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BOARD GAMES ON THE PATH TO ENVIRONMENTAL EDUCATION FOR SUSTAINABILITY

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Abstract

The response to global Anthropocene challenges requires a reimagined science education, shifting its goal from supplying human capital with skills and capabilities in specific areas toward educating scientifically literate citizens who can make informed sustainable choices (Gough, 2021; Luttenberger & Mandić, 2022). Aiming to contribute to such change, this article explores the intersection of STEAM (Science, Technology, Engineering, Arts, and Mathematics) education and education for sustainability (EfS), emphasizing the need for innovative frameworks and tools to facilitate a transition toward a more sustainable future. As gamification emerges as a powerful mechanism for engaging learners, fostering scientific literacy, and driving sustainable practices, this article presents an original framework that leverages the synergies between these areas and supports the design of three STEAM educational board games addressing environmental education for sustainability.

Keywords: *education for sustainability; environmental education; board games; STEAM; living labs.*

Introduction

In the face of pressing global challenges brought about by the Anthropocene era, there is a growing recognition of the need for a paradigm shift in education. STEM (Science, Technology, Engineering and Mathematics) education has long been focused on specific subject areas, while the emerging STEAM (adding Arts to STEM) approach emphasizes a more holistic, humanistic, and interdisciplinary perspective. In this context, EfS has primarily centered on environmental education, often forgetting its integration with the social and economic pillars. To effectively address the complex issues of the Anthropocene and foster a generation of environmentally conscious global citizens, a convergence of STEAM education and sustainability education is imperative. This integration calls for efforts in the development of innovative frameworks and tools that can facilitate the transition toward a more sustainable future. One such tool that has gained prominence in the realm of sustainability education is gamification. By incorporating game design principles into educational contexts, gamification has proven to be a powerful mechanism for engaging learners and promoting behaviour change toward sustainability. However, for gamification to be truly effective in fostering scientific literacy and driving sustainable practices, it must itself be underpinned by theoretical frameworks that align with the desired transformative goals.

This article explores the intersection of STEAM education and EfS, emphasizing the importance of theoretical frameworks and tools in driving meaningful change, focusing on the relevance of gamification processes. The first section presents a literature review on environmental education in the context of EfS, concentrating on STEM/STEAM approaches, concluding that more holistic frameworks and interactive learning materials are necessary (Maidatsi, Christopoulou & Oikonomou, 2022). The second section presents a literature review on the use of games in EfS, identifying factors affecting their effectiveness.

Drawing on insights from existing literature and research, the final section presents an original framework that aims to bridge the gap between STEAM education, sustainability education, and gamification, offering a structured approach to designing three educational board games that promote environmental literacy and sustainable decision-making. The three games will be described according to the framework's key elements.

STEM/STEAM Approach to Education for Sustainability

Education is a critical motor and an outcome of sustainability. If quality education for all is recognized as a Sustainable Development Goal (SDG), EfS is necessary to develop students' knowledge, values, agency and actions that lead to a sustainable society (Rodrigues-Silva & Alsina, 2023). The United Nations Educational, Scientific, and Cultural Organization (UNESCO) argues for orienting EfS through different learning techniques, such as teaching contextually, working collaboratively with students, using project-based approaches, fostering problem-solving (Maidatsi et al., 2022) and interdisciplinarity pedagogy (Maidatsi et al., 2022; Rodrigues-Silva

& Alsina, 2023). In line with these recommendations, STEM and STEAM are defended as relevant approaches centered on interdisciplinary teaching and associated with meaningful, active and authentic learning, focused on hands-on inquiry and open-ended exploration (Maidatsi et al., 2022), but differ regarding the scope of education (Rodrigues-Silva & Alsina, 2023). The first represents a pedagogy concentrating efforts on technological knowledge areas of Science, Technology, Engineering and Mathematics, whereas the latter represents the inclusion of arts and humanities, demanding a broader curriculum scope (Maidatsi et al., 2022; Rodrigues-Silva & Alsina, 2023).

Sustainability-oriented education is referred to as Education for Sustainability (EfS) (Rodrigues-Silva & Alsina, 2023), Education for Sustainable Development (EfSD) (Maidatsi et al., 2022), or Education for Resilience and Sustainability (EfRS) (Luttenberger & Mandić, 2022). As the terms are used interchangeably, we assume the designation "Education for Sustainability (EfS)." Analyzing current scenarios of EfS, it is possible to identify a focus on the environmental pillar, where an intersection is noticeable between environmental-oriented education and STEM/STEAM educational approaches. Nevertheless, traditional STEM curricula still exist in silos and are seriously constrained by the disciplinary structure, fostering few transdisciplinary perspectives. This reflects the absence of social and economic pillars that signal embracing the complexity of sustainability. Such aspects highlight the tension between STEM education's goal of supplying human capital with skills and capabilities in specific areas and the aims of sustainability education: producing scientifically literate societies and active, democratic citizens (Gough, 2021). Research highlights these scenarios and underscores the need to rethink science education, in response to global Anthropocene challenges, to foster scientifically literate global citizens who can make informed decisions for a sustainable future (Gough, 2021; Luttenberger & Mandić, 2022).

Table 1 identifies these challenges and outlines proposals for shifting towards more holistic frameworks in curriculum design and instructional planning (Gough, 2021; Luttenberger & Mandić, 2022). Similarly, there is also a need for new pedagogical strategies and interactive learning materials that apply STEAM knowledge and skills to foster competencies in investigating sustainable issues and developing visions for action and change, fostering sustainability (Rodrigues-Silva & Alsina, 2023) (see Table 2).

Table 1
Research on current scenarios of EfS, in the intersection between environmental-oriented education and STEM/STEAM educational approaches (source: authors)

Authors/Year	**Educational Context**	**Study Aim**	**Intersection between environmental-oriented education and STEM educational approaches**	**Paradigm/Framework Shifts Towards a Reimagined Science Education for Sustainability**
Gough (2021)	Australia's education system	Analyzes the Australian Government's STEM and climate change education policies and programs through an ecological education lens and finds gaps.	Reflects a vision for society to be engaged in and enriched by science which has, as its prime focus, building skills and capabilities in STEM. Government's policies and projects in education ignore intergovernmental environmental initiatives.	Calls for the Australian education agenda to include meaningful engagement with climate change and biodiversity-related topics through ecological education in the school curriculum and discusses what a reimagined school science curriculum could look like.
Kanaki et al. (2022)	Primary education (first and second graders)	Investigates the association between algorithmic thinking and performance in environmental study.	Supports the orientation of education towards strengthening environmental education to improve sustainability and stimulate environmental protection and public health through computational thinking (CT).	Advocates for the synergistic learning of CT and STEM fields and supports game-based learning and educational practices that see students as active creators rather than passive consumers of digital technology.
Rodrigues-Silva & Alsina (2023)	Early childhood education	Explores the intersection between interdisciplinary STEM/STEAM educational approaches and Early Childhood Education for Sustainability (ECEfS).	Most studies focus on sustainability's environmental pillar and address the discipline of science more frequently. STEM has a substantial presence in the literature reflecting on overseeing social issues.	Calls for the incorporation of knowledge closely related to understanding societies, using a STEAM approach instead of STEM. Accordingly, there is a need for pedagogical strategies that apply STEAM knowledge and skills to foster children's action competence.
Axelithioti et al. (2023)	Higher education (engineering courses)	Explores how higher education prepares engineers to address the climate crisis via engineering curricula analysis.	There is evidence of the dissociation of engineering education from climate-related content.	Calls for a novel approach that goes beyond curricula analysis to integrate Mitigation, Adaptation, and Climate Change (MACC) within module outlines, paving the way for future integration.
Liu & Kan (2024)	Higher education (Taiwan's system)	Evaluates the current situation of education for sustainable development, climate change education, and environmental education in a nationwide context.	Relevant courses are more concentrated in the STEM and bioscience fields. The curricula, however, are seriously constrained by the disciplinary structure and foster few transdisciplinary perspectives.	Suggests breaking disciplinary silos to incorporate interdisciplinary approaches that bridge STEM fields with environmental and sustainability concepts to promote systemic thinking.
Zoller (2015)	Secondary and higher education	Presents and discusses a pre-post research design on systems thinking, evaluative thinking, and decision-making capabilities in "sustainability thinking."	Contemporary science education in secondary and tertiary levels is mainly disciplinary in science, technology, and engineering courses.	Defends a paradigm shift from Low-Order Cognitive Skills (LOCS) to High-Order Cognitive Skills (HOCS), promoting transdisciplinary learning aimed at "sustainability thinking."
Nugroho et al. (2019)	Higher education (pre-service teachers)	Predicts the effects of a STEM approach based on local wisdom in enhancing sustainability literacy.	Education in STEAM requires that teachers possess teaching knowledge beyond their fields of specialization and are able to link science learning to the real world or local culture.	Proposes integrating the STEM approach with character-based Local Wisdom Education as a contextual and culturally relevant solution in environmental education. Emphasizes "minds-on," "hands-on," and "hearts-on" teaching.
Maidatsi et al. (2022)	STEM education	Studies the integration of sustainability and environmental education into STEM education.	Traditional education fails to offer deep conceptual knowledge applied to STEM and Environmental education, requiring a long process for integration to achieve sustainable development via education.	Calls for standards to provide frameworks for curriculum and instructional design that combine STEM, sustainability, and new technologies. Advocates for real-world learning supported by interactive materials, IoT technologies, and formative assessment strategies.
Luttenberger & Mandić (2022)	International organizations and professional associations	Analyzes the features of education for resilience and sustainability based on strategic documents from international organizations and associations.	In developing curricula for resilience, educators must shift the mindset from controlling nature to participating with nature. Regarding STEM, this implies going beyond workforce development to cultivate critical thinking and sustainability mindsets.	Suggests adopting a whole-institution/systems-thinking approach that connects various disciplines, integrating STEM fields with social-emotional learning and civic engagement. Highlights the role of STEM in addressing local and global sustainability challenges through citizen science.

Table2
Strategies and use of interactive learning materials, towards a reimagined science education for sustainability (source: authors)

Proposed strategies and use of interactive learning materials	**Authors/Year**	**Findings regarding science education for sustainability**
Non-scholar educational initiatives	Griswold(2013)	Community education programs supporting the development of green jobs.
	Cooke,etal. (2013)	Identify the barriers in engaging the public in media coverage regarding inland fish conservation issues.
	Faria, Klima, Posen,& Azevedo (2015)	Effectiveness of outreach STEM programs with a combined focus on STEM and climate change
	Kney, Citrin, & Clark (2016)	Informal education environmental STEM camp, supported by an informal educational platform.
Hands-on environmental science laboratory activities	Wagner, McCormick,& Martinez (2017)	Presents and accesses a hands-on laboratory activity for an introductory environmental science course integrating STEM and energy literacy.
	Costa, Ferreira, & Pinho (2023)	Presents an interdisciplinary approach intended to raise awareness for Sustainable Development Goals in the context of the physics of sound.
Citizen science-based school projects	Klütsch, etal. (2021)	Identifies how the components of school-based citizen science projects link to certain learning outcomes for scientific and environmental education.
	Μιονι (2022)	Educational project harmonizing educational plans with the recommendations of the United Nations Sustainable Development Goals (UN SDGs) to improve STEAM teaching.
Local-based lessons on environmental education	Tadena&Salic-Hairulla (2021a,2021b)	Develops and examines the effectiveness of the local-based lessons on environmental education, using STEM.
Use of students' lived experiences in real-world scenarios	Vyas&Dalvi(2023)	Examines teachers' use of students' lived experiences in real-world scenarios in environmental education with a STEAM framework.
Immersive internships	Felege,Romsdahl, Hunter,Hunter,&Ellis- Felege (2019)	Explore immersive internships in STEM areas to develop a set of knowledge, skills, and abilities critical to a translational workforce in sustainability.
Use of digital technology for advancing STEAM education	Puškar, etal. (2023)	Presents a project/teaching methodology for integrating educational robotics, STEAM, and environmental education.
	Kanaki, Kalogiannakis, Poulakis,&Politis(2022)	Presents synergies between CT and STEM fields.
	Tsikalakis, et al.(2023)	Uses SCRATCH code as ane ducational tool for education for sustainable development.
	Kanaki,et al.(2022)	High lights the necessity to adopt gamified educational practices that face students as active creators rather than passive consumers of digital technology.
LearningLaboratories	Boykin, Wood, Bochis, & Olcmen (2010)	Explores Living Learning Laboratories and particularly STEM/STEAM Learning Labs in schools.
	Bartholomew, Otto, & Serban (2023)	Explores Living Learning in other settings, such as libraries, museums,and industrial settings.
	August, et al.(2011, 2016)	Explores Living Learning Laboratories in virtual settings.
	Hewes, Latorre, Sisson, & Hake (2023); Pandian & Australia (2018); Rawat Lawrence & Gooden (2017)	Explores Living Learning Laboratories as"Learning Labs"or "Maker spaces"to engage students in subjects such as genomic, research using robots and aviation/aerospace education.

The Use of Games in Education for Sustainability

As gamification—the use of game design principles in non-gaming areas—becomes more common in education, the concepts of Serious Games (SG) and Game-Based Learning (GBL) are becoming more important. Serious Games aim to provide more than just entertainment, focusing on learning and training goals, while GBL involves using gameplay, like SG, to achieve specific educational outcomes. GBL supports Problem-Based Learning (PBL) in promoting active learning, discussions, exploration and effective teaching of complex concepts. It enhances social interactions and argumentation skills and fosters collaborative and creative problem-solving (Scurati, Kwok, Ferrise, & Bertoni, 2023), being one of the possible ways to teach the essence of complex topics.

In research on current scenarios of gamification for EfS—see Table 3—it is possible to identify three clusters, reflecting the use of board games in different contexts for different purposes.

STEAM board games towards a reimagined environmental Education for Sustainability

Towards a reimagined science education that addresses environmental challenges in the context of EfS and aims to educate scientifically literate global citizens who make informed choices towards a sustainable future, a STEAM (instead of STEM) educational approach, already mentioned by the UN for achieving the SDGs, seems to be a more appropriate solution for rethinking EfS. In this context, several methodologies, such as gamified interventions and living labs, have been used as engaged practices in formal and non-formal education. On the other hand, board games as interactive learning materials have been actively used in environmental education and EfS not only to engage in learning and encourage pro-environmental behaviour change in a logic of education for sustainable consumption but also to increase students' knowledge and skills, training them to understand, reflect, and commit to the resolution of issues in the complex web of challenges related to sustainability. This logic aligns with education for sustainable production and consumption and citizen participation in sustainable innovation. In the convergence of these contexts, this paper presents a new framework that has supported the design of three board games as tools of environmental EfS. It also provides a short description of the games aligned with the framework as well as their intervention context.

Table3
Research on current scenarios of gamification for EfS

Use of gamification for EfS	**Authors/Year**	**Findings regarding science education for sustainability**
Use of gamification to intrinsically motivate engagement and encourage behaviour change in EfS	Monteiro & Sousa(2024)	SG, including learning and training goals, can act as an active educational tool for sustainability.
	Scuratietal.(2023)	In tailoring learning experiences to meet educational goals, if digital games better simulate complicated situations and provide real-time feedback, board games illustrate complex systems and enhance social interaction offering a differentiated social dynamic.
	Douglas & Brauer(2021)	Gamification promotes pro-environmental and sustainability actions across various thematic areas and sustainability education in general; gamified interventions designed to increase knowledge about a topic rarely lead to behaviour change unless a lack of knowledge was preventing individuals from adopting a certain behaviour; researchers have not yet determined which specific aspects best promote these results.
	KragićKok et al.(2020)	Only in some cases does higher participation in gamified activities correspond to a greater increase in reported sustainable behaviours as seen in games designed to promote better consumption habits of both water and electricity.
	DiPaolo & Pizziol (2024); Banerjee,Horn & Davis (2016)	Relevant aspect relates to incorporating reward mechanisms into the activities rather than providing information alone and game playing in a broader social context, focusing on learning not as a formal transmission of knowledge, but as a contextualized co-construction of knowledge within apprenticeship-like relationships.
Use of board games in engaging participants, communicating science in a simplified way, and increasing knowledge about complex environmental and sustainability themes	Carreira, Aguiar, Onça & Monzoni (2017); Fjællingsdal & Klöckner (2020)	Board games induce reflection on behaviour rather than elucidating the details about specific topics such as climate change and energy.
	Yusa&Hamada(2023);Parrondo,Rayon- Viña, Borrell & Miralles (2021)	In role-playing board games used as education tools, environmental issues are not addressed as isolated subjects but from a transdisciplinary and collaborative perspective, thinking about the sustainable use and management of natural resources.
	González-Robles & Vázquez-Vílchez (2022); Tsai, Liu, Chang & Chen (2021)	Gamedesign focuses not only on the acquisition of knowledge related to the environment,sustainability,and the SDGs, but in understanding the interconnection between all these factors, incorporating systemic concepts of economy, policies,society,and ecology.
	Chen&Ho (2022)	Report the development of games for EfS, designed to reshape environmental education in the curriculum,engaging learners not only by improving their perception and knowledge but also attitudes regarding SDGs.
	Yusa&Hamada(2023);Shimabukuroetal. (2022); Yusa & Hamada (2023)	Board games must be assessed both in playability and educational value; authors speak of the delicate balance between enjoyability and learning. Games became a more effective learning tool for EfSD when supported by mechanisms for integration into teaching debriefing).
Use of board games aiming for increased commitment to make decisions regarding challenges related to sustainability	Coz&Mathevet(2024);Lanezkietal. (2020)	Role-playing games demonstrate efficacy for stakeholders' engagement and meaningful interaction, trust, and knowledge sharing between players, facilitating decision- making processes regarding the challenges of sustainability.
	Coz&Mathevet(2024);Lanezkietal. (2020); Keijser et al. (2018)	Multistakeholder participatory approach and interdisciplinary and transdisciplinary approaches are used to discuss complex environmental-related themes.
	Cleland,Dray,Perez,Cruz-Trinidad& Geronimo (2012)	Board games supporting systems thinking and decision- making processes have also been explored with training engineering students for sustainability in various contexts, as well as bolstering EfS capacity in future primary-school teachers.
	Monteiro & Sousa (2024); Scurati et al. (2023); Kurisu Okabe, Nakatani, & Moriguchi(2021);CostaCésar,daGama Pivetta,&Mendes(2022);Vázquez-Vílchez, Garrido-Rosales, Pérez-Fernández & Fernández-Oliveras(2021)	Computer-assisted role-playing games are a two-way learning tool: for science communication and sustainability education and for data collection informing research.
	Clelandetal.(2012);OrduñaAlegríaetal. (2020)	In designing games as educational tools, user-friendliness is often prioritized over model accuracy, but when used overly simplistic, games fail to stimulate or challenge students.
	Kurisuetal.(2021);Scuratietal.(2023); Cleland et al. (2012); Monteiro & Sousa (2024)	Game efficacy is related to debriefing,which can take several formats, leading to self-assessment mechanisms during gameplay.
	Lanezkietal.(2020)	Co-design/participatory design is crucial for the expansion of the learning content, the improvement of the gameplay, and the balancing of the difficulty level. Example of such approaches are Rapid Games Designing (RGD) and the involvement of students as co-creators, using DBL.

Building the Framework

The framework – Table 4 – is intended as a set of relevant specific aspects that provide a foundation for structuring the games, not a framework for the game design process. It incorporates into the SALL key principles for supporting the establishment of Living Labs in Open Schools (Aguirre, Artheu, Laval & Merzagora, 2021), the principles of the STEAM educational approach, as well as the best practices and insights from the current literature review on gamification. The aim was to support the design of games that intend to educate scientifically literate global citizens (sustainability for education) able to make informed choices and participate in user-driven innovation processes towards a sustainable future (education for sustainability). Adding to the three specific key aspects supporting the game design, two transversal key aspects were identified and addressed. One refers to the necessity to define learning and training goals (Monteiro & Sousa, 2024) that are specific and/or transversal (Shimabukuro et al., 2022). These goals should reflect the evolution from an environmental education focused on changing consumer behaviour to a more holistic perspective focused on understanding complex production and consumption systems, in line with the concept of circular economy (Winans et al., 2017).

Other refers to the critical role of debriefing in game-based learning, as games became a more effective learning tool for EfSD when supported by mechanisms to integration prior or post gaming (Chen & Ho, 2022; Kurisu et al., 2021; Monteiro & Sousa, 2024; Scurati et al., 2023).

Using the framework for structuring games

Based on this framework, three games were fully designed and produced by UC Exploratório – Centro Ciência Viva da Universidade de Coimbra, a science centre in Portugal. These games are part of a non-formal game-based educational project, ***Adaptação às Alterações Climáticas***, which promotes environmental literacy and raises awareness about climate change mitigation and adaptation. The project is aimed at fostering educational success among middle school students. The project has been implemented in schools within a Portuguese Intermunicipal Community (NUT II region). During the 2023/2024 school year, 162 sessions were conducted, reaching a total of 3,119 students and 259 teachers.

Table 4
Framework integrating SALL key principles, STEAM approach principles and insights from gamification, supporting the design of STEAM board games addressing environmental EfS

Relevant aspects for design	**SALL Living Lab project key principles**	**STEAM approach principles**	**Insights from gamification (GBL and SG)**
1. Defining and contextualizing the problem or question	Identifying the real question, using participants' experience (Aguirre et al., 2021).	Engaging in authentic learning (Rodrigues-Silva & Alsina, 2023). Implementing character-based Local Wisdom, as a means of contextual learning (Nugroho et al., 2019).	Facilitating awareness and understanding of managing local resources and resolving environmental issues, in the complex web of challenges (Monteiro & Sousa, 2024).
2. Building a community for co-creation	Building a community for co-creation, based on open innovation methods involving all actors (Aguirre et al., 2021).	Facilitating meaningful learning (Rodrigues-Silva & Alsina, 2023). Promoting disciplinar and transdisciplinar STEM (Luttenberger & Mandić, 2022). Integrating of STEM fields with social and emotional learning and civic engagement, developing thinking skills multiliteracies and socio-emotional intelligence (Luttenberger & Mandić, 2022).	Balancing enjoyability and user-friendliness with learning accuracy (Chen & Ho, 2022, 2022; Yusa & Hamada, 2023) Combining interdisciplinary and transdisciplinary approach (Parrondo et al., 2021; Shimabukuro et al., 2022) and adopt a multistakeholder participatory approach (Cleland et al., 2012; Coz & Mathevet, 2024; Keijser et al., 2018; Lanezki et al., 2020; Lankford & Craven, 2020; Orduña Alegría et al., 2020) to communicate science in a simplified way. Focusing in understanding the interconnection between all factors (González-Robles & Vázquez-Vílchez (2022), increasing knowledge about complex environmental and sustainability themes, inducing reflection on behaviour rather than to elucidate the details about specific topics (Yusa & Hamada, 2023). Enhancing social interaction through board games (Scurati et al., 2023), which are more effective in a broader social context, focusing on learning as a contextualized co-construction of knowledge (Banerjee et al., 2016; Di Paolo & Pizziol, 2024)
3. Discovering, discussing and testing solutions	Finding real solutions and quick prototyping by putting ideas in practice and testing them (Aguirre et al., 2021).	Engaging in active learning- involving students' actions (Rodrigues-Silva & Alsina, 2023). Incorporating arts, focusing on the process of exploration, play, risk-taking, making mistakes, self-evaluation and feedback (Rodrigues-Silva & Alsina, 2023).	Promoting behaviour change in games by incorporating reward mechanisms (Di Paolo & Pizziol, 2024; Douglas & Brauer, 2021). Supporting systems thinking and decision-making processes (Costa César et al., 2022; Kurisu et al., 2021; Monteiro & Sousa, 2024; Scurati et al., 2023).

For each game, themes and learning goals were defined according to the project's objectives. The starting point for each game is a real question or challenge, based on personal experience and local information, which is incorporated into the game narrative to promote meaningful learning. A context is created for the community of participants to apply and mobilize knowledge and skills to address the challenge within a ***coopetition*** mindset—an amalgamation of competition and cooperation, a concept commonly used in business literature but applied here to simulate real-world settings. Presenting solutions involves fostering creativity and critical thinking and developing ideas through experimental trial-and-error processes supported by progression mechanisms. Whenever possible, prototyping is encouraged. Debriefing is a key part of the process, as the games are designed as central tools for structured educational activities mediated by trained monitors.

Next we will introduce the games, highlighting the operationalization of the key aspects supporting the design of STEAM board games for environmental Education for Sustainability (EfS), based on the framework we propose.

"Apanhados pelo Clima" - Depicted in Figure 1, this game was designed as an educational escape room (Tercanli et al., 2021) adapted for portability. It aims to raise awareness about the impacts of climate change on our lives and to promote reflection and debate regarding mitigation and adaptation strategies specific to the region. The game emphasizes the significant role of science in decision-making on these issues.

1. Defining and contextualizing the problem or question: Supported by participants' everyday experiences, a compelling narrative helps to identify the problem and clarify concepts related to how climate change affects their lives. The game's purpose is established: to assist scientists in collecting data and finding possible solutions to local climate challenges, which are locked in a safe that participants must open by the end of the game.
2. Building a community for co-creation: Using regional climate scenarios and working against the clock, participant teams mobilize knowledge and skills to follow clues, solve puzzles, and gather information to tackle various climate challenges, fulfilling their mission. Based on interdisciplinary STEAM learning, these activities aim to enhance education and scientific literacy while fostering the development of skills outlined in the *Profile of Students at the End of Compulsory Schooling* (Ministério da Educação/Direção-Geral da Educação, 2017). Key competencies include collaborative work, problem-solving, research, information organization and emotional management.
3. Discovering, discussing, and testing solutions: A hybrid methodology integrates a specific developed app, which conveys information and acts as a progression mechanism, enabling a trial-and-error approach. A final, simple questionnaire - an integral part of the game - encourages self-assessment of learning and allows participants to share their views on climate change solutions. Although teams compete to complete the assigned task within a set time frame, the safe containing the solution to the climate crisis can only be opened when all teams complete their mission, reinforcing the *coopetition* mindset.

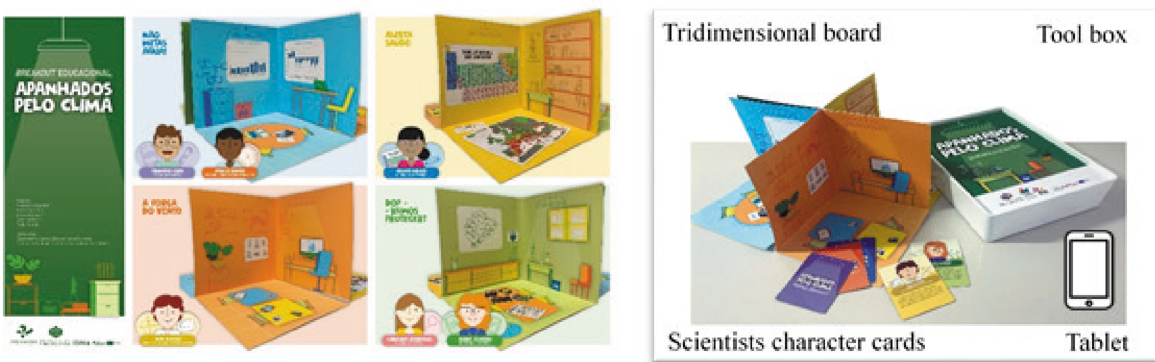

Figure 1
Representation of the materials produced for "Apanhados pelo Clima"

The contents of the safe ignite a debate on individual and collective actions for climate change mitigation and adaptation in the region.

"Escolhas Energéticas" - Depicted in Figure 2, this game focuses on the importance of supporting renewable energies as a critical contribution to achieving greenhouse gas emission reduction targets and mitigating/adapting to climate change within the region. The learning objectives include not only enhancing students' understanding of renewable energy sources and raising awareness about sustainable energy consumption habits, but also identifying specific territorial factors involved in making sustainable decisions regarding energy production and consumption, as well as understanding how these processes connect to impacts of climate change.

1. Defining and contextualizing the problem or question: The activity challenges participants to design appropriate infrastructures that ensure access to energy produced from renewable sources for all citizens of a given territory. This must follow a logic of sustainable energy production, distribution, and consumption while preventing or mitigating climate change impacts, thereby aligning with SDGs 7, 12, and 13.
2. Building a community for co-creation: Each team participates using a classic game board that provides information about a specific territory, its resources, and its community's energy needs. As participants take turns, roll the dice and progress on the board, they individually collect resources and face unpredictable environmental, social, and economic events that affect resource availability. This encourages players to engage with the complexities of sustainable energy management.
3. Discovering, discussing, and testing solutions: Based on simplified data about renewable energy technologies, the team collectively identifies the resources needed to build one or more energy production plants. They calculate and present a proposal to meet the community's energy needs.

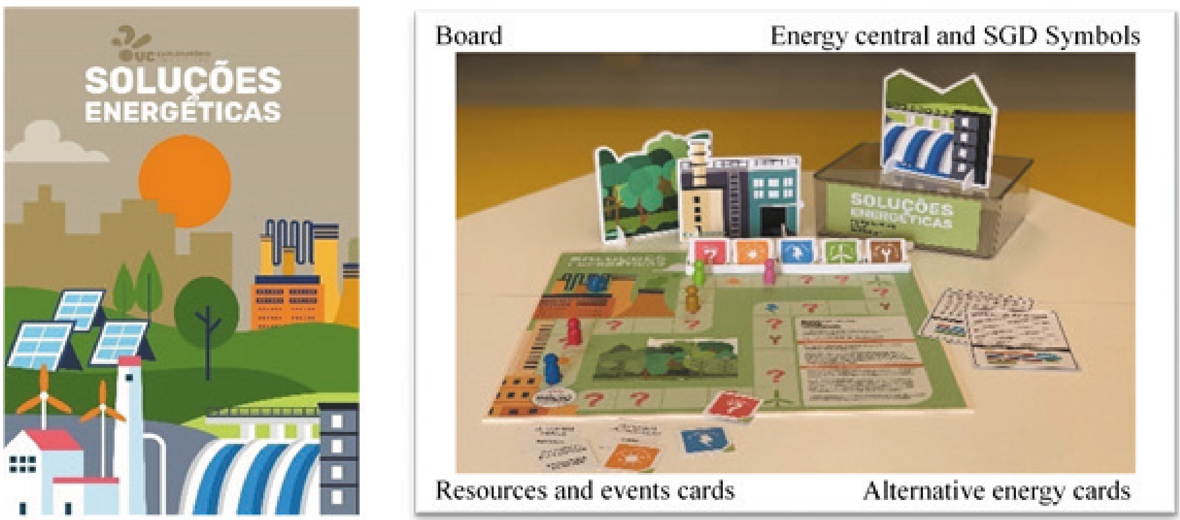

Figure 2
Representation of the materials produced for "Escolhas Energéticas"

A debate evaluates the costs and benefits of the teams' choices, addressing factors such as resource availability and environmental impact. Additionally, students select an SDG to which their actions contribute and provide justification for their choice.

"Foco na Embalagem" - Depicted in Figure 3, this green design game (Wang et al., 2022) focuses on issues related to the production, consumption, and disposal of food packaging and their links to climate change. The game aims to encourage the development of more sustainable food packaging solutions.

1. Defining and contextualizing the problem or question: The activity is introduced through a comic book narrative illustrating a student's exploration of the linear economy model of food packaging and its environmental impact. The storyline highlights the problem of plastic packaging and the need for sustainable alternatives, inspired by EU initiatives like improving packaging design, promoting reuse and recycling, and transitioning to bio-based and compostable plastics. It also aligns with the Circular Economy Action Plan and the European Plastics Pact's focus on single-use plastics.
2. Building a community for co-creation: The narrative encourages participants to reflect on their consumption habits and analyze the product life cycle. Using a sustainability indicator, teams assess the economic, environmental, and social impact of existing food packaging (converted into

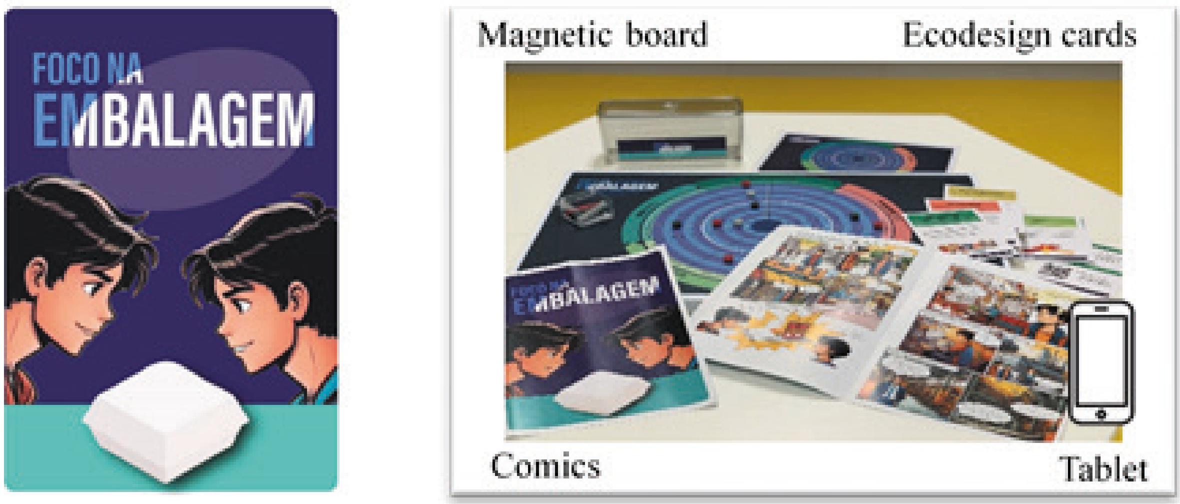

Figure 3
Representation of the materials produced for "Foco na Embalagem"

points). They are then challenged to eco(re)design packaging, guided by Circular Economy principles and scientific advances, emphasizing how small changes can drive significant regional and global impact.

3. Discovering, discussing, and testing solutions: Teams propose alternative food packaging solutions, reassessing impacts to achieve a better balance in their sustainability scores. Finally, a digital AI tool is used to create a prototype of their redesigned packaging, demonstrating how their solution mitigates environmental and social impacts without sacrificing economic viability.

Challenges of game development, game set up and implementation

Echoing the presented framework, structuring and designing board games for EfS requires defining themes and learning/training goals, constant exchange of ideas and knowledge between a multidisciplinary team and multiple testing sessions, being a time-consuming and human resources demanding process.

In the context of a non-formal game-based educational project, debriefing assumes a critical role for game efficacy as a learning tool for EfSD. To ensure the fulfilment of learning and training objectives and adaptation to diverse students in educational environments – Figures 4 to 6 - it is required to draw up a pedagogical plan as well as pedagogical guides to support the implementation prior, during and post gaming. In the same sense, game set up and implementation was mediated by monitors that were specific trained for those purposes.

Figure 4
"Apanhados pelo Clima" set up and implementation in educational environment.

Figure 5
“Escolhas Energéticas” set up and implementation in educational environment.

Figure 6
“Foco na embalagem” set up and implementation in educational environment.

Conclusion

In line with the main purpose of the study, a framework is presented as a set of relevant specific aspects, related to game play, that provide foundation for structuring board games, on the path of environmental education for sustainability, incorporating living lab key principles, STEAM educational approach principles and taking in consideration insights from gamification, particularly regarding factors affecting the effectiveness of board games as a tool for environmental education and EfS.

In this framework, three specific key aspects related to game play - identifying the problem, building a community for co-creation and presenting solutions/prototyping – as well as two transversal key aspects related to game set up and implementation – definition of learning and training goals and methods for debriefing - were identified.

It is noticeable that not all the developed games complied with the five key elements of the framework, particularly regarding presenting and testing solutions. There is, therefore, room for improvement in applying the framework to game design for environmental education and EfS.

Limitations and future work

There are numerous limitations to the study, and further research is suggested. While the study presents the framework and its application in designing the three games, it doesn't describe the iterative process of game design. The evaluation of the games as educational tools is limited to empirical assessment by the team and basic surveys conducted with students and teachers. These surveys address students' engagement and satisfaction, as well as teachers' perspectives on the relevance of the games, the achievement of the action's goals, and perceived learning outcomes. Further investigation should evaluate the games as educational tools, assessing its playability and learning and training objectives, working towards a validation of the framework. More ambitiously, future research should focus on whether the use of games can lead to observable long-term changes in participants behaviour towards sustainability. Additionally, research should also focus on participatory game design, including students, specialists and educators and future educators in producing better and more effective STEAM oriented board games on the path of environmental EfS, and promote pro-environmental engagement in future teachers as suggested by Vázquez-Vílchez, Garrido-Rosales, Pérez-Fernández & Fernández-Oliveras (2021).

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