of the ministry of agriculture, users reported a relatively lower novelty (thus, a lower "attractiveness") of the choices introduced in the middle turns compared to that of other roles.

5.4.2 Pre/post tests results and the effects on the learning outcomes

As detailed in previous Section 5.2, during Sustain gameplay players receive feedback in terms of: (i) environmental sustainability and (ii) population happiness. However, it was not Sustain's goal to make players identify explicit relations between these variables (environmental sustainability and population happiness) and the sustainable development of an area. Instead, as stated before, Sustain educational aim is to raise awareness on the *complexity* of managing an urban area.

In order to assess whether this educational goal was achieved or not, the pre/post test questions contained Likert scale items, based on the feedback variables (environmental sustainability and population happiness) and on the difficulty of balancing human and natural needs in the management of a city. Table 5.3 presents the statements and summarizes the results, presenting median and inter-quartile range for pre-test and post-test questions and the *p* value resulting from the Wilcoxon non-parametric test applied over the Likert scale items [3].

Statement	Pre-Test		Post-Test		p
	Median	IQR	Median	IQR	
(S1) Population happiness is important in the sustainable development of a city	4	1	5	1	0.3142
(S2) Environmental sustainability is important in the sustainable development of a city	4	1	4	1	0.1604
(S3) It is challenging to balance human and natural needs in the management of a city	4	1	5	1	0.0071

Table 5.3 Summary of Likert scale items and their responses.

[3] This is the methodology suggested by [194] for analyzing individual Likert-based questions

From the data summarized in Table 5.3, it can be noticed that IQR remained the same in all situations, while median increased by one in post-test conditions for statements S1 and S3. Therefore, this could be interpreted as a similar impact for statements S1 and S3. However, the Wilcoxon test identified statistical relevance only for the answers of S3. This way, we believe this is a quantitative indication that, other than identifying isolated concepts relations with sustainability (which is represented by statements S1 and S2), players understood that managing a city is a challenging multi-faceted task (statement S3).

Additionally, the post-test questionnaire contained a question in which players are requested to write about the identified challenges to the sustainable development of a city. The answers were analyzed through open coding, and results indicated that several players reported the difficulty in contemporaneously balancing the several (contrasting) elements involved. For instance, testers affirmed to be defiant to "make people happy and find balance between nature and production", and to "increase the population number, without exacerbating pollution levels". We suggest that these answers corroborate that players successfully understood the main educational message of Sustain.

5.4.3 Video analysis results and sustain effectiveness as a tool for promoting collaboration

Answering the second research question (i.e. does Sustain represent an effective tool to support collaboration among users?) requires an in–depth analysis of the player behavior during the game sessions. In order to perform such analysis, we first extracted pieces of information about the "qualified" time spent by players during the sessions. As previously stated in Section 5.3.1, these data were obtained by carefully annotating the video recordings of the sessions, according with the CPMs defined in [179].

In order to contextualize the proposed CPMs to the game scenario of Sustain, the following ones were used according to their original definition:

- *Laughter or excitement together*, when participants collectively express fun or excitement for a game related event.
- *Helping each other*, any occurrence of helping events.

	CPM1	CPM2	CPM3	CPM4	CPM5	CPM6
AVG	0.042	0.022	0.002	0.000	0.400	0.086
VAR	5.9E-4	4.5E-5	3.4E-5	0.0	1.0E-2	2.5E-3

Table 5.4 Averaged percentage (first row) and variance (second row) of game time assigned to each CPM (Laughter or excitement together, CPM1, Helping each other, CPM2, Waited for each other, CPM3, Got in each other way, CPM4, Worked Out Strategies, CPM5, Global Strategies, CPM6)

- *Waited for each other*, when one player waits for the other to catch up
- *Got in each other way*, when the actions of one player interfere with the intentions of another player, hindering his strategy.

On the contrary, we slightly modified the definition of the following CPMs:

- *Worked Out Strategies*, when two or more player discuss on a specific action to take within the Sustain environment (apply, remove or confirm actions, skip turn).
- *Global Strategies*, when players discuss a general strategy to apply to the game even without taking a direct action.

In order to extract the CPMs, the session recordings were manually annotated by one researcher using ANVIL [195] and reviewed by at least a second researcher. Finally, the time spans related to each CPM were summed and normalized with respect to the session length. The averaged normalized results over all groups and their variance are summarized in Table 5.4.

Despite the relatively low number of samples (which might affect negatively the study, increasing the margin of error), these data seem to indicate that Sustain is an effective cooperative tool. On average, about 50% of game time was dedicated to defining and discussing game strategies, either at global or local level (sum of CMP5 and CMP6). This evidence is supported by the high correlation (0.7, $p = 0.02$) between the final game score and the Worked Out Strategies (CPM5). In other words, groups which actively discussed their strategy and collectively decided which actions to perform tend to have better results in the game.

An in–depth analysis of CPM5 results can provide a more solid support to this latter statement. As it can be seen in Table 5.4, the variance of CPM5 is relatively low. As a matter of facts, most of the data are well centered around the average of the distribution, with the only exception of two evident outliers. If we remove these two samples from the distribution, the remaining ones are included in the interval 0.408 ± 0.071 (therefore close to the average value of 0.400 reported in Table 5.4). The first outlier is largely lower than this average (0.187) and the final score of the group was the worst among all players (and also significantly different, being 43% lower than the average one, while the score of the second lowest is "only" 22% below the average). Analyzing the video recording, we could observe that players in this group were mostly acting individually, with seldom moments of real communication and critical discussion. In other words, there was no effective collaboration within them, and this heavily affected the performances in the game. As a further indication, the second last group in terms of CPM5 was also the second last in terms of final score. Again, video analysis allowed us to verify the low quality of the communication and discussion in this case.

On the other hand, the second outlier is significantly higher (0.556) than the CPM5 average and the group is the runner-up in terms of final score. As a matter of facts, we could observe a fruitful discussion and collaboration among members which, again, reflected on the final score (this time, in positive terms).

Given the relevance of intra–group discussions about the definition of the development politics to undertake (both in terms of learning outcomes and success in the game), we think that the previous numbers about the available actions and game variable values analyzed during a game turn (see Section 5.4, suggest that having such a readily information for players was an effective support for communication and collaboration among players. This intuition is supported by the strong correlation (0.7, $p = 0.04$) between CPM5 and the sum of total numbers of action descriptions and variable values analyzed.

Finally, we also report that we found a moderate negative correlation (-0.3) between the number of skipped turns and the game score. Although also this result is not statistically significant, we think it is a further indication of the fact that we should improve the definition of available actions and their costs for all the roles, since a lack of suitable/attractive choices (or the impossibility to perform them) during a turn seems to be detrimental for the final game success.

Chapter 6

Conclusions

This thesis discussed educational games in the context of sustainability issues. Sustainability learning is a challenging topic, which demands dealing with complex scenarios, originated from intertwined dimensions (economic, environmental and social) and several (and often contrasting) points of view (householders, policy-makers, families, communities). In this context, collaborative tools might facilitate the emergence of learning in sustainability complex scenarios, through dialogue-based decision making, creativity, flexibility and critical reflection. EGs, in specific, are promising tools concerning the development of effective learning approaches, as they enable cognitive, behavioral and affective engagement, which, in turn, favor processes of participation, inquiry and social learning that challenge unsustainable practices. Furthermore, EGs allow the creation of virtual environments (where players can safely manipulate variables and inspect future scenarios) and enable shared experiences that offer situated and socially mediated learning contexts.

Thus, in order to investigate EGs to sustainability, the work started examining theoretical models for the design and evaluation of EGs, and surveying the state of the art of SSGs. The findings from this theoretical investigation led to the design and development of two educational games - *WaterOn!* and *Sustain* - which exploited different approaches to (collaborative) sustainability learning. In particular, their differences span the educational focus, target audiences, design models and interactive technologies used. In short, the main contributions of this thesis are the following:

- present an in–depth analysis of the theoretical tools for both design and evaluation of educational games (Chapter 2);
- review the state of the art of the existing sustainability games, suggesting as well open questions for further research (Chapter 3);
- detail the design and development of WaterOn!, a collaborative game for children based on mobile devices, TUI and shared virtual environments (Chapter 4);
- present the design, development and evaluation of Sustain, a collaborative game for raising awareness about the complexity related to managing sustainable development, based on mobile devices and AR technologies (Chapter 5).

These contributions can be further detailed in light of the overarching research questions, defined as premise of this work and recalled in the following:

- RQ1: Which are the theoretical models that underlie educational games design?
- RQ2: Which is the current state of the art of the developed sustainability games?
- RQ3: How to design educational games aiming to foster learning and collaboration in sustainability scenarios?

Concerning RQ1, the contribution of Chapter 2 is **the analysis of recent theoretical models for EGs design**, which can be focused on either pedagogic design or PX aspect. Besides informing the rest of our work, we think that the results of this research represent a useful reference for researchers in EG area willing to pick a suitable model for their project (or, possibly, to propose a new model). Furthermore, our discussion of the theoretical models surveyed allowed us to **identify and suggest the following topics for future research**:

- indication 2.1: design, develop and asses a larger number of EGs based on these theoretical models.
- indication 2.2: focus on how to map learning goals to game goals;

- indication 2.3: tailor models to specific domains and target audiences.
- indication 2.4: merge different models, or propose new ones targeting the identified weakness of the current approaches.

Then, Chapter 3 approaches RQ2 by surveying the current state of the art of SSGs. The main contributions of this Chapter are three:

1. **the definition of a taxonomy** (summarized in Table 3.3), which classifies SSGs according to their purpose (educational or motivational), target audience, interaction patterns and sustainability aspects they approach. This taxonomy provides a current picture of SSGs available online or produced in research and commercial contexts.
2. **the identification of key design guidelines expressly envisaged for SSGs** (Table 3.5). In Chapter 2 we reported the opinion of several researchers ([30, 34–36]) highlighting the necessity to base the serious games' design on sound theoretical models that encompass theories from both pedagogy and game design fields. We also reported that it would be interesting to have design models tailored to specific domains. To this end, we collected and related guidelines from several authors, attempting to identify the key design aspects explicitly focused to SSGs. We also discussed to which extent the examined SSGs embody the key design aspects presented. From this analysis, we derived the general conclusion that several of the key concepts defined could benefit from further exploration, in order to fully exploit the capabilities of educational and motivational SSGs.
3. **the presentation of open problems and potential areas of future research**. From this discussion it was possible to conjecture indications for future research, namely:
    - indication 3.1: validate the practical application of key design aspects previously presented;
    - indication 3.2: define and assess novel theoretical models for SSGs, possibly integrating also the PX perspective;
    - indication 3.3: integrate "alternative" interaction tools (such as: full and partial body motion capture, augmented reality, gesture recognition, TUIs and wearable devices) in SSGs design;

- indication 3.4: design and assess more (collaborative and competitive) multi-player SSGs;
- indication 3.5: further investigate the effectiveness of SSGs, specially focused at the achievement of the learning outcomes and the appearance of long-term lasting effects.

Chapter 4 focus on RQ3 and presents the design of WaterOn!, a SSG whose design was informed by several outcomes of previous Chapters. First, WaterOn! approaches indication 2.1, as its design is mainly based on RETAIN ([56]). To the best of our knowledge, WaterOn! is the first mobile game to be developed being based on this mode. Then, WaterOn! employs several technological tools to favor cooperation (thus approaching approach indication 3.4): (i) mobile devices (which allow co-located players to move freely within the environment), (ii) a projected screen (offering a shared representation of the scenario, aimed at supporting players' discussion and coordinated actions), and (iii) tangible user interfaces (TUIs). The last two items refer to indication 3.3, i.e. exploiting "alternative" interaction tools in the development of SSGs.

Unfortunately, the limited tests that were carried out prevent WaterOn! to offer final answers regarding RQ3, since (at this research stage) is not possible to ascertain players' achievement of the pedagogical or collaborative outcomes. However, we believe that WaterOn! still represents a valid contribution, as it might serve as an **example of the practical application of the chosen theoretical tools**, which is hopefully useful for other SSGs designers. In addition, during WaterOn! design process it was possible to conjecture **indications for further enhancement of RETAIN design model**:

- indication 4.1: include in RETAIN possible strategies capable of stimulating children's interest after the game sessions;
- indication 4.2: explore a possible integration of RETAIN with theoretical models based on flow concept, such as the Flow model or the EFM model.

Indication 4.1 may follow other successful examples as [106], while indication 4.2 presents an exciting possibility of investigating indication 2.4 (merging different models to solve the imbalance between pedagogic and PX aspects).

Finally, Chapter 5 introduces Sustain, a SSG that (similarly to the work detailed in Chapter 4) was based on several indications from previous Chapters. First Sustain approaches indications 3.3 and 3.4, by exploring AR-based interaction and collaborative gameplay. Then, Sustain exploits in–game analytics, which - according to the discussion of indication 3.5 (see Section 3.6) - may help analyze the effectiveness of serious games. Furthermore, Sustain is based on the key design aspects previously identified (summarized in Table 3.5), and, therefore, approaches as well indication 3.1 (i.e., validating the key design guidelines).

Again, we believe that Sustain is an innovative tool, since it is, to the best of our knowledge, the first mobile game whose design is based on the identified guidelines, and also the first SSG to merge AR-based interaction and collaborative multiplayer gameplay to raise awareness about the complexity related to managing sustainable development. In comparison to the work detailed in Chapter 4, we expect Sustain to be a second point of view over RQ3, approaching contrasting instructional approaches (direct instruction in WaterOn! and social constructivism in Sustain), distinct target audiences (children in WaterOn!, mature in Sustain), and different interaction solutions (VR and tangible interaction in WaterOn!, co–located augmented reality in Sustain).

Sustain assessment indicated, in general terms, the success of the game in achieving its desired objectives both in terms of learning and collaboration outcomes. We think that the main contribution of this Chapter is **detailing an innovative and (according with our tests) successful mix of theoretical tools and technologies**. We hope that the positive evaluation results represent an initial step towards the validation of the theoretical guidelines and technological tools adopted. However, this outcome could certainly be extended through deeper investigations. In general, we could extract four indications for future research:

- indication 5.1: separately evaluate each guideline;
- indication 5.2: further explore adaptivity;
- indication 5.3: test different target audiences;
- indication 5.3: enhance AR representation.

First, an isolated evaluation of each guideline's impact could help better comprehend their efficacy. Our research indicates that the guidelines worked as a group, but is it true that each guideline harnesses the expected behaviors from players? We believe that such investigation would enforce the validity of the adopted guidelines, and help to identify possible new ones.

Then, we also believe that Sustain could further explore the design guidelines related to adaptivity concept. Particularly, events like natural disasters that induce non-player planned disruptions, would require players to adapt to new conditions and, thus, would allow discussing an aspect that is currently overlooked in SSGs (as stated in 3.5.1).

In addition, Sustain was designed targeting a mature game audience (which can be noted, for instance, in the language present in the game). However, since CMS games are also interesting for younger target audiences (as identified in Section 3.3.1), we believe that it might be interesting to test the game with younger and, if possible, combined audiences. Such investigation might validate Sustain as a multi-age targeted game, which is a need for in current SSGs [4].

Finally, we suggest that AR could be further explored in Sustain. In specific, a feature that was prototyped but is not included in the final game (due to time constraints), is the management of interactions from multiple players on the same construction. For example, when the ministry of energy focuses a house block, the building's rooftops could glow when it is possible to install solar panels on them. If the mayor points at the same block, the view could highlight places to build more houses. Therefore, AR in Sustain could further enhance the representation of different points of view over the same problem.

In addition, having generated positive impact in learning outcomes, we expect that Sustain may be considered as a useful tool to educational practitioners interested in provoking sustainability-relevant reflections. In this context, Sustain proposes a collaborative tool that could be applied in both formal learning environments (as classrooms) or for offering post-lessons reflections (to be played in students' home, for instance). Such application would allow interesting possibilities, such as the investigation of Sustain's outcomes compared with those from non-interactive learning materials (in a way similar to what was done in [159]).

As for the limitations of this work, for the theoretical part of this research (Chapters 2 and 3) we believe that it would be interesting to increase the quantity of theoretical models and SSGs analyzed. Despite our efforts to collect and evaluate data through rigorous systematic processes, sustainability learning is an expanding field. Novel theoretical tools and several SSGs have appeared in last two years and, thus, were not included in our review. A refinement of this research is sorely needed to have an up–to–date list of theoretical tools, together with their analysis and discussion.

Concerning the practical part (Chapters 4 and 5), a major limitation of the thesis refers to the evaluation of the proposed games. WaterOn! still lacks a thorough systematic assessment. Sustain was evaluated with ad-hoc groups organized by convenience, a fact that does not ensure a representative distribution of the envisaged target audience and, therefore, raises concerns about the generalization of the results. Future works will include the systematic evaluation of WaterOn!, and further validation of Sustain, especially in comparing the game capabilities of promoting and fostering collaboration with that of more standard tools (e.g., paper-based games) aimed to reach the same objective.

Concerning future perspectives, the scientific investigation presented in this thesis underlines the potentialities of SSGs as learning tools. However, it also highlights that, in spite of the many interesting and relevant results, much work has still to be done to fully leverage on their potentialities. Several theoretical tools remain unexploited. Exciting possibilities emerge with innovative interaction technologies. Thorough evaluation is needed to help defining the effectiveness of sustainability games. Concerning these points, we hope that this thesis provides a contribution to the current state of the art towards the establishment of serious games as effectual educational tools for sustainability.

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Appendix A

Final list of papers included in Chapter 2 literature review

A.1 Papers directly found through keywords search

Table A.1 Papers directly found through keywords search. Selected papers (P) and corresponding theoretical models.

P	Model	Year	Authors	Title
1	GOM-II	2007	Amory A.,	Game object model version II: a theoretical framework for educational game development
2	EFM	2008	Song M., Zhang F.,	EFM: A model for educational game design
3	RETAIN	2008	Gunter G. A., Kenny R. F., Vick E. H.,	Taking educational games seriously: using the RETAIN model to design endogenous fantasy into standalone educational games
4	EGDF	2009	Ibrahim R., Jaafar A.,	Educational games (EG) design framework: Combination of game design, pedagogy and content modeling

5	DGBL	2009	Zin N. A. M., Jaafar A., Yue W. S.	Digital Game-based learning (DGBL) model and development methodology for teaching history
6	Is	2010	Annetta, L. A.,	The "I's" have it: A framework for serious educational game design.
7	Flow	2012	Kiili K., de Freitas S., Arnab S., Lainema T.,	The Design Principles for Flow Experience in Educational Games

A.2 Papers added after reference search

Table A.2 Papers added after reference search. Selected papers (P) and corresponding theoretical models.

P	Model	Year	Authors	Title
1	ADGBL	2007	Phit-Huan T, Siew-Woei L., Choo-Yee T.,	Adaptive digital game-based learning framework
2	TLT	2008	Fong-Ling F., Sheng-Chin Y.	Three layered thinking model for designing web-based educational games
3	GEM	2010	Nacke L. E., Drachen A., Göbel, S.	Methods for evaluating gameplay experience in a serious gaming context
4	Playability	2012	Ibrahim, A. et. al.	Educational Video Game Design Based on Educational Playability: A Comprehensive and Integrated Literature Review

Appendix B

Final list of papers included in Chapter 3 state of the art review

B.1 Papers directly found through keywords search

Table B.1 Selected papers (P) and corresponding SSGs. Rows in italics identify papers belonging to a SSG already reported by other paper (e.g. papers 3 and 4 refers to the same SSG of paper 2).

P	SSG	Year	Authors	Title
1	Modern Mayor	2014	Alinikula P., Latikka J.-L., Paanajärvi J.	Gaming for good changing the game for corporate sustainability
2	Futura	2011	Alissa N. Antle and Allen Bevans and Josh Tanenbaum and Katie Seaborn and Sijie Wang	Futura: Design for Collaborative Learning and Game Play on a Multi-touch Digital Tabletop
3	*Futura*	*2011*	*Alissa N. Antle and Allen Bevans and Josh Tanenbaum and Katie Seaborn and Sijie Wang*	*Balancing act: Enabling public engagement with sustainability issues through a multi-touch tabletop collaborative game*

4	*Futura*	*2014*	*Alissa N. Antle and Jillian L. Warren and Aaron May and Min Fan and Alyssa F. Wise*	*Emergent Dialogue: Eliciting Values During Children's Collaboration with a Tabletop Game for Change*
5	Velix	2011	Baeriswyl M.C., Przepiorka W., Staake T.R.	Identifying individuals' preferences using games: A field experiment in promoting sustainable energy consumption
6	Life Tree	2013	Cheah W.S., Wei T.Z., Kee B.H., Mohamad F.S.	Interactive mobile game for learning about sustainablity education
7	Energy Life	2010	Christoffer A., and Giulio Jacucci and Luciano Gamberini and Tatu Nieminen and Topi Mikkola and Carin Torstensson and Massimo Bertoncini	EnergyLife: Pervasive Energy Awareness for Households
8	Alberto's Gravimente Toys	2010	Ferraz M., Romão T., Câmara A.	The "Alberto's Gravimente Toys": Children's fiction on technological design
9	*Energy Life*	*2011*	*Luciano Gamberini et. al.*	*Saving is Fun: Designing a Persuasive Game for Power Conservation*
10	*Energy Life*	*2012*	*Gamberini L., Spagnolli A., Corradi N., Jacucci G., Tusa G., Mikkola T., Zamboni L., Hoggan E.*	*Tailoring feedback to users' actions in a persuasive game for household electricity conservation*
11	Ducky	2016	Glogovac B., Simonsen M., Solberg S.S., Löfström E., Ahlers D.	Ducky: An online engagement platform for climate communication

12	Acttention	2015	Gram-Hansen S.B., Ryberg T.	Acttention – influencing communities of practice with persuasive learning designs
13	Ghost Hunter	2014	Horn M.S.	Beyond video games for social change
14	Greenify	2013	Joey J. Lee and Eduard Matamoros and Rafael Kern and Jenna Marks and Christian de Luna and William Jordan-Cooley	Greenify: Fostering Sustainable Communities via Gamification
15	Viaggia Rovereto	2015	Kazhamiakin R., Marconi A., Perillo M., Pistore M., Valetto G., Piras L., Avesani F., Perri N.	Using gamification to incentivize sustainable urban mobility
16	The sustainability game	2015	Lameras P., Petridis P., Dunwell I.	Raising awareness on sustainability issues through a mobile game
17	Super Energy Apocalypse	2010	Lars Doucet and Vinod Srinivasan	Designing Entertaining Educational Games Using Procedural Rhetoric: A Case Study
18	EcoFactory	2016	Margoudi M., Oliveira M., Perini S., Taisch M.	Using drawings as an assessment tool: The impact of EcoFactory serious game in primary education
19	Prometeruse quiz	2015	O'Donnell B., Jouy P.	Learning from mistakes: A Quiz to Drill Climate Experts
20	*Viaggia Rovereto*	*2016*	*R. Kazhamiakin; A. Marconi; A. Martinelli; M. Pistore; G. Valetto*	*A gamification framework for the long-term engagement of smart citizens*

21	AgriVillage	2015	Rui Prada and Helmut Prendinger and Panita Yongyuth and Arturo Nakasoneb and Asanee Kawtrakulc	AgriVillage: A Game to Foster Awareness of the Environmental Impact of Agriculture
22	eVision	2013	Santos B., Romão T., Dias A.E., Centieiro P.	eVision: A mobile game to improve environmental awareness
23	Fishing with Friends	2015	Sarah D'Angelo and D. Harmon Pollock and Michael Horn	Fishing with Friends: Using Tabletop Games to Raise Environmental Awareness in Aquariums
24	LandYOUs	2015	Schulze J., Martin R., Finger A., Henzen C., Lindner M., Pietzsch K., Werntze A., Zander U., Seppelt R.	Design, implementation and test of a serious online game for exploring complex relationships of sustainable land management and human well-being
25	*LandYOUs*	*2014*	*Seppelt R., Martin R., Finger A., Henzen C., Lindner M., Pietzsch K., Werntze A., Zander U., Schulze J.*	*Experiences with a serious online game for exploring complex relationships of sustainable land management and human well-being: LandYOUs*
26	We Spire (former Practically green)	2013	Stevens S.H.	How gamification and behavior science can drive social change one employee at a time
27	Dubuque water portal	2012	Thomas Erickson and Mark Podlaseck and Sambit Sahu and Jing D. Dai and Tian Chao and Milind Naphade	The Dubuque Water Portal: Evaluation of the Uptake, Use and Impact of Residential Water Consumption Feedback

28	IdleWars	2015	Tolias E., Costanza E., Rogers A., Bedwell B., Banks N.	IdleWars: An evaluation of a pervasive game to promote sustainable behaviour in the workplace
29	EcoPanel	2016	Zapico J.L., Katzeff C., Bohné U., Milestad R.	Eco-feedback visualization for closing the gap of organic food consumption

B.2 Papers added after reference search

Table B.2 Selected papers (P) and corresponding SSGs.

P	SSG	Year	Authors	Title
1	Climate Race	2012	Simon, Jonathan, Marco Jahn, and Amro Al-Akkad	Saving energy at work: the design of a pervasive game for office spaces
2	Desertification Story	2009	Zualkernan, Imran A et. al.	A role-playing game-based learning platform for environmental awareness
3	ecoCampus	2016	Ayer, Steven K, Messner, John I and Anumba, Chimay J.	Augmented Reality Gaming in Sustainable Design Education
4	Eco Island	2009	Shiraishi, Miyuki et. al.	Using individual, social and economic persuasion techniques to reduce CO 2 emissions in a family setting
5	Energy Battle	2012	Geelen, Daphne and Keyson, David and Boess, Stella and Brezet, Han	Exploring the use of a game to stimulate energy saving in households
6	GAEA	2011	Centieiro, Pedro et. al.	A location-based multiplayer mobile game to encourage pro-environmental behaviours
7	Heroes of Koskenniska	2010	Laine, Teemu H and Sedano, Carolina Islas and Sutinen, Erkki and Joy, Mike	Viable and portable architecture for pervasive learning spaces
8	LEY!	2011	Madeira, Rui Neves et. al.	LEY!: persuasive pervasive gaming on domestic energy consumption-awareness

9	Perfect-Ville	2014	Yiannoutsou, Nikoleta, Kynigos, Chronis and Daskolia, Maria	Constructionist designs in game modding: The case of learning about sustainability
10	Power Agent	2009	Gustafsson, Anton, Katzeff, Cecilia and Bang, Magnus	Evaluation of a pervasive game for domestic energy engagement among teenagers
11	Power Explorer	2009	Gustafsson, Anton et. al.	Power explorer: a casual game style for encouraging long term behavior change among teenagers

Appendix C

List of analyzed sustainability games

1. Acttention [196]
2. AgriVillage [197]
3. Alberto's Gravimente Toys [115]
4. Catchment Detox, ABC Science, http://ab.co/2m2LaJI
5. Citizen Science, University of Wisconsin, http://bit.ly/2mSBBfR
6. City Rain, Ovolo Corporation Inc., http://bit.ly/2mlfeCO
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Appendix D

List of rules of Sustain fuzzy logic system

D.1 Rules for environmental sustainability variable

1. IF Pollution IS Hazardous THEN Sustainability IS Terrible
2. IF Pollution IS Unhealthy AND Transportation IS Scarse AND Food IS Scarse AND Energy IS Scarse THEN Sustainability IS Terrible
3. IF Pollution IS Unhealthy AND Transportation IS Scarse AND Food IS Scarse AND Energy IS Good THEN Sustainability IS Terrible
4. IF Pollution IS Unhealthy AND Transportation IS Scarse AND Food IS Good AND Energy IS Scarse THEN Sustainability IS Terrible
5. IF Pollution IS Unhealthy AND Transportation IS Scarse AND Food IS Good AND Energy IS Good THEN Sustainability IS Bad
6. IF Pollution IS Unhealthy AND Transportation IS Good AND Food IS Scarse AND Energy IS Scarse THEN Sustainability IS Terrible
7. IF Pollution IS Unhealthy AND Transportation IS Good AND Food IS Scarse AND Energy IS Good THEN Sustainability IS Bad
8. IF Pollution IS Unhealthy AND Transportation IS Good AND Food IS Good AND Energy IS Scarse THEN Sustainability IS Bad

9. IF Pollution IS Unhealthy AND Transportation IS Good AND Food IS Good AND Energy IS Good THEN Sustainability IS Average

10. IF Pollution IS Good AND Transportation IS Scarse AND Food IS Scarse AND Energy IS Scarse THEN Sustainability IS Bad

11. IF Pollution IS Good AND Transportation IS Scarse AND Food IS Scarse AND Energy IS Good THEN Sustainability IS Bad

12. IF Pollution IS Good AND Transportation IS Scarse AND Food IS Good AND Energy IS Scarse THEN Sustainability IS Bad

13. IF Pollution IS Good AND Transportation IS Scarse AND Food IS Good AND Energy IS Good THEN Sustainability IS Good

14. IF Pollution IS Good AND Transportation IS Good AND Food IS Scarse AND Energy IS Scarse THEN Sustainability IS Average

15. IF Pollution IS Good AND Transportation IS Good AND Food IS Scarse AND Energy IS Good THEN Sustainability IS Average

16. IF Pollution IS Good AND Transportation IS Good AND Food IS Good AND Energy IS Scarse THEN Sustainability IS Average

17. IF Pollution IS Good AND Transportation IS Good AND Food IS Good AND Energy IS Good THEN Sustainability IS Awesome

D.2 Rules for happiness variable

1. IF Sustainability IS Terrible THEN Happiness IS Terrible

2. IF Sustainability IS Bad AND Leisure IS Scarse THEN Happiness IS Terrible

3. IF Sustainability IS Bad AND Leisure IS Good THEN Happiness IS Bad

4. IF Sustainability IS Average AND Leisure IS Scarse THEN Happiness IS Average

5. IF Sustainability IS Average AND Leisure IS Good THEN Happiness IS Good

6. IF Sustainability IS Good AND Leisure IS Scarse THEN Happiness IS Average
7. IF Sustainability IS Good AND Leisure IS Good THEN Happiness IS Good
8. IF Sustainability IS Awesome AND Leisure IS Scarse THEN Happiness IS Average
9. IF Sustainability IS Awesome AND Leisure IS Good THEN Happiness IS Awesome

D.3 Rules for incoming citizens variable

1. IF Happiness IS Terrible THEN IncomingCitizens IS Terrible
2. IF Happiness IS Bad AND WorkingPlaces IS Scarse AND Housing IS Scarse THEN IncomingCitizens IS Terrible
3. IF Happiness IS Bad AND WorkingPlaces IS Scarse AND Housing IS Good THEN IncomingCitizens IS Bad
4. IF Happiness IS Bad AND WorkingPlaces IS Good AND Housing IS Scarse THEN IncomingCitizens IS Terrible
5. IF Happiness IS Bad AND WorkingPlaces IS Good AND Housing IS Good THEN IncomingCitizens IS Average
6. IF Happiness IS Average AND WorkingPlaces IS Scarse AND Housing IS Scarse THEN IncomingCitizens IS Terrible
7. IF Happiness IS Average AND WorkingPlaces IS Scarse AND Housing IS Good THEN IncomingCitizens IS Average
8. IF Happiness IS Average AND WorkingPlaces IS Good AND Housing IS Scarse THEN IncomingCitizens IS Terrible
9. IF Happiness IS Average AND WorkingPlaces IS Good AND Housing IS Good THEN IncomingCitizens IS Good
10. IF Happiness IS Good AND WorkingPlaces IS Scarse AND Housing IS Scarse THEN IncomingCitizens IS Terrible

11. IF Happiness IS Good AND WorkingPlaces IS Scarse AND Housing IS Good THEN IncomingCitizens IS Good
12. IF Happiness IS Good AND WorkingPlaces IS Good AND Housing IS Scarse THEN IncomingCitizens IS Terrible
13. IF Happiness IS Good AND WorkingPlaces IS Good AND Housing IS Good THEN IncomingCitizens IS Awesome
14. IF Happiness IS Awesome AND WorkingPlaces IS Scarse AND Housing IS Scarse THEN IncomingCitizens IS Bad
15. IF Happiness IS Awesome AND WorkingPlaces IS NOT Scarse OR Housing IS NOT Scarse THEN IncomingCitizens IS Awesome