Leveraging a Collaborative Augmented Reality Serious Game to promote Sustainability Awareness, Commitment and Adaptive Problem-Management

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Abstract

The sustainable development of our global world requires innovative educational approaches to foster people's ability to pursue common goals under ever-changing and uncontrollable environmental conditions. Serious games can meet this need by engaging learners in collective problem-solving activities that mimic real-world sustainability problems and scenarios. This paper presents the design and evaluation of Sustain, a collaborative and co-located multiplayer sustainability serious game. Sustain is an Augmented Reality based urban development game that aims to promote player awareness and commitment to sustainability problems and enhance players' ability to address these problems through collaborative and adaptive problem management approaches. Sustain was developed based on nine key game features that implement principles of serious game design tailored for sustainability. The evaluation of the game leveraged a multimodal approach that included in-game analytics, questionnaires, and observational data from ninety-nine participants and aimed to assess learning outcomes and identify relationships between game features and effects achieved. Results suggest that Sustain was effective in changing players' awareness of and commitment towards sustainability issues. Team adaptive behaviours and increasing collaborative interactions were observed during the game, even during phases that did not

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require close collaboration, which is altogether suggestive of increased collaborative and adaptive problem-management capabilities. These findings suggest that the development of sustainability serious games based on design principles and features similar to those implemented in Sustain can lead to impacts crucial for sustainability education.

Keywords: augmented reality, collaborative learning, serious games, design framework, sustainability, education for sustainable development

1. Introduction

In 1987, the global community formally recognised the importance and urgency of promoting sustainable development, defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987, p. 43). Since then, Education for Sustainable Development (ESD) has been progressively theorised, operationalised, implemented and evaluated (WCED, 1987; UNDPI, 1994; UNESCO, 2005; Tilbury and Wortman, 2004; Buckler and Creech, 2014; O'Flaherty and Liddy, 2018; Edwards et al., 2020).

ESD aims to empower individuals and societies to see our planet as a global community with a shared future, protect the ecosystem, value diversity, identify collective needs and pursue common interests (UNESCO, 2005; Buckler and Creech, 2014). To achieve these goals, complex problem scenarios such as global warming, pandemics, and geopolitical crises must be addressed. These scenarios present three distinctive features that make them extremely difficult to treat. Firstly, they are driven by interconnected and often conflicting environmental, economic and social factors. Therefore, sustainability issues should be tackled by adopting a systemic perspective, suitable to promote and balance three closely interrelated elements (Harris, 2009):

- *economic sustainability*, by continuously producing adequate quantities of goods and services while maintaining manageable levels of governance and debt, and avoiding sectorial imbalances that threaten agricultural or industrial production;
- *environmental sustainability*, by maintaining a stable resource base, avoiding over-exploitation of renewable resources, depletion of non-renewable resources and preserving the ecosystem;

- *social sustainability*, by achieving equitable distribution of resources and wealth, adequate provision of social services (e.g. healthcare and education), equal opportunities, and political accountability and participation.

Secondly, sustainability scenarios involve multiple stakeholders with different and potentially conflicting interests and needs (Tilbury, 2004; Conklin, 2005; Smaliukiene, 2007; Jones, 2014; Fabricatore and Lopez, 2014; Houghton and Tuffley, 2015; Diniz dos Santos et al., 2019; Fabricatore and Lopez, 2020). Consequently, addressing sustainability issues requires exploring and harmonizing diverse worldviews by involving all affected stakeholders in collective dialogue and collaborative decision making (Conklin, 2005; Fabricatore and Lopez, 2014; Houghton and Tuffley, 2015; Fabricatore and Lopez, 2020). Thirdly and finally, the factors that define sustainability problems change over time, and so do the ways these factors interact (Jones, 2014; Rittel and Webber, 1973; McDaniel and Driebe, 2006; Fabricatore and Lopez, 2020; Fabricatore et al., 2020). Moreover, seemingly simple, small-scale interactions can originate emergent global phenomena whose large-scale effects cannot be traced back to their origins, nor predicted from observation of small-scale interactions (McDaniel and Driebe, 2006; Fabricatore and Lopez, 2020; Fabricatore et al., 2020). Consequently, sustainability scenarios are highly uncontrollable and cannot be definitively solved (Rittel and Webber, 1973; Fabricatore and Lopez, 2020; Fabricatore et al., 2020). Therefore, they should be tackled through iterative problem management approaches suitable to achieve and maintain satisfactory conditions through continuously planning, acting, and adjusting strategies based on ongoing monitoring of evolving circumstances (Rittel and Webber, 1973; Jones, 2014; Fabricatore and Lopez, 2020; Fabricatore et al., 2020).

In this context, ESD should empower people "to make informed decisions for environmental integrity, economic viability, and a just society for present and future generations while respecting cultural diversity", and act on those decisions (Buckler and Creech, 2014, p. 20). Despite the promising progress made over the last two decades, ESD remains an open challenge (Buckler and Creech, 2014; O'Flaherty and Liddy, 2018; Edwards et al., 2020). In particular, innovations are needed to find more effective ways to engage learners in real or simulated sustainability problem scenarios (Buckler and Creech, 2014; Agbedahin, 2019; McCowan, 2019; Fabricatore and Lopez, 2020), with the threefold aim of: (i) promoting *awareness* of and *commitment* to sustainability issues (UNDPI, 1994; UNESCO, 2005; Agbedahin, 2019); (ii) generating opportunities to explore complex, multi-stakeholder sustainability problem scenarios, and to comprehend their mechanics, relationships and implications (UNDPI, 1994; Tilbury and Wortman, 2004; McCowan, 2019); and (iii) fostering learners' ability to tackle sustainability issues through collaborative and adaptive problem management approaches (CAPM) (Buckler and Creech, 2014; Edwards et al., 2020; Fabricatore et al., 2020).

Given these requirements, in this paper we present the design and evaluation of Sustain, a collaborative and co-located multiplayer sustainability serious game (SSG). Sustain is an urban development game[1] based on Augmented Reality (AR) that aims to promote players' awareness and engagement with sustainability issues related to urban development, and improve players' ability to conduct CAPM processes.

2. Related works

Serious Games for sustainability.

In the last decades, SSGs have been increasingly developed with the specific purpose of promoting the integrated development of capacities and sensibilities relevant to engage players in sustainability problem scenarios (Janakiraman et al., 2018; Diniz dos Santos et al., 2019; Stanitsas et al., 2019). There is growing empirical evidence that SSGs can produce attitude change (Janakiraman et al., 2018), foster apprehension of sustainability knowledge (Wu and Lee, 2015; Stanitsas et al., 2019), promote awareness and understanding of sustainability issues (Katsaliaki and Mustafee, 2015; Madani et al., 2017), promote collective activities (Katsaliaki and Mustafee, 2015; Emblen-Perry, 2018), and stimulate critical skills such as problem-solving, communication, negotiation, and monitoring emotional intelligence (Katsaliaki and Mustafee, 2015).

The literature shows that collaborative SSGs can successfully promote three key types of sustainability-related learning: (i) *cognitive learning*, stimulating knowledge acquisition or restructuring (e.g., understanding the mechanisms of climate change); (ii) *normative learning*, promoting learners' ability to change their assumptions and worldviews (e.g., developing a sense of commitment to sustainability issues); and (iii) *relational*, fostering learners'

[1]An urban or city-development game is a simulation game in which players act as planners and leaders of a city and are responsible for its growth and management strategy

ability to understand others' mind-sets, build trust, and be willing to collaborate with others (den Haan and van der Voort, 2018). Nonetheless, further research is needed to address open problems in these areas, and to improve methodological approaches to the design and evaluation of SSGs (den Haan and van der Voort, 2018; Diniz dos Santos et al., 2019; Stanitsas et al., 2019; Hallinger et al., 2020).

Concerning cognitive learning, SSGs should promote a holistic understanding of sustainability issues and consider the complex interactions among social, environmental, and economic factors (Fabricatore and Lopez, 2014; Diniz dos Santos et al., 2019; Stanitsas et al., 2019). However, most of the SSG research to date has addressed these themes separately (Hallinger et al., 2020; Stanitsas et al., 2019). This emphasizes the need for more empirical research that promotes an integrative understanding of these three dimensions by engaging learners in scenarios characterized by a tight interplay among them (Stanitsas et al., 2019).

Normative learning is critical to adapt and thrive in changing, unpredictable, and non-fully-controllable conditions (Fabricatore and Lopez, 2020). Accordingly, SSGs should be leveraged to develop learners' capacity to adapt their worldviews and assumptions (Fabricatore et al., 2020), and to promote attitudinal changes conducive to appreciation of and commitment to sustainable development (Janakiraman et al., 2018). However, few studies have focused on normative learning (den Haan and van der Voort, 2018), suggesting the need for SSGs that can foster this learning by providing opportunities for individual and collective reflection, dialogue and negotiation suitable to promote critical self-reflection on one's perspectives and behaviour beyond the game (Tanenbaum et al., 2013).

Given the importance of collaboration in sustainability problem scenarios (Edwards et al., 2020), relational learning should be a central focus of SSGs (den Haan and van der Voort, 2018). However, several reviews report that few collaborative SSGs have assessed relational learning outcomes den Haan and van der Voort (2018); Diniz dos Santos et al. (2019); Stanitsas et al. (2019) and emphasise that promoting meaningful social interactions and collaboration skills through SSGs remains an urgent open problem.

In terms of methodological issues, the effectiveness of SSGs should be evaluated by looking at changes in learners' knowledge, attitudes and behaviour in relation to specific sustainability problems and scenarios, taking into account both short- and long-term effects (Janakiraman et al., 2018; Diniz dos Santos et al., 2019; Hallinger et al., 2020). To address these needs, assessment of the impact of SSGs should be multimodal, integrating multiple measures and using both in-game learning analytics and out-of-game assessment approaches (den Haan and van der Voort, 2018; Diniz dos Santos et al., 2019). Finally, there is a need for more evidence-based, prescriptive SSG research that can guide the effective design, evaluation and use of SSGs (Hallinger et al., 2020).

AR-based SSGs: unexploited potentialities.

Recent advances in AR technologies offer significant potential to enhance the ability of SSGs to promote player engagement in collaborative problem-solving activities (Diniz dos Santos et al., 2019). Recent reviews show that non-digital role-playing games and board games can be an effective way to engage learners in sustainability problem scenarios and promote meaningful social interactions, active negotiation and collaboration (Stanitsas et al., 2019; Hallinger et al., 2020). The *augmented tabletop* format leverages AR to integrate these forms of non-digital game-based learning into digital gameplay activities that take place in simulated mixed-reality scenarios (Liarokapis and de Freitas, 2010). This enhances collaboration opportunities by overlapping a simulated task space with a physical space (Billinghurst et al., 2002; Wang and Dunston, 2011; Lukosch et al., 2015). In particular, the literature suggests that people in AR environments, as opposed to traditional screen-based collaborative environments, tend to relate to their peers in ways similar to non-technology mediated face-to-face interactions (Lukosch et al., 2015).

Despite its potential, AR has hardly been explored in SSGs. EcoCampus Ayer et al. (2016) and GreenDesign (Salman and Riley, 2016) are two AR games that respectively aim at teaching sustainable building design and sustainable engineering practices in formal education. However, they do not consider gameplay interactions among players, nor do they support social interactions through AR. FunergyAR (Fraternali and Gonzalez, 2019) combines an individual quiz-based activity with a multiplayer card game to promote energy-efficient behaviour among students. FunergyAR uses AR extensively in individual quizzes, but only to unlock specific cards, without any AR-based support for group activities. City of Life (Al-Hammadi et al., 2018) is a sustainable city development game consisting of a main city-building activity and several AR-based mini-games where players have to achieve certain sustainability goals to collect the resources needed to build a city. Therefore, AR is not essential for the main gameplay activity. Finally, EcoGotchi (Polycular) is a Tamagotchi-style AR mobile game, where the player has to take care of a living creature whose well-being depends on the player's eco-friendly skills, knowledge and behaviour. The game is single-player, but allows sharing achievements via social networks.

All these works show a tendency towards limited use of AR and do not provide support for collaborative and group activities. In addition, learning outcomes were only assessed in two cases. In EcoCampus, students playing the AR game were able to produce more creative designs in less time and achieved better learning outcomes than two control groups working with pen and paper (Ayer et al., 2016). City of Life led to an overall increase in sustainability knowledge, although the small number of participants (six volunteers) prevents generalisation of these results (Al-Hammadi et al., 2018).

The needs identified in the current state of the art motivated us to design Sustain as a multiplayer AR-based collaborative SSG. To enhance *cognitive learning*, Sustain specifically aimed to promote holistic awareness of sustainability by engaging players in urban development scenarios that integrate social, economic and environmental factors. To promote *declarative learning*, Sustain aimed to foster attitudinal changes focused on commitment to sustainability by designing the game to require players to consider alternative perspectives, conflicting interests and the negative impact of individualistic choices on the common good. To promote *relational learning*, Sustain engages players in collaborative problem management processes, by having them take on different roles and continuously negotiate and reconcile conflicting interests to achieve common goals. AR was used to develop Sustain as an augmented, collaborative and co-located board game whose learning outcomes were assessed adopting a multimodal approach. This approach integrates questionnaires and in-game learning analytics to explore the impact of the game on players' awareness and commitment towards sustainability, and their ability to engage in collective problem management processes.

3. Design guidelines

Sustain was designed based on a set of guidelines extrapolated from sound theoretical frameworks. Several conceptualisations for the design and analysis of serious games have been proposed (e.g. Wouters et al. 2010; Carvalho et al. 2015). However, to the best of our knowledge the only framework that explicitly focuses on SSGs is the one proposed in Fabricatore and Lopez (2014). This presents game design principles beneficial to promote sustainability learning through the definition and integration of four key aspects of SSGs scenarios: *sustainability contextualisation*, defined by the setting, player roles, motivations and opportunities for action; *player agency*, defined by the gameplay problems presented to players and the approaches allowed/required to address them; *player adaptivity*, defined by the environmental conditions requiring player adaptation; and *sociality*, defined by gameplay situations and mechanisms promoting meaningful social interactions. We derived from this framework the guidelines listed in Table 1.

Table 1: Design guidelines: game features fostering sustainability learning

What to design	**How**
Sustainability contextualisation	(DG1) Contextualise gameplay activities in scenarios that: (i) involve settings and game objectives reflecting real-world issues and integrate social, economic and environmental sustainability dimensions; and (ii) offer to players multiple sustainability-relevant roles, underpinned by different interests/needs and associated with specific actions.
Player agency	(DG2) Present to players: (i) opportunities to choose roles and self-define game goals and strategies; (ii) ill-defined problems, requiring players to continuously explore and critically interpret changing events and relationships in the game world, reflecting on present and past game states, and forecasting future states; (iii) actions/interactions possibilities mimicking the real-world, with the opportunity to act across real and virtual environments; and (iv) gameplay actions influenced by conflicting constraints and requiring management of limited resources.
Player adaptivity	(DG3) Plan gameplay activities: (i) affected by changing environmental conditions, due to events that players cannot fully anticipate nor control, and which require adaptation of their goals and plans; and (ii) structured in phases, allowing players to explore and evaluate gameplay situations without strict time-limits.
Sociality	(DG4) Define game objectives, tasks and environmental conditions: (i) requiring the engagement of multiple players in different roles; and (ii) requiring players to collaborate as well as deal with conflicting interests.

The relevance of involving player in CAPM was highlighted in Fabricatore and Lopez (2014) and fully analysed in Fabricatore and Lopez (2019) and Fabricatore et al. (2020), from which we derived the guidelines used in Sustain to support CAPM (Table 2). Fabricatore et al. (2020) explicated that complex problems such as sustainability issues should be continuously managed, through iterative and adaptive processes involving collaborative meaning-making, action and learning. Accordingly, the authors stressed that games aimed at fostering CAPM should present collective gameplay tasks requiring players to iteratively evaluate circumstances, plan, execute actions,

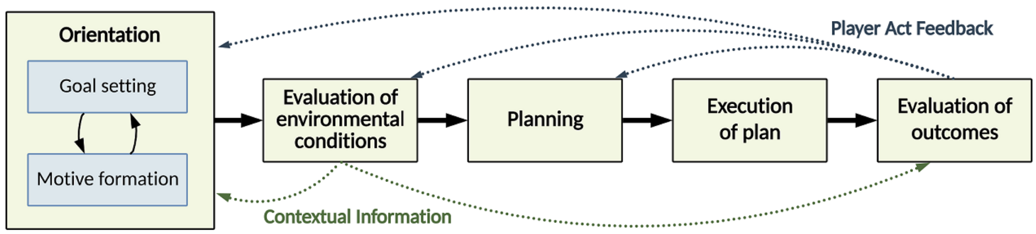

Figure 1: Articulation of the gameplay activity - adapted from Fabricatore and Lopez (2019)

and revise their decisions, structured after the Human Factors model for game-based learning proposed in (Fabricatore and Lopez, 2019) (figure 1.)

Given the importance of collaboration in ESD and SSGs, multiplayer SSGs should be designed based on guidelines specifically conceived to foster the development of collaborative skills (den Haan and van der Voort, 2018; Diniz dos Santos et al., 2019). Among the available design frameworks focused on fostering collaboration in SGs (Diniz dos Santos et al., 2019), we relied on the suggestions of Rocha et al. (2008), Reuter et al. (2014) and Zagal et al. (2006) to extract the design guidelines summarised in Table 3.

Table 2: Design guidelines: game characteristics fostering CAPM

What to design	**How**
Iterative structure of gameplay tasks	(DG5) Define gameplay tasks as iterative processes: (i) aimed at pursuing open-ended goals, requiring continuous improvement or maintenance of desirable conditions rather than achievement of a set end-state; (ii) driven by and promoting collective meaning-making, i.e. formation and update of shared knowledge representations and attitudes; (iii) requiring progressive construction and adaptation of solutions, involving iterative definition and revisions of plans and objectives, and driven by continuous evaluation of activity outcomes and relevant environmental information (Figure 1); and (iv) eliciting activity-based learning as the development of knowledge representations, skills and attitudes relevant to pursue shared goals.
Meaning-making information flows	(DG6) Define gameplay information flows to be provided to players to: (i) support meaning-making required to define and revise plans and objectives, and evaluate environmental information; and (ii) promote mental representations relevant to orient the development of desirable knowledge, attitudes and skills.

Table 3: Design guidelines: game characteristics fostering collaboration

What to design	**How**
Diversity and complementarity of player roles	(DG7) Offer to players different roles that provide specific and complementary skill sets and actions (Rocha et al., 2008), in order to (i) help players to be more involved in their role; and (ii) promote communication and co-operation among the different roles, making each role necessary for the effective coordination and performance of players' complementary actions.
Shared and constrained goals	(DG8) Define shared goals for all players and provide them with *limited resources* to accomplish collective tasks (Rocha et al., 2008), in order to: (i) emphasise players' need to team up and find creative solutions to gameplay challenges; and (ii) prevent a single player from taking control of the group by performing all actions or commanding the others.
Traceability of gameplay payoffs to players' decisions	(DG9) Offer to players opportunities and means to reflect on the consequences of their actions (Zagal et al., 2006), in order to enable players to: (i) understand how their decisions affected themselves and others; (ii) identify wrong decisions; and (iii) experience "expectation failures", when they realise that the outcomes of their actions are not as good as expected, or even detrimental.
Collective progression	(DG10) Articulate collective gameplay activities in phases, enabling players to engage in individual tasks and decision-making processes, but requiring players to converge, share information and coordinate their activities before moving on to the next phase (Reuter et al., 2014). To this end, control transition across phases through *Gathering gates*, i.e. gameplay situations requiring players to wait for others because they can only progress together (Reuter et al., 2014).

4. The Sustain AR game

4.1. Game outline

Sustain is an AR-based city management game for three players who work together to expand a fictional city area by taking on different policy-maker roles. The game environment simulates a real-world scenario in which players must achieve a threefold goal: maximising the environmental sustainability of the city, its population and the satisfaction of its citizens. The game is divided into six turns that integrate individual and collective activities. In each round, players first agree on a collective development plan to improve the state of the city. Then they select a limited number (maximum two per player) of individual actions suitable to pursue the planned goals. The actions are role-specific and are made available incrementally in each round (e.g. the mayor can only build houses or factories in the first round, while in the second round she is given the opportunity to also expand public transport). The players deploy their actions in AR (through a tablet) on a virtual game board that represents the city area and its landscape. At the end of a turn, players can monitor their progress towards the agreed goals and evaluate the impact of the deployed actions on the state of the city. Actions directly affect local impact factors (e.g. housing, jobs and transportation), which in turn determine the global state of the city based on rules that are not fully predictable. The game thus requires players to ascertain the direct local impacts of their actions, recognise changes in the global state of the city and infer how these may have been influenced by the identified local impacts[2]

At the end of the sixth and final round of the game, players are presented with an overall assessment of their urban development efforts. Since an unsustainable city will result in dissatisfied citizens leaving it, sustainable practises are essential to succeed in the game. Furthermore, achieving Sustain's game objective requires active collaboration between players, underpinned by an understanding of the game mechanics that govern the various interwoven elements and the complex environmental impacts created by players' individual and collective decisions. Sustain is therefore aimed at an audience composed of adults and young people able to mentally manipulate concepts and formulate hypotheses in order to predict future events (Jansen, 2011).

[2]For a general video description of the Sustain gameplay, see `http://tiny.cc/Sustain_GameDescription`

Sustain was developed around nine key game features (GFs). Based on the guidelines listed in Tables1-3, these features were designed through a systemic approach so that their interplay could promote sustainability awareness, commitment to sustainability and CAPM. In the following, we explain how these features (introduced in section 4.2) operationalise the adopted design guidelines (section 4.3), and highlight their expected impacts and underlying rationale (section 4.4). The comprehensive mapping between design guidelines, game features and expected outcomes is shown in Table 4.

Sustain was designed and developed through multiple iterations of prototyping and evaluation phases to validate game features and optimise usability and user experience. This process was highly collaborative and transdisciplinary. All authors were involved as experts in different fields and contributed to integrate perspectives from game design, sustainability, ESD, complex systems and AR development.

4.2. Core design features

GF1: Gameplay problems mirroring real-world scenarios involving the interplay of economic, social, and environmental dimensions. Sustain requires players to achieve a common goal by managing a system of interconnected local-impact and global variables, modelled to reflect authentic sustainability problems accounting for interplaying economic, social and environmental factors. Eight local-impact variables represent the state of the city: available *food* and *housing* resources, *leisure* and *transport* opportunities, *pollution* and *energy* levels, *jobs*, and the *city's communal budget*. These are directly affected through the available gameplay actions. Each of these actions has a cost associated with it, which is deducted from the budget when it is implemented. Changes in the local-impact variables determine the value of three further variables that describe the global state of the city: the degree of sustainability, of the *environment*, the *population* and its *happiness*. Such a local-to-global network provides the basis for introducing uncertainty and unpredictability into the game through the mechanisms implemented by GF2 and GF6. To help players manage their choices and activities, the game UI provides rich visual information about global and local-impact variables. This allows players to continuously monitor the state of the game and predict the impact of an action before it is executed (Figure 2, bottom). Furthermore, Sustain's play space includes a central shared screen displaying a comprehensive snapshot of individual choices, collective decisions and game state, readily available as a "what did we do, and how did it go?" feedback throughout each turn (Figure 2, top).

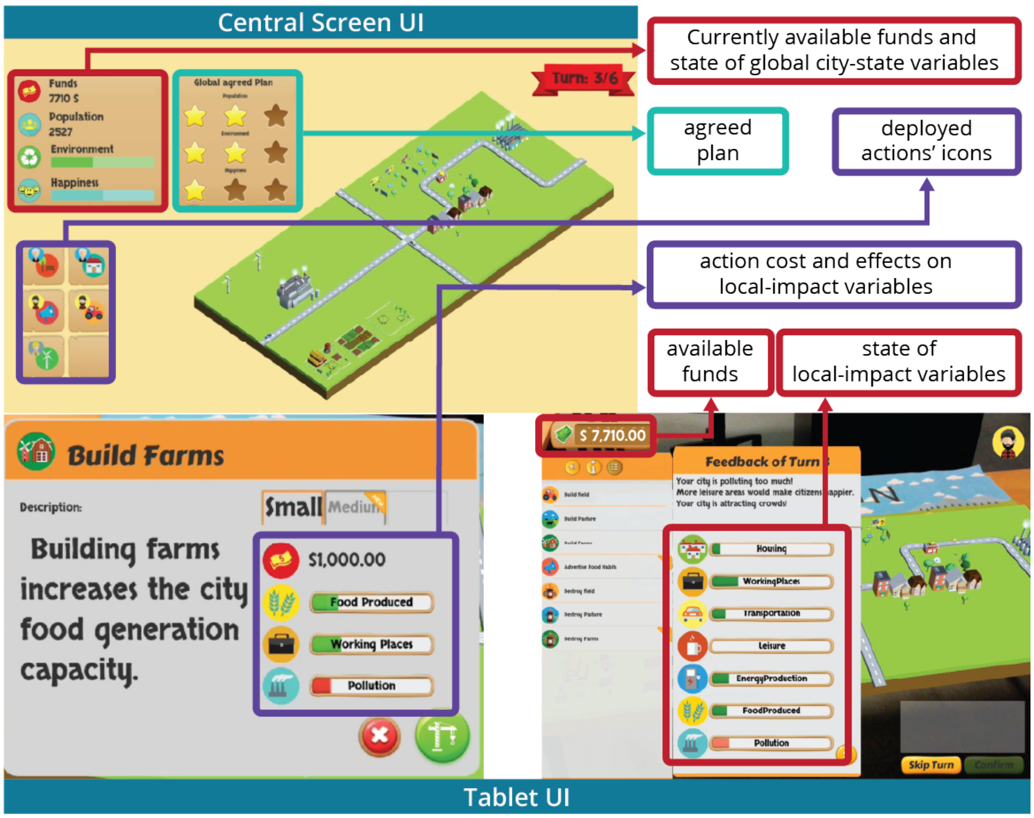

Figure 2: Summary of the in-game information provided to players. **Top:** a view of the central shared screen showing the city-state variables, the available funds, the commonly agreed development plan and the list of actions proposed by players in the current turn. **Bottom:** two different views of the tablets' UI, showing the effect of the selected action on the local-impact variables and their values at the beginning of the current turn.

GF2: Shared, open-ended and ill-defined goals. The need to simultaneously increase the environmental sustainability of the city, its population, and the happiness of its citizens represents a common, open-ended, and ill-defined game goal. Since changes in the global game state occur through the interplay of all players' actions at each turn, this goal can only be pursued collectively. Furthermore, the goal requires players to continuously improve the global game state, with no preestablished ideal state to achieve. Finally, there are multiple ways to improve the game state at each turn, without

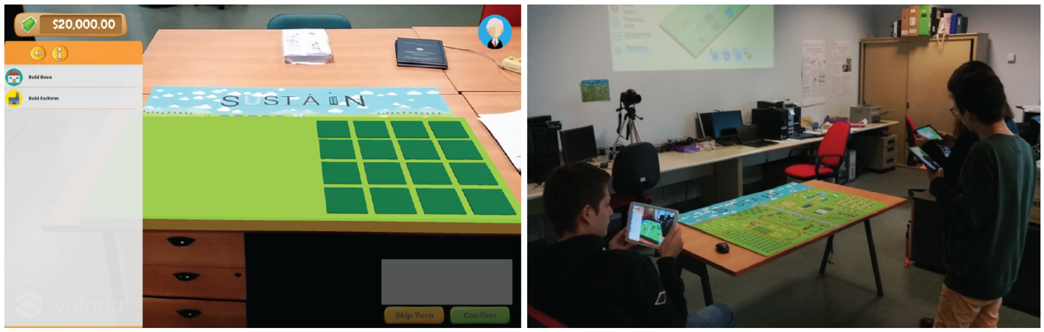

Figure 3: **Left:** tablet AR UI visualising the game space. In this case, only urban areas are available for the mayor to build a house. **Right:** a view of the layout of the physical game space, which offers players the possibility to freely move in the environment and observe the AR game board from different perspectives.

a clear optimal strategy. As a result, players cannot fully predict the outcomes of their plans and must constantly revise their individual and collective strategies.

GF3: Different player roles, with complementary role-specific actions and possibly conflicting interests. Sustain requires each player to assume a different realistic policy-maker role. The *Mayor* oversees the development of the built environment. The *Minister of Energy* is responsible for developing an energy matrix that includes renewable (wind and solar) and non-renewable (coal, gas, or nuclear fusion) energy sources, as well as waste management in urban areas. The *Minister of Agriculture* is responsible for defining governmental policies on agriculture, forests, and food production, as well as conducting educational campaigns to promote healthy eating. Each role has its own responsibilities, potentially conflicting priorities, and distinctive capabilities. These are determined by role-specific actions and resources that affect the variables in the game in different ways, and are progressively made available to the player. Overall, this makes the roles complementary and equally important to the development of the city. To facilitate collaboration, the game UI includes individual and collective prompts designed to continuously share information about what each role is doing and what should be considered together (see Figure 2).

GF4: Shared and limited resources needed for individual actions, requiring negotiation and agreement.

Planning and deploying actions requires players to manage a limited pool of shared resources. Specifically, the game space comprises an urban and a countryside area, each structured as a 4×4 grid of locations where actions can be deployed. Each location can only be used once, and is available depending on players' role and intended actions (e.g., Figure 3). Furthermore, deploying an action reduces the city's limited shared budget. Hence, by decreasing the budget, each player's action may limit what other players can do. Space and budget constraints thus require players to collectively and continuously discuss and agree on game plans, identifying and coordinating complementary actions, and considering the roles, interests and abilities of all players. To support this process, Sustain continuously provides information useful to monitor the game state, explore possibilities, and anticipate the future (e.g., remaining funds, available actions and map locations – see Figure 2)

GF5: AR-supported autonomous exploration and deployment of actions. Sustain requires players to individually address problems and make decisions to alter game scenarios in meaningful ways, even in the presence of collective game goals and shared resources. To this end, players are engaged in mandatory phases of individual exploration and implementation of strategies to contribute to collectively-agreed plans, as described in GF8. Players manage these activities using their individual tablets, which exploit marker-based AR to provide a role-specific interactive view of the game scene. The marker is the tabletop map representing the urban area and landscape to be developed (Figure 3, right). An AR representation of the game scene is overlaid to the tabletop map in the tablet screen, including general and role-specific game state information, and a list of role-specific actions available to each player (Figure 3, left and Figure 2, bottom). AR allows players to intuitively navigate the game scene and share their role-specific game view with other players, albeit this is not mandatory.

GF6: Non deterministic local-to-global effects, introducing uncertainty and unpredictability. The values of the global variables are determined by a fuzzy logic system based on the effects of players' actions on local-impact variables. Thus, a given configuration (i.e., set of values) of the eight local-impact variables may generate multiple plausible global city states (i.e., alternative values for the variables *environment*, *population*, and their *happiness*). This introduces uncertainty into the game by making the relationships between local and global factors non-fully-predictable. At the same time, the game provides players with information that allows them to interpret variations in global outcomes, and hypothesise how these might have been affected by changes in local-impact variables. Altogether, these

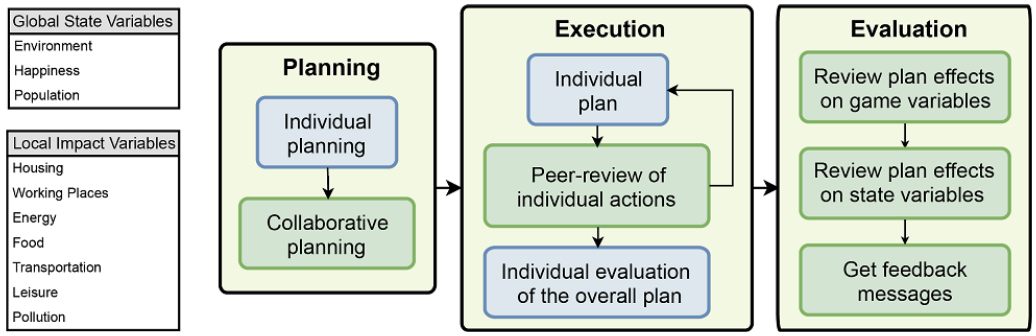

Figure 4: Global state variables, local impact variables, and turn flow highlighting individual (blue) and collective (green) activities.

characteristics allow the system to be perceived as non-fully-controllable nor predictable, but also not random. By extension, they promote investigation and awareness of uncertain but plausible relationships between local-impact and global variables, interpreting how their role-specific actions *can directly and certainly* affect local-impact variables, and how these *may likely and indirectly* affect the global state of the game.

GF7: Turn structure, allowing iterative problem management and gameplay evolution. A Sustain game is divided into six turns, each corresponding to six months of in-game fictional time. Each round involves collective planning, individual actions deployment, and final evaluation of the results of the collective plan, as detailed in GF8. The structure of the game turns is intended to ensure that the game state evolves incrementally; that players have regular checkpoints to monitor the state of the game; and that the iterative formulation and adaptation of strategies to incrementally improve the game state is facilitated.

GF8: Within-turn gameplay phases, combining individual and collaborative activities

Each game turn in Sustain is divided into distinct phases whereby individual and collective activities interweave, as detailed below and illustrated in Figure 4.

Planning phase. This requires participants to work together to define a common plan and agree on what should be accomplished by prioritising the local-impact and the global variables they want to improve. A plan is defined by assigning priority-stars to local-impact variables (up to three stars per variable, out of a total of five available stars) and global variables

Figure 5: The shared screen (**left**) and tablet (**right**) interfaces of the collaborative planning phase. Players can use stars to highlight their priorities in terms of state and game variables. Role icons in the shared screen view represent the priorities that each player assigned through their tablet UI (**left**) during the individual planning phase. To support the planning phase, the central screen also displays the current game state, and recommendations proposed by the game to improve the city.

(a maximum of five stars per variable, out of a total of seven available stars). In the planning phase, each player must first propose an individual plan that focuses on the overall sustainability goals rather than those specific to their role. Then, all players must discuss their respective plans to define a mutually agreed plan (Figure 5).

Execution phase. In this phase, players develop individual strategies using a maximum of two building actions, with the freedom to either contribute to the agreed collective plan or pursue alternative goals. All actions selected by the players are then listed in a procedure that is subject to a peer evaluation, whereby each player can approve or reject it. If the procedure is rejected, it becomes invalid and the players must discuss and select alternative actions (Figure 6). This process is repeated until all players approve the procedure, which is finally executed. Then, each user must provide an individual evaluation of the collectively-approved procedure on a "five-star" Likert scale (1: very dissatisfied, 5: very satisfied).

Evaluation phase. In this final phase, the central screen provides players with an overview of the planning and execution phases. The overview is divided into three sections, each containing specific game information. The first section compares the actual effects of the executed procedure on the variables with local-impact, with those agreed upon by the players in the planning phase. The second section does the same with global variables.

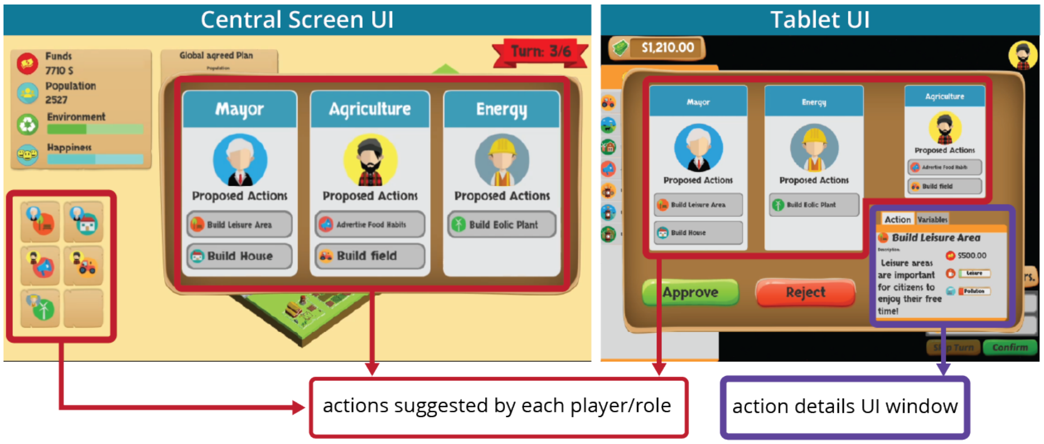

Figure 6: Peer review phase. The shared screen (**left**) shows the current proposed plan as the list of actions deployed by each role. Each player, through their individual tablet (**right**), can analyse the effects of the actions deployed by other players and eventually approve or reject them.

The last section provides contextual feedback in the form of hints, warnings, and advice about the current evolution of the city (Figure 7), to facilitate the identification of strategies suitable for overcoming challenges in subsequent rounds of the game. To support thinking processes, sections are presented sequentially and on-demand, as a new section begins only when each player agrees to continue via their tablet UI.

Overall, Sustain's within-turn structure ensures that players can only progress together. They must maintain a shared understanding of individual and collective goals, and iteratively agree on motives (e.g., priorities of global and local variables), decisions (e.g., action choices), and evaluations (e.g., performance outcomes) related to the management of global and local variables.

GF9: Co-located play space. Sustain's layout provides enough space for three players to move freely in the physical game environment and communicate through verbal and nonverbal cues. Communication is also supported by the central shared screen which, as detailed in GF2, displays comprehensive data about the game and the players' activities (Figure 3, right).

4.3. Operationalisation of design guidelines

The sustainability game design guidelines presented in Tables 1-3 were operationalised through Sustain's nine core design features as summarised in

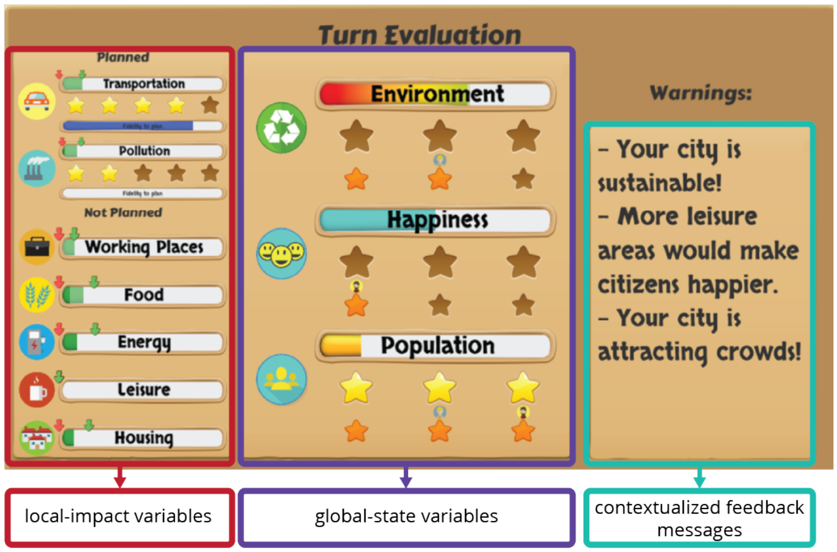

Figure 7: The three sections of the executed plan review showed on the central screen.

table 4 and detailed below.

- *Sustainability contextualisation* (DG1): the integration of GF1, GF2 and GF3 requires players to deal with authentic and multi-dimensional sustainability issues.

- *Player agency* (DG2): the interplay of features GF1-GF6 enables players to freely self-define goals and explore and transform an authentic sustainability scenario through both individual and collaborative role-playing dynamics.

- *Player adaptivity* (DG3) is implemented through bolstering uncertainty and unpredictability in the game and facilitating players' exploration of complex relationships and reactions to unforeseen circumstances. To this end: GF2 requires players to continuously self-define and pursue open-ended collective goals; GF6 generates uncertain and unpredictable game state changes; GF7 and GF8 organise the gameplay in phases structured as a problem-management process suitable to define and revise game goals and strategies, explore game circumstances, and react to game events.

- *Sociality* (DG4): the integration of GF3, GF4, GF8, and GF9 promotes social interaction by creating a shared gameplay process requiring collective action and decision-making, and providing a shared physical play space enabling meaningful face-to-face interactions.

- The *iterative structure of gameplay tasks* (DG5) is defined by the integration of GF2, GF7, and GF8, which require players to continuously improve the state of the city through a tailored gameplay loop that (a) compels players to engage in cycles of exploration, planning, and action that simulate adaptive problem management processes, and (b) can only progress based on collectively-agreed interpretations of the game's circumstances.

- As for the *meaning-making information flows* (DG6), all the core game features comprise UI and/or game scene elements designed to continuously convey information relevant to interpret present and past game circumstances, anticipate possible futures, and learn about the scenario at hand.

- In order to provide adequate *diversity and complementarity of player roles* (DG7), GF3 ensures that players have unique roles with specific interests, abilities and resources. These were designed to require synergistic action while also creating conflict possibilities, thus compelling constant dialogue and consensus building.

- *Shared and constrained goals* (DG8) is implemented by GF2 and GF4, whose interplay requires players to agree on how best to use limited shared resources, negotiating individual interests for the common good, and without the ability to fully predict whether an agreed resource allocation will effectively improve the state of the city.

- *Traceability of gameplay payoffs* (DG9): since full traceability of players' decisions is not possible in games set in ill-defined and uncertain scenarios (Fabricatore et al., 2020), GF7 and GF8 were designed to give players the time and information they need in each round to evaluate the impact of their actions on the game state, while preserving the uncertainty, fostered by design through GF2.

- *Collective progression* (DG10) was implemented through GF8, which ensures that players can only progress through agreeing collective decisions at each phase of each game turn.

4.4. Expected impacts

The expected results of our operationalisation of the design guidelines are that the interplay of Sustain's core features would promote overall sustainability learning by engaging players in sustainability scenarios defined by systemic, complex and ever-changing problems and conditions. As summarised in Table 4, these features should create conditions that are considered in the literature as beneficial for promoting the following outcomes:

- *Sustainability awareness.* The interaction of GF1-4, GF6 and GF7 aims to provide players with opportunities to critically analyse, openly discuss, and collaboratively propose specific solutions to global sustainability problems characterised by multiple interdependent dimensions and limited resources. The literature suggests that this is key to promote sustainability awareness (Angelidou and Psaltoglou, 2017; Buckler and Creech, 2014; Tilbury and Wortman, 2004). In relation to SSGs, Fabricatore and Lopez (2014) indicate that a holistic understanding of sustainability can be fostered through game activities that are embedded in sustainability-related scenarios (GF1, GF4), and require players to embody roles with different priorities and action capabilities (GF3), to define goals themselves (GF2), to establish cause-effect relationships (GF6), and to negotiate their plans with other stakeholders (GF7). This would involve players in adopting different perspectives to understand the conditions, problems and mechanics relevant to acting in sustainability contexts, thus promoting awareness of the intricate dynamics that govern sustainability scenarios. We therefore expected that playing Sustain would encourage the development and adaptation of players' mental models by encouraging them to consider different perspectives and negotiate solutions according to available resources. This will create an awareness of sustainable development as a multidimensional, collective and participatory issue.

- *Commitment to sustainability.* The integration of GF1, GF2, GF4 and GF5 engages players in problem situations with competing dimensions and needs, requiring them to negotiate and agree on shared solutions through a process of collective and individual exploration, reflection and decision-making. During this process, participants must reveal and revise their own beliefs, assumptions and biases about sustainable development, and reflect on how individual actions can lead to collective change. According to the literature (Tilbury and Wortman, 2004; Fabricatore and Lopez, 2014), this would not only encourage the development of shared viewpoints, but also prompt players to take responsibility for their individual decisions and proposals. Commitment to sustainable development is promoted when individuals learn to negotiate and articulate a shared vision of possible futures (Tilbury and Wortman, 2004). In addition, taking responsibility for the outcomes of personal decisions and views promotes a sense of control and agency (Fabricatore and Lopez, 2014), which affects how individuals perceive themselves in relation to their own communities and leads to greater motivation and commitment to action (Tilbury and Wortman, 2004; Agbedahin, 2019; Fabricatore and Lopez, 2020).

- *CAPM.* Overall, the features from GF2 to GF9 were designed to force players to deal with uncertainty and unpredictability while encouraging collaboration and adaptation throughout the process. In particular, GF2, GF7 and GF8 force players to engage in a cyclical, problem-based turn structure that involves uncertain relationships (determined by the fuzzy logic system) between local and global action effects. We assumed that these features would foster players' ability to continuously adapt their goals and strategies, accounting for non-fully-predictable circumstances and promoting a balanced development of the scenario at hand (Checkland and Poulter, 2010; Fabricatore and Lopez, 2019, 2020). Furthermore, GF2-9 enforce the interweaving of individual and collective activity phases. This is crucial for ESD, as it promotes the ability to continuously develop, harmonise and integrate one's own views and mental models with those of others, in order to build shared perspectives that reflect common interests, and pursue these interests accordingly (Tilbury and Wortman, 2004; Fabricatore and Lopez, 2020).

Table 4: Mapping among design guidelines, game features and expected outcomes

	Design Guidelines										Outcomes		
Features	DG1	DG2	DG3	DG4	DG5	DG6	DG7	DG8	DG9	DG10	Awareness	Commitment	CAPM
GF1: gameplay problems mirroring real-world scenarios and involving multiple sustainability dimensions	✓	✓				✓					✓	✓	
GF2: shared, ill-defined goals	✓	✓	✓		✓	✓		✓	✓		✓	✓	✓
GF3: different player roles, with complementary role-specifications, and possibly conflicting interests	✓	✓		✓		✓	✓				✓		✓
GF4: shared and limited resources needed for individual actions, requiring negotiation and agreement		✓		✓		✓		✓			✓	✓	✓
GF5: AR-supported autonomous exploration and deployment of actions		✓				✓						✓	✓
GF6: not deterministic local-to-global effects		✓	✓			✓					✓		✓
GF7: turn structure, allowing iterative problem management and gameplay evolution			✓		✓	✓			✓		✓		✓
GF8: within-turn gameplay phases, combining individual and collaborative activities			✓	✓	✓	✓			✓	✓			✓
GF9: co-located play space				✓		✓							✓

DG1:sustainability contextualisation, DG2:player agency, DG3:player adaptivity, DG4:sociality, DG5:iterative structure of gameplay tasks, DG6:meaning-making information flows, DG7:diversity and complementarity of player roles, DG8:shared and constrained goals, DG9:traceability of gameplay payoffs, DG10:collective progression

5. Experimental Study

We conducted a quasi-experimental study aimed to address the following research questions (RQs):

- RQ1: does playing Sustain foster a change in players' sustainability awareness?
- RQ2: does playing Sustain promote a change in players' commitment to sustainability issues?
- RQ3: does Sustain promote CAPM?

The study involved 99 volunteers recruited among students and PhD candidates of Politecnico di Torino in Italy. Participants possibly knew one another but had not previously worked together. The students belonged to different faculties of engineering and architecture. They received no credits for their participation, which was entirely voluntary. We randomly assigned participants to 33 groups of three players each. The number of groups and participants per group was estimated using the G-Power software, based on a priori power analysis for both correlations and pre-post paired comparisons, using a conservative small effect size of 0.3 and small correlation of 0.3, power $(1-\beta) = 0.80$, and $\alpha = 0.05$). As for the participants' characteristics, 76% of them were male, and their age range spanned between 20 and 29 ($M = 23.3$, $SD = 2.02$). Concerning technology awareness, 87 participants had previous experience with AR (four of them frequently, six regularly and the remaining rarely). Similarly, 74 participants reported being occasional (39) or frequent (35) gamers.

5.1. Procedure

Playing sessions were conducted in a laboratory equipped with the devices and setup necessary to play Sustain. All sessions lasted approximately one hour, and were video and audio recorded for analysis. Each group played one session, with only one group per session. Before playing the game, we asked participants to complete a pre-test questionnaire aimed at evaluating their awareness of sustainability-related themes. Then, participants were given time to familiarise with Sustain through a "training stage" consisting in two gameplay turns. This aimed at facilitating the comprehension of the main game mechanics and UI interactions. A "live" tutorial was presented to provide players with information regarding the game context, the roles they could assume, and step-by-step instructions on how to use the game interface. To avoid external conditioning, players were not explicitly instructed nor encouraged to discuss the motivation of their actions, or establish shared strategies. After the tutorial, each group played Sustain for six gameplay turns. Finally, players completed a post-test questionnaire to collect information about their gaming experience, and to measure changes in their sustainability awareness.

5.2. Data collection

Pre and Post-test questionnaires. The questionnaires (available in Appendix A) were created ad hoc for this study, and required participants to express their agreement on several statements using a five-point Likert scale (1 = strongly disagree; 5 = strongly agree).

The pre-test questionnaire included eight items organised into two subscales: (i) *sustainability awareness* (5 items, Cronbach's $\alpha = 0.60$), exploring players' awareness of sustainability themes regarding the relevance of urban planning in achieving environmental regulations, the impact of economic growth on the community's quality of life, and the complexity of the main challenges in the management of a sustainable urban area; and (ii) *commitment to sustainability* (3 items, $\alpha = 0.70$), evaluating participants' motivation to engage with the development of their community. Items for the sustainability awareness and commitment scales were based on validated instruments, i.e. the New Environmental Paradigm (NEP) scale (Dunlap et al., 2000), and the Sustainability Consciousness Questionnaire (Gericke et al., 2019). These were adapted to address awareness of general principles for sustainable urban design (UN-Habitat report, 2009), and willingness to adopt sustainable behaviours. The pre-test questionnaire also gathered data on participants' sociodemographic profile, and familiarity with AR and games.

The post-test questionnaire included 29 items. The first eight were the same statements included in the pre-test questionnaire. The remaining ones were organised into three sub-scales: (i) *elicitation of sustainability thinking skills* (six items, $\alpha = 0.75$), exploring to what extent players perceived that the game required them to use skills associated with sustainability thinking; (ii) *perceived affordances for collaboration* (five items, $\alpha = 0.67$), aimed at understanding the relevance of the game's design features in supporting collaboration; and (iii) *perceived quality of collaboration* (four items, $\alpha = 0.72$). This questionnaire also included items examining players' perceptions regarding their interest for and immersion in the game AR-based scenario, individual motivations to collaborate, and overall enjoyment with the game. These were included to explore the overall gameplay experience, given that players' active involvement in and enjoyment of gameplay dynamics is crucial to promote game-based learning (Fabricatore and Lopez, 2019; Stanitsas et al., 2019).

Video analysis. All videos were annotated using ANVIL software (Kipp et al., 2014), based on a coding schema jointly developed by all authors. The schema aimed at identifying and classifying *verbal activity* and *joint attention* displayed by each group. *Verbal activity* was coded identifying all time intervals where at least one player produced an utterance. *Joint attention* was coded identifying all time intervals in which two or three players focussed on the same object, and describing these as a tuple composed of (i) the object of shared attention (e.g. tablets, central screen or other players), (ii) the number of players displaying shared attention, and (iii) the time length of the event. The coding schema was initially formulated based on literature on collaboration assessment and computer-supported collaborative learning (CSCL) (Isenberg et al., 2010; Martinez-Maldonado et al., 2013). It was then iteratively refined through a collaborative analysis of three random videos, discussing coding criteria, generating new categories/codes, and excluding ambiguous categories/codes. Finally, three researchers annotated all the session videos, resolving a few disagreements and ambiguities through consensus.

In-game analytics. Sustain records a variety of fine-grained data concerning game state, in-game activities and player actions. These include information such as play and debriefing times, number of actions analysed, confirmed and withdrawn actions, evolution of game state variables, and UI interactions.

5.3. Indicators and data analysis

Based on theoretical considerations and empirical findings reported in the literature, data collected from different sources were analysed and aggregated to formulate indicators suitable to answer our research questions. These are described below and summarised in Table 5.

Sustainability awareness refers to the ability to acknowledge the existence of critical issues affecting sustainable development, recognise the relevance of their implications, and understand the key mechanisms that define their complexity and the challenges that they pose (Buckler and Creech, 2014; McCowan, 2019). We measured sustainability awareness was measured as the difference between pre/post scores on the *Sustainability awareness* scale from the pre and post-test questionnaire.

Commitment to sustainability represents a disposition to act individually or collectively to improve sustainability issues (Buckler and Creech, 2014; Tilbury and Wortman, 2004). In our study, it was measured assessing the difference between the pre/post scores of the *Commitment to sustainability* scale from the questionnaires. We also investigated the role of Sustain in promoting sustainability-thinking as perceived by players, through the *elicitation of sustainability-thinking skills* sub-scale. This was to explore whether a change in player commitment was associated to the thinking processes expected to be promoted by Sustain's design features.

CAPM consists in an iterative and collective process whereby participants work together to identify, achieve, and maintain desirable states of affairs while coping with uncertain and unpredictable conditions (Rittel and Webber, 1973; Jones, 2014). Such a process involves continuous adaptation of goals and plans (Checkland and Poulter, 2010; Jones, 2014), as well as shifts in team coordination processes to respond to changing circumstances (Burke et al., 2006; Maynard et al., 2015). CAPM can thus be observed through the variation of goals and plans according to a shared understanding of the current situation, and through changes in collaborative dynamics aimed at achieving desired outcomes. For this study, we developed the following indicators to examine team adaptation and collaboration dynamics relevant to achieve a balanced city growth throughout the game turns.

- *Coupling style* describes the extent to which team members' actions are coordinated (Tang et al., 2006). Verbal activity and joint attention are the main elements that define the coupling style. Collaborators who talk while focusing their attention on the same external object, person or event are said to be working tightly-coupled, whereas focus on different objects or lack of verbal interactions is considered indicative of loosely-coupled work (Isenberg et al., 2010; Martinez-Maldonado et al., 2013). Groups typically alternate between loosely and tightly-coupled collaboration depending on task characteristics and the individuals' need or willingness to collaborate (Tang et al., 2006). Studies involving co-located collaboration have found that there is a relationship between task success and the amount of time spent working tightly-coupled (Isenberg et al., 2010; Martinez-Maldonado et al., 2013). In our study, *tight-coupling* was defined as the percentage of time players simultaneously engaged in verbal and joint attention activities during gameplay (data from video analysis).

- *Satisfaction with collaboration* has been associated with improved team coordination and adaptation (Burke et al., 2006; Notari et al., 2014). In this study, we used (i) the individual measure of *satisfaction with the collaborative plan* reported by players at the end of each phase of collaborative planning (data from game analytics); and (ii) the *perceived quality of collaboration* declared by players in the post-questionnaire. We also examined (iii) players' motivations to collaborate, and (iv) the *perceived affordances for collaboration* (data from post questionnaire) to understand player satisfaction in light of personal motivations to collaborate, and the perceived role of Sustain's design features in fostering collaboration dynamics.

- *Team adaptation* is a process that evolves over time in which team members make adjustments to their cognitive, interpersonal, and behavioural actions to meet expected or unexpected demands (Burke et al., 2006). In our study, we analysed adaptation in terms of the appropriateness of the collaborative plan to evolve the current game state toward the overall game objective, i.e., achieving a balanced growth of the global state variables (environment, population, and happiness). In each turn t, players were presented with the state of these variables at the end of the turn $t-1$. Consequently, they had to plan together how to allocate resources in the coming round, taking into account the need to (a) compensate imbalances that had emerged in $t-1$ and (b) further increase global variables values. We considered the first point (a) particularly relevant to investigate adaptive decision-making, assuming that an adaptive plan formulated at the beginning of a new turn should reflect a clear attempt to offset current imbalances in the game state. Hence, we investigated team adaptation by analysing the relationship between the vectors CP_t^i, representing the *collaborative plan* of resource allocation formulated by team i in turn t, and CRA_{t-1}^i, representing the *compensatory resource allocation* plan, i.e., the ideal resource allocation that team i should have deployed in turn t, to compensate imbalances between global variables originated in turn $t-1$. These two vectors were compared through a cosine similarity test (Cha, 2007), assuming that a higher similarity between an ideal and an effective resource allocation would be indicative of a stronger attempt to respond to the need to compensate unbalances, as required by Sustain's goals. To compute CRA_t^i, we first defined as $S_{t-1}^i = [e_{t-1}^i, p_{t-1}^i, h_{t-1}^i]$ the normalised global state vector, i.e. the vector containing the values of the global variables environment, population and happiness in $t-1$, each divided by its respective maximum value achievable in the game. Then, we defined as $ms_{t-1}^i = \max\{e_{t-1}^i, p_{t-1}^i, h_{t-1}^i\}$, i.e., the maximum value achieved by any normalised state variable in $t-1$. Finally, the compensatory resource allocation vector was defined as $CRA_t^i = [ms_{t-1}^i, ms_{t-1}^i, ms_{t-1}^i] - S_{t-1}^i$.

- The *balanced growth* of global variables is a measure of how balanced the current global state of the city is, and represents the path that teams (collaboratively) take to achieve the game goal. At the end of each turn t, this indicator is computed as the sum of squared differences (SSD) between the normalised values of the three global variables in S_t^i. Thus, the lower the SSD, the more balanced the current global state of the city.

The general approach to data analysis included the use of: (i) descriptive statistics for all variables; (ii) Pearson correlations, to explore associations between variables; (iii) Hierarchical Linear Modeling (HLM) growth-curve unconditional models with time as the only predictor at level 1 (centred on Turn 1), in order to examine the trajectories of time-varying indicators over the playing session.

Specific data analysis techniques were also performed to analyse questionnaire sub-scales and items. For frequency analyses, responses 4 and 5 on the Likert scale were aggregated to indicate agreement or positive viewpoints. The Wilcoxon signed-rank test was used to investigate pre and post differences, as the Shapiro-Wilk test revealed non-normal distribution. Effect sizes between pre and post scores were thus computed using r= Z/sqrt(N).

Table 5: Indicators used to answer our RQs. For each item we report the data source (i.e. Pre and Post-test questionnaires, PPQ, Video analysis, VA, and In-game analytics, GA) and the performed data analysis.

Indicator	Data Source	Data analysis
Sustainability awareness	PPQ	Wilcoxon signed-rank test
Commitment to sustainability	PPQ	Wilcoxon signed-rank test
Tight coupling	VA	Descriptives and HLM growth curve modeling
Satisfaction with collaboration	GA and PPQ	Descriptive statistics and Pearson correlations
Team adaptation	GA	Cosine similarity and HLM growth curve modeling
Balanced growth of global variables	GA	SSD and HLM growth curve modeling

6. Empirical results

6.1. Gameplay experience

Players spent an average of 32'32" (SD = 11'28") playing Sustain. Almost all players had fun (96%), and felt challenged by the game and committed to its objectives (85%). The majority also felt that AR made the game more exciting (69%), allowing them to feel more immersed in the play experience (66%).

6.2. Sustainability awareness

A significant difference was found in the *sustainability awareness* scale between the pre and post measures ($Z = -3,211, p = 0.001$, effect size $r = 0.22$).

6.3. Commitment toward sustainability

Results from the questionnaire scale *commitment to sustainability* show a significant increase in players' willingness to commit to the development of their own community ($Z = -2.270, p = 0.023$), although the effect size is small ($r = 0.16$). Results from the questionnaire sub-scale *elicitation of sustainability-thinking skills* show that the vast majority of players (88%) perceived that the game stimulated thinking processes and sensibilities vital for sustainability. There is a small, significant correlation between the players' perceptions of thinking processes elicited by Sustain and their changes in commitment to sustainability ($r_{(198)} = 0.21, p = 0.03$).

6.4. CAPM

6.4.1. Tight coupling

On average, the groups spent 32% of their playtime working *tightly coupled*. Teams displayed different levels of coupling depending on the different turn phases of the game. The lowest levels of tight coupling were observed during the individual planning (9% of the phase) and the individual evaluation phases (7%), which were designed to require higher levels of individual activity. Similarly, the highest levels of tight coupling were observed during the collaborative planning (27%) and the final review phases (63% respectively), which were designed to promote collective discussion and agreement. Interestingly, similar levels of tight coupling were also observed during the execution phase (27%), where players had to propose individual actions according to their specific role capabilities, and were not required to collaborate.

Two separate growth-curve analyses were conducted to investigate the tight coupling during the total gameplay time and during the execution phase. For the total gameplay time, the results showed a non-significant variation across turns in the amount of time the teams spent tightly coupled. However, in the execution phase there was a significant linear increase in close coupling over time (Table 6). There is a significant variance in the tight coupling at the beginning of the game play session, but a non-significant difference in the rate of change of the groups over time. This reveals an homogeneous increase in the players' tight coupling that was not significantly affected by the players' starting level.

6.4.2. Satisfaction with collaboration

In the post questionnaire, the overall quality of collaboration was rated as good by the majority of players (85%). More than 80% of the players explicitly stated that Sustain's game design and visualisation features facilitated group discussion and agreement. Furthermore, in each turn players were highly satisfied with the devised collaborative plan ($M = 3.96, SD = 0.85$), and this satisfaction level did not change significantly across turns. We also found a significant association between players' *perceived affordances for collaboration* and both *perceived quality of collaboration* ($r(97) = 0.43, p < 0.001$) and average satisfaction with the collaborative plans ($r(97) = 0.25, p = 0.014$). In addition, the vast majority of players acknowledged that collaboration was motivated by the need to find the best in-game solution (93%) and the achievement of game goals (89%), while only 11% of players felt obliged to co-operate with other players.

Table 6: HLM growth models for Tight-coupling, Team adaptation and Balanced growth.

	Tight-coupling		**Team adaptation**		**Balanced growth**	
Parameter	Coef.	Std.Error	Coef.	Std.Error	Coef.	Std.Error
Fixed Effects						
Intercept	$19.78^{\dagger}$	1.95	$64.40^{\dagger}$	2.13	$23.24^{\dagger}$	2.82
Turn	$22.66^{\dagger}$	0.48	$4.62^{\dagger}$	0.66	-1.89*	0.92
Random Effects						
Variance Intercept	80.43^{*}	32.91	2.38	5.40	$1.77^{\ddagger}$	0.72
Variance Slope	1.32	2.10	0.05	0.04	$0.21^{\ddagger}$	0.07
Covariance Intercept-Slope	4.01	6.39	1.14	7.84	$-0.58^{\ddagger}$	0.22

Note: †: $p < 0.001$; ‡: $p < 0.01$; *: $p < 0.05$

6.4.3. Team adaptation

The HLM analysis of the *team adaptation* are presented in Table 6. The unconditional model with time as predictor showed a significant increase in similarity of 4.62 from turn to turn ($p < 0.001$). This means that the collective plan formulated at the beginning of a new turn increasingly resembled the ideal resource allocation required to offset current imbalances in the game state. The intercept and slope variances were not significant, indicating a negligible variation of cosine similarity between teams at the beginning of the game and over time.

6.4.4. Balanced growth of global variables

The sum of squared differences (SSD) between the normalised values of the three global variables defining the state of the city showed a decrease of -1.89 from turn to turn. The HLM growth-curve analysis revealed a significant decreasing trend in these differences (Table 6), indicating an increasingly-balanced growth of the three variables over time. In addition, there is a significant variation in the teams' initial SSD and in their rate of change, suggesting that additional variables could be used in the future to explore predictors of these differences.

7. Discussion

The aim of this paper was to present the design and evaluation of Sustain, an AR-based multiplayer SSG developed to promote sustainability learning by engaging players in urban development scenarios defined by systemic, complex and uncertain conditions. Sustain specifically aimed to foster players' awareness of and commitment with sustainability issues, and improve their ability to continuously address complex goals and changing circumstances through CAPM processes. To achieve this, our study first identified key SSG design guidelines that were used to design a core gameplay system consisting of nine interplaying game features engineered to improve sustainability awareness, commitment, and CAPM capabilities. Effective impacts in these three dimensions were finally ascertained using a multimodal approach that integrates in-game and out-of-game data to achieve a comprehensive understanding of cognitive, normative and relational learning effects. In the following, we discuss our findings in relation to our research questions (Section 5), accounting for design features and the theoretical framework underpinning the game.

7.1. Impacts on sustainability awareness (RQ1)

Sustain was designed to promote a holistic understanding of the factors that affect sustainability, which is key to address its complex, multidimensional and evolving nature (Fabricatore and Lopez, 2020). Accordingly, we expected that Sustain's core features would promote players' cognitive learning and consequently increase their awareness of the complex relationship between urban development, social wellbeing and environmental change.

In line with our expectations, we found a significant change in the *sustainability awareness* questionnaire scale after playing the game. Although the effect size was small, we consider this a promising result, given the relatively short play time (only about 32 minutes on average). This suggests that playing Sustain was effective in promoting holistic understanding of the factors underlying sustainable development. This is likely due to the specific features of the game design explicitly implemented to promote the intended cognitive learning outcomes. First, the urban development game required players to put the abstract concepts of sustainable development into practice. This likely enabled them to grasp the connection between local actions and global consequences (Madani et al., 2017). Second, by repeatedly planning and implementing similar tasks under changing conditions, players were likely able to test their evolving knowledge and progressively acquire a comprehensive understanding of the factors influencing sustainable development and their interconnections, thanks to an iterative exploration of concrete situations that mimicked real-world dynamics (Fabricatore et al., 2020). Third, Sustain gameplay required players to constantly shift from individual to collective processes and from global to local actions. This likely helped players explore and understand the multiple perspectives and levels of decision-making involved in developing sustainable solutions (Stanitsas et al., 2019). Overall, these features probably facilitated a rapid and holistic understanding of the complex interplay of heterogeneous sustainability factors involved in urban development scenarios.

The results of our study are consistent with previous research showing the potential of SSGs to promote cognitive learning (den Haan and van der Voort, 2018; Hallinger et al., 2020), which is particularly relevant in the current sustainability landscape (Armitage et al., 2018). People who are aware of complex sustainable issues show better abilities to identify problems, are more sensitive to their potential consequences and are more inclined to behave sustainably (Steg et al., 2014). Recent literature therefore emphasises the importance of raising awareness of sustainable urban development, especially among young people, in order to address the challenges that cities are currently facing and to improve society's capacity to act (Angelidou and Psaltoglou, 2017).

7.2. Impacts on commitment toward sustainability (RQ2)

Promoting normative learning, intended as changes in people's views and opinions about their role in sustainability issues, is a critical but challenging endeavour (Dahl, 2012; den Haan and van der Voort, 2018). Such changes are key drivers towards more sustainable societies, even if they are the most difficult to achieve (Dahl, 2012). In line with the literature (Steg et al., 2014; Tanenbaum et al., 2013), Sustain was designed to alternate between individual and collective tasks in order to promote dialogue, reflection and re-evaluation of personal knowledge and beliefs. Consequently, we expected players to perceive that Sustain stimulated thinking and affective processes conducive to reflection, collective reformulation of ideas, and increased commitment to the development of their own community.

This study found a small but significant increase in players' willingness to commit to the development of their own community. Previous literature emphasised that changes in viewpoint take time to occur (Dahl, 2012; den

Haan and van der Voort, 2018). Therefore, major increases were not expected after a short playing session. Furthermore, the results of the questionnaire scale *elicitation of sustainability-thinking skills* show that almost 90% of the players felt that the game stimulated thinking processes and sensibilities described as crucial for sustainable development (Tilbury and Wortman, 2004; Fabricatore and Lopez, 2014), e.g. by stimulating a sense of care for the city they were managing, and fostering understanding of others' goals and perspectives. This study also found a small correlation between perceived elicitation of thinking processes and changes in commitment. Even such a small association between these variables is an encouraging result, indicative that SSGs like Sustain may indeed foster normative learning. Specifically, personal transformations are more likely to occur when information about sustainable development is situated in scenarios promoting exploration, dialogue and affective engagement (Fabricatore and Lopez, 2014). Our findings thus suggest that SSGs can promote personal transformations by integrating these aspects in meaningful contexts requiring players to think critically, and collaboratively find solutions to sustainability problems.

7.3. Impacts on collaborative and adaptive problem management (RQ3)

Dealing with sustainability issues requires the continuous management of problem situations involving multiple and potentially conflicting factors and actors, which constantly evolve in ways that cannot be fully predicted or controlled (Rittel and Webber, 1973; Fabricatore and Lopez, 2020). Problem management processes should be *adaptive*, to respond to evolving circumstances and unpredictable events (McDaniel and Driebe, 2006; Fabricatore and Lopez, 2020), and *collaborative*, to harmonise the interests and actions of the involved stakeholders (Checkland and Poulter, 2010; Jones, 2014). Therefore, fostering CAPM capabilities is central to ESD. To promote CAPM, Sustain was designed as an open-ended urban development game in which players (a) pursue a shared goal defined by the interplay of multiple and conflicting variables; (b) engage in iterative processes that integrate collaborative and individual tasks whose outcomes cannot be fully predicted; and (c) interpret different, potentially conflicting, but complementary roles.

Accordingly, we expected to find evidence of Sustain's effectiveness in promoting players' ability to continuously collaborate, adapt to unpredictable circumstances, and iteratively improve the state of their urban development scenario.

Regarding collaboration, the results of this study suggest overall that (a) players recognised the relevance of collaboration in the game, were consistently satisfied with the results of their collaboration, and appreciated that the game facilitated collaboration; (b) the intensity of players' collaborative efforts increased over time, as reflected in the increase of tightly-coupled interactions between players; and (c) players collaborated to a significant extent, even when this was not enforced by the game.

Questionnaire data revealed that a large majority of players recognised that Sustain promotes collaboration and actually facilitates collaborative dynamics. Furthermore, the conjunct analysis of questionnaire data and in-game analytics revealed that most players were highly satisfied with the quality and results of their collective efforts (i.e. collaborative plans) throughout the gameplay activity, and that players satisfied with the quality of their collaboration or collective plans also appreciated that Sustain provided means to facilitate collaboration. Overall, this suggests that Sustain's design (a) implemented collaboration affordances recognised by players; (b) fostered consistently positive perceptions of the quality of collaborative processes; and (c) facilitated discussion and negotiation processes that led to satisfactory collective solutions. More than 90% of the players also recognised that collaboration was actually relevant to address the problem situations presented by Sustain, rather than being merely enforced by the game. This suggests that Sustain's design features made collaboration intrinsically motivated by the game mechanics, and thus meaningful to progress in the game. According to the literature, this is key to promoting sustainability learning through gameplay (Fabricatore and Lopez, 2014).

Observational data showed that players' tendency to work closely together increased significantly over time, which is considered by the literature a key indicator of collaborative ability (Isenberg et al., 2010; Martinez-Maldonado et al., 2013). Furthermore, the in-game analytics reflecting players' satisfaction with their team's collective plans showed a high level of appreciation that did not change significantly over time. Overall, this suggests that players became more collaborative over time and that their satisfaction with the outcome of collective decision-making (i.e., collaborative plans) was consistently high.

The above findings are particularly interesting when considering the interpersonal dynamics in individual vs. collective gameplay activities. Based on previous literature (Tang et al., 2006; Isenberg et al., 2010), we expected significant variation in *coupling styles* across game phases, with loosely-coupled collaboration being prominent in the individual planning, execution and evaluation phases (which did not require interaction between players), and more closely-coupled interactions predominant during the collaborative planning and collective review phases (which were explicitly designed to elicit discussion and collaborative decision-making).

Our findings partially confirmed these expectations, with the lowest degree of coupling during the individual planning and evaluation phases, and a significantly higher degree of tight coupling during the collaborative planning and final (collective) review phases. However, *tight-coupling* was similar during the collaborative and execution planning phases, although the latter did not require collaboration. This was likely due to players frequently interacting during the execution phase in order to check each other's devices and exchange information to identify individual actions suitable to implement collectively-agreed plan. Monitoring and predicting teammates' acts represent fundamental mechanisms for coordinated action (Vesper et al., 2010; Sebanz and Knoblich, 2009). Sustain has likely promoted these mechanisms by providing role-specific information through each player's device, and allowing players to freely interact anytime. This may have enabled players to monitor each other's actions, and share information to keep their mental models aligned and coordinate their actions, making collaboration valuable even when it was not compulsory.

The increasing tendency of teams to work in a tightly-coupled manner found in this study can also be interpreted as the development of team *adaptation* capabilities over time. Maynard et al. (2015) argue that teams adjust their interpersonal processes as an adaptive reaction to expected or unexpected demands. In this sense, the results of this study suggest that players successfully adapted to the unpredictably-evolving state of the cities they managed, as they (a) improved their collaborative behaviours in response to changes in game state, (b) responded by formulating plans reflecting clear attempts to compensate for undesirable unbalances among global game state variables, and (c) managed to promote increasingly-balanced game states.

In addition, this study analysed whether teams' collaborative plans reflected a significant attempt to adapt to evolving game states by compensating unbalances among the three global game state variables (population, environment, and happiness), as required by Sustain's overarching game goal. To this end, we examined the temporal changes in similarity between the vectors representing the collaborative plans developed by the teams in any given game turn t, and the ideal resource allocation required in that round to compensate unbalances between the global game state variables. The results show that the similarity between these two vectors tends to increase over time, and that this trend is significant. This suggests that the teams' cooperative plans reflect an increasingly accurate attempt to respond to the need to balance the global game state variables.

Finally, by analysing the changes in the discrepancies between the three global game state variables, we investigated the results of the teams' attempts to balance the game state over time. We found that the values of state variables exhibited a significant tendency to become increasingly similar. This suggests that the teams succeeded in progressively balancing their cities, as required by the game.

Overall, the results of this study suggest that players showed a significant tendency to increase their closely-coupled collaborative interactions, and to attempt to promote the balanced growth of their cities by compensating unbalances between global game state variables in each gameplay turn. This is arguably a strong indication that Sustain provided opportunities to promote collaborative formulation of adaptive problem management approaches that proved effective in increasingly achieving the overarching game objective.

7.4. Value of AR technologies

In order to overcome the limitations of previous AR-based SSGs described in section 2, AR was leveraged as a central element of Sustain's core activities. In particular, to enhance the contextualisation of learning, AR affordances were designed to keep players continuously focussed on the sustainability-related meanings of goals, actions and events characterising the complex scenarios they managed (Fabricatore et al., 2020; Scavarelli et al., 2020). AR was also leveraged to enable players to move and interact freely in the physical game space, and to provide opportunities to share information concerning individual roles and views through meaningful face-to-face interactions. These features are particularly important in ESD, since they define social learning spaces suitable to promote changes in individual viewpoints and behaviour through meaningful collaborative interactions (Muro and Jeffrey, 2008; Tilbury, 2004). Furthermore, our evaluation suggests that players found that the game was overall enjoyable, and that AR was able to immerse them in the game experience. This may have further increased players' motivation to engage in the proposed complex problem management activities (Fabricatore et al., 2020). In conclusion, these findings seem to support the effectiveness of AR technologies in enhancing the impact of SSGs and promoting motivating social learning.

7.5. Impacts of our work on ESD

Given the nature of the Sustain's core features, the impact of its use, and the analytical approaches used to ascertain these impacts, we believe that our work can benefit ESD in several ways.

Sustain as a learning tool. Sustain can be used to enrich learning activities that aim to achieve objectives that are crucial for ESD but not easily achievable without appropriately designed interactive simulations.

Reuse of Sustain's core gameplay system to develop new urban development games. Sustain's core features are not tied to the player roles, gameplay actions, resources and scenarios specifically implemented in this game. Therefore, Sustain's core gameplay system can be used to develop different urban development games by modifying elements already present in Sustain (e.g. changing the scenario, the actions and resources available to develop a city, the semantics of achievement indicators such as "happiness", and so on), or by adding new elements (e.g., non-player controlled events affecting the game state). The effects of these games could then be analysed to investigate whether they promote learning impacts similar to Sustain's, in order to further corroborate the effectiveness of Sustain's core gameplay system, and provide insights into adding more features to the system.

Expanding Sustain's gameplay system and design guidelines to develop games for different sustainability domains. We believe that the approach taken in designing Sustain's core features can be extended to other contexts involving complex systems learning in relation to sustainable development. This type of learning requires educational approaches emphasising collaboration and adaptation (Diniz dos Santos et al., 2019). Therefore, the design guidelines for collaboration and CAPM used in Sustain could be integrated with other domain-specific design guidelines, in order to extend and adapt Sustain's core gameplay system to design other types of games based on sustainability scenarios other than urban development.

7.6. Research limitations

The limited playing time might have affected players' attitudes, skills and knowledge development, preventing the identification of stronger associations between variables. However, we emphasise the positive effects in terms of increases in sustainability awareness and commitment, as well the development of the team adaptation capabilities and effectiveness in jointly tackling sustainability open-ended problems.

Another limitation is that changes in the game scenario are only due to players' actions. The unpredictable relationship between the local impact of these actions and their indirect effects on the global state of the city does indeed introduce uncertainty into the game, which in turn elicits team adaptation. However, to further strengthen CAPM, the current design could be improved by introducing non-player-triggered events (e.g. floods or earthquakes) that affect the global and local game state in disruptive and unpredictable ways (Fabricatore et al., 2020).

Finally, sustainability awareness and commitment were measured by few items and scales developed ad hoc for this study. The use of validated instruments could serve to assess impacts more reliably and allow comparisons with other studies.

8. Conclusions

This article presented the urban development game Sustain and the results of an evaluation of its effectiveness in promoting sustainability learning. The core gameplay features of Sustain were carefully designed based on a sound theoretical framework, so that their interplay could foster players' awareness of and commitment with sustainability, and their ability to engage in CAPM processes. Our findings suggest that the game (and its features) did indeed promote these learning effects.

For future work, we are considering repeating our experiment, extending the evaluation period and introducing multiple play sessions and delayed evaluation, in order to better assess both the extent and durability of the learning effects. In addition, we are planning a new study based on a randomised control trial design. Here, we hypothesise that an experimental group using Sustain should show better sustainability learning gains than a control group.

Finally, we would like to investigate the relative importance of Sustain's core gameplay features. As explained earlier, these features were designed to interact and produce systemic effects. This makes it difficult to conduct reductionist analyses of isolated game features (e.g., by creating and evaluating game variants with/without specific features). However, we believe that multivariate analysis approaches could be used to examine how players' engagement with different features may affect the variance in learning outcomes. This could be useful to gain new insights into the relative importance of the features included in Sustain's core gameplay system.

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Appendix A. Pre and post-test questionnaires

All items are to be answered on a 5-point scale (1 – 'strongly disagree' to 5 – 'strongly agree')

Table A.7: Items for *Sustainability awareness* scale (pre and post questionnaires)

A	**Sustainability awareness**
Pre and post	People with limited comprehension of problems can generate global changes.
Pre and post	Urban planning and development is a valuable resource to achieve ecological regulation.
Pre and post	Anticipating impacts of urban growth is crucial to improve community livability.
Pre and post	Misuse of natural resources can cause serious social problems.
Pre and post	The environment should be protected because it has an enormous value in maintaining or enhancing the quality of life for humans.

Table A.8: Items for *Commitment to sustainability* scale (pre and post questionnaires)

B	**Commitment to sustainability**
Pre and post	I feel motivated to contribute to my own community's development.
Pre and post	I feel I am capable of contributing to my own community's development.
Pre and post	I am interested in knowing about how I could contribute to my own community's development.

Table A.9: Items for *Elicitation of sustainability thinking skills* scale (post questionnaire)

C	**Elicitation of sustainability thinking skills**
Post only	The game encouraged me to understand the other players' goals and perspectives.
Post only	The game made me aware that individual values affect collective actions.
Post only	The game required me to balance personal priorities with community needs.
Post only	While playing the game I cared for the wellbeing of the city we were managing
Post only	While playing the game, I felt that my decisions could make a difference.
Post only	My experience in the game can help me understand possible impacts of my decisions in real life.

Table A.10: Items for *Perceived affordances for collaboration* scale (post questionnaire)

D	**Perceived affordances for collaboration**
Post only	Exchanging ideas with other players was key to find the best use of available resources.
Post only	Collaborating with other players was essential to be successful in the game.
Post only	The game layout and environment (room, table, devices) made it easy to discuss with others.
Post only	The game features available to control and progress in the game were helpful to define collective goals and strategies.
Post only	The game visualisation tools were useful when discussing the collective plan.

Table A.11: Items for *Perceived quality of collaboration* scale (post questionnaire)

E	**Perceived quality of collaboration**
Post only	I actively participated in the group discussion.
Post only	The discussion between players was good.
Post only	I felt all players worked to achieve a mutual understanding of the problem.
Post only	The collective strategies were better than the individual ones.

Table A.12: Single items evaluating game experience (post questionnaire)

F	**Game experience**
Post only	I had fun playing Sustain.
Post only	Using AR in the game allowed me to feel more immersed in the game.
Post only	AR made the game more interesting.