STE(A)M Learning Ecologies and creativity: A typology of open schooling projects based on stakeholder and learner engagement

Running title: STE(A)M Learning Ecologies

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Acknowledgments
We are grateful to all learners and stakeholders who participated in the pilot STE(A)M Learning Ecologies. This research was funded by the European Union's Horizon program under Grant Agreement No 101094648. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Declaration of Interest
The authors have no conflict of interest to declare.

STE(A)M Learning Ecologies and creativity: A typology of open schooling projects based on stakeholder and learner engagement

1. Introduction

Open schooling projects have been continuously funded over the last decade by the European Union as a major investment to address declining student interest in STEM careers, the gender gap in STEM, and the rather confined growth observed in science-based innovation and entrepreneurship (STE(A)M Learning Ecologies, 2024). Open schooling is based on the core premise that collaboration of formal education providers with a diverse array of stakeholders, including non-formal education providers and enterprises, would allow learners engage in real-life creative problem-solving and stimulate interest in science (European Commission, 2015). In the same report where it endorsed open schooling, the European Commission also highlighted the need to move from STEM to STE(A)M, in order to integrate science, technology, engineering, and mathematics with all ("A") other subjects and disciplines (European Commission, 2015). Such a focus on integration seems to be necessary for operationalizing learners' access to authentic learning contexts and overcoming the siloed approach that still prevails in several European curricula. Open schooling is expected to bridge formal learning with non-formal learning across educational levels, make learning much more relevant and creative for learners and foster 21st century skills (European Commission, 2024). The transformative change that open schooling is hoped to achieve includes bringing learners beyond school walls and offering opportunities for community engagement (STE(A)M Learning Ecologies, 2024). The cross-fertilization of learning experiences from different learning settings would ultimately enhance informed decision-making and community well-being, foster career awareness and improve employability and competitiveness (European Commission, 2024; Okada et al., 2024; STE(A)M Learning Ecologies, 2024).

Although open schooling has not yet been institutionalized in most European countries (STE(A)M Learning Ecologies, 2024), several EU-funded projects have adopted the open schooling perspective. The project that paved the way for open schooling was "Open School for Open Societies – OSOS", implemented between 2017 and 2020 (https://cordis.europa.eu/project/id/741572). OSOS delivered an "Open Schooling Roadmap for Schools" (Author et al., 2017), which described how schools can be empowered to facilitate transformative change aiming towards open schooling. This included: (1) reconceptualization of students as creators/producers rather than consumers and their work as creation/production rather than consumption; (2) securing innovative learning resources through networking with stakeholders; (3) adopting an integrated STE(A)M educational approach; (4) fostering distributed teacher leadership through peer learning and collaboration. The next waves of EU projects on open schooling were funded under the action grants for "Open Schooling and Collaboration on Science Education" in the 2018, 2019, and 2020 calls (11 projects, overall), and under the action grants for "Open Schooling for Science Education and a Learning Continuum for All" in 2022 (another 3 projects). The 2018-2020 projects were expected to: (1) promote school networking with stakeholders, including industry partners and civil society organizations; and (2) empower schools to become agents of community well-being. The emphasis in the last call in 2022 shifted from schools to whole stakeholder partnerships, in order to: (1) develop a rich set of learning resources; (2) promote stakeholder engagement through participatory processes; and (3) engage learners in real-life challenges to encourage creativity (for a detailed account of all EU-funded open schooling projects, see Authors et al., 2023a).

Previous studies showed that open schooling projects can facilitate the transformation of a considerable number of schools to innovation hubs within local communities and across different countries (Author et al., 2021; Author et al., 2023). Specifically, data collected in a pre-post-test arrangement from several hundred schools engaged in the Open School for Open Societies – OSOS project showed that, on average, these schools were successful in taking up innovation and adopting the Open Schooling Roadmap (Author et al., 2021; Author et al., 2023). Indeed, improvement was observed at the management and process levels, including vision, leadership, and stakeholder involvement, as well as for teachers' professional development. Although the change was greater for schools that scored relatively low in the pre-test measurements, there was also room for improvement for schools that started with relatively high pre-test values. Previous research using instruments and data collected within the framework of the CONNECT project (Inclusive Open Schooling Through Engaging and Future-oriented Science – CONNECT; https://cordis.europa.eu/project/id/872814) has documented that open schooling can increase secondary school students' connection with science, and more specifically, that this is valid for both male and female learners (Okada, 2024). Another finding of this research was that teachers highlighted how students' interest in science led them to engage in science activities beyond everyday school practice (Okada, 2024). Even though the above results from OSOS and CONNECT are quite encouraging, more evidence from more projects is needed to explore and justify the impact of open schooling and to scale-up effective strategies and policies for its uptake and sustainability across Europe.

Despite the considerable funding of open schooling projects from the EU, relevant publications documenting stakeholder and learner engagement have been scarce. To address this lack, we will present an analysis of open schooling initiatives launched within the frame of the STE(A)M Learning Ecologies – SLEs project (https://www.steamecologies.eu/). A STE(A)M learning ecology (SLE) promotes stakeholder networking to contribute learning resources for learner engagement. These are then employed by students to create learning artefacts, which reflect their accumulating knowledge and skills. Authentic learning experiences are co-developed by students, their teachers, and other stakeholders, while addressing real-world problems. The pilot cycle of the project (September 2023-August 2024) involved 12 pilot SLEs in 12 European countries (Cyprus, Germany, Greece, Ireland, Italy, Malta, Norway, Portugal, Romania, Serbia, Slovakia, Spain). The mature cycle (September 2024-August 2025) will include at least 10 different SLEs in each of the reference countries, and will build on lessons learnt and good practices gained during the pilot cycle. To provide guidance and insight to new SLEs during the mature cycle, we analyzed several data sources, for instance, the learning artefacts of students and two templates completed by stakeholders in the pilot SLEs, namely, a participatory pedagogical design template and a participatory scenario development template. The main outcomes of our analysis include a typology of SLEs, and several design aspects addressing stakeholder synthesis (diversity) and interaction, learning resources, and support provided to learners. Based on these results, we will conclude with a set of policy recommendations, which we expect to elaborate upon further with additional data from the mature cycle of the project.

1.1 STE(A)M Learning Ecologies and creativity

Creativity has been defined as production of novel ideas, artefacts or solutions, which can prove useful within a particular social context (Plucker et al., 2004; Runco &

Jaeger, 2012). The concept of SLEs offers the opportunity for creative collaboration and outcomes in two dimensions, namely, stakeholder engagement and learner engagement. First, a stakeholder acting as the initiator of the SLE (e.g. formal or non-formal education provider or any other stakeholder) leads the establishment of a stakeholder coalition, which makes available learning resources and support, and works to arrange these resources along a learning activity sequence and create a learning path. Second, students are invited to use learning resources and enact learning activities to address a real-world problem. In doing so, students create tangible and original learning artefacts. This configuration allows the stakeholder network to set up an enabling environment for learning, which unfolds within a unique social context. In that regard, SLEs foster a contextual and situated account of creativity (Glăveanu et al., 2019; Van der Zanden et al., 2020), which facilitates both stakeholder collaboration for pedagogical design as well as learner collaboration to produce learning artefacts. Stakeholder diversity and supply of heterogeneous learning resources can be instrumental for bridging formal and non-formal learning settings, and offering novel and open-ended learning opportunities, which are not favored in traditional classrooms (Richardson & Mishra, 2018). Stakeholder involvement and the context-dependency of SLEs can prove decisive for perspective-taking, which catalyzes the delivery of novel outcomes by students (Rubenstein et al., 2019). Furthermore, co-creation of solutions to real-world challenges distributes learning incentives across all actors involved, which means that all actors in an SLE can serve simultaneously as educators and learners.

An SLE is a physical and socio-cultural learning context co-developed by diverse stakeholders to engage students in STE(A)M. We consider learning products (LPs) as the manifestation of student creativity in SLEs. We define LPs as any artefact constructed by learners themselves, anytime they use learning resources to enact learning activities (see Author, 2016a; Authors et al., 2018). LPs provide a solid anchorage of SLEs in learner-centered pedagogical approaches based on constructionism (Papert, 1993) and constructivism (Hmelo-Silver et al., 2007; Author, 2016) and can be physical or digital. Some products can have a more central place within a sequence of learning activities and other products can have a more secondary role. All LPs, however, reflect learner knowledge and skills and can be used to diagnose learner performance and operationalize formative assessment, peer assessment or summative assessment (Authors et al., 2014; Author, 2016a). Such an option can address the gap reported by Perignat and Katz-Buonincontro (2019), who highlighted the lack of empirical data documenting creativity in their integrative review of literature on STEAM education published between 2007 and 2018. Even in learning settings like makerspaces, where learner creativity in STE(A)M is explicitly linked to the design and delivery of tangible artefacts, a thorough approach and analysis of what students are able to create when employing tools to undertake learning activities is largely lacking (Soomro et al., 2023). Using LPs for assessment presents advantages over psychometrics with pre- and post-test scales, which are still prevalent but tend to treat learner engagement as a “black box” (Kocak et al., 2021; Richardson & Mishra, 2018; see also Soomro et al., 2023, in this regard). Moreover, LPs may offer a solution for “decentralizing” both assessment and learner support from educators, only, to other stakeholders engaged in open schooling projects, as long as learners would be given the opportunity to present their work to these stakeholders and benefit from their feedback and guidance (see Wilson, 2021). Overall, LPs can facilitate an alignment of curriculum standards and pedagogical design, implementation, and assessment, exactly because they reflect knowledge and skills needed for their creation. Such an arrangement would be crucial for formal education in order to strike an optimal balance between structure, on the one hand, and.flexibility, one the other, so that pedagogical design can sustain the open-ended character of SLEs and allow learners to adapt LPs to their changing needs and desires or changing contexts. Such balancing of freedom and guidance was singled out as supportive of creativity development (Van der Zanden et al., 2020).

Learner engagement in SLEs is promoted within an overall vision of fusing open schooling with integrated STEM learning or STE(A)M (Authors et al., 2023a). Such a fusion seeks to integrate science, technology, engineering, and mathematics not only with art, but with all ("A") other subjects (European Commission, 2015), including humanities and the social sciences (Quigley et al., 2017). Integration aims to develop the STE(A)M literacy needed to address real-world problems, which cannot be satisfied by approaching different subjects and disciplines in a fragmented manner. It also signifies the considerable challenge of handling the increased complexity of content marked by interdisciplinarity. There have been numerous calls for respecting the autonomy and distinguishing features of each different discipline, while opting for STE(A)M (Langlois et al., 2024; Tytler et al., 2021). To this end, a much more robust epistemological discussion is necessary to better justify integrated STEM proposals (McComas & Burgin, 2020; Ortiz-Revilla et al., 2020). At the same time, however, integration harbors opportunities for innovation, because creative solutions usually emerge at the interface between disciplines (European Commission, 2015). In this regard, recent contributions shed light on cross-cutting themes, for instance, modelling, which could offer valid bridges across disciplines (Develaki, 2020; Reynante et al., 2020), and proposed theoretical frameworks, which can illustrate shared characteristics in the nature of knowledge and inquiry practices to overcome disciplinary silos (Quinn et al., 2020). In line with such approaches, our perspective allows integration to be discussed from both an instructional and a learning perspective. This implies that designing STE(A)M open schooling projects should take advantage of all possible capacity and interactions between stakeholders when it comes to supplying content; however, learners also need to be ready and competent to handle content complexity. In this regard, SLEs need to embrace 21^{st} century skills, which are indispensable for addressing interdisciplinarity and lifelong learning (Authors et al., 2023a; see also Bequette & Bequette, 2012), for instance, communication, collaboration, critical thinking and problem solving, creativity and innovation (European Commission, 2019; OECD, 2019). This adds another aspect to the pedagogical design of SLEs, one that indicates a shift towards process-based learning (European Commission, 2015) to foster 21^{st} century skills.

Stakeholder engagement in a SLE includes the following main stages, which are needed to develop a unique learning setting enabling learner engagement and operationalize the SLE concept: (1) Getting started: An SLE starts with an initiator (provider of formal or non-formal education or any other stakeholder taking the lead) singling out a real-world challenge to work with. Some first learning objectives can be formulated already at this stage, but these will be enriched when more stakeholders join the SLE. (2) Building the partnership: Stakeholder mapping is paramount here to identify public, private and civil society organizations that can offer learning resources. The SLEs consortium deemed a minimum of the initiator plus two different stakeholders to be necessary for securing learning resources and learner support (Authors et al., 2023b). (3) Co-creating the SLE: Stakeholders co-create the main learning paths. These demarcate learning resources available along a sequence of learning activities, LPs to be created by learners, and support to be provided to learners. (4) Implementing and monitoring the SLE: To scaffold stakeholder interaction and learner engagement, two templates are completed by stakeholders. The participatory pedagogical design template (Appendix A) describes key aspects of learner engagement. The participatory scenario development template (Appendix B) describes different scenarios for stakeholder engagement in terms of resources and time to be invested. Both templates are revisited when learners are engaged, for monitoring the SLE, taking any corrective action, if needed, and optimizing the impact and sustainability of the SLE. (5) Documenting learner engagement: All actors reflect upon LPs created by learners as a manifestation of learner engagement.

1.2 Research questions

The research questions to be addressed in this paper are the following:

(1) What types of SLEs can we identify based on their pedagogical design and learning path (e.g. learning resources, sequencing of learning activities), as well as the LPs created by students?

(2) What are the similarities and differences between types of SLEs in terms of learner and stakeholder engagement?

Having a typology of SLEs will offer the opportunity to delve deeper into the strengths and weaknesses of each type of SLE as far as learner and stakeholder engagement are concerned, provide much more user-tailored guidance to new SLEs to be established, suggest directions for future research, and streamline policy recommendations to achieve optimal investment of resources and impact.

2. Methods

2.1 Participants

Participants were stakeholders and learners in 12 SLEs. Table 1 presents the descriptive characteristics for all 12 SLEs in the pilot phase of the project. There was considerable variety in terms of challenges addressed and geographical coverage, including locations in the Mediterranean (ES, CY, IT, PT, GR, MT), the Balkans (RO, RS), central Europe (SK, DE), and Northern Europe (IE, NO). Most SLEs were initiated by providers of non-formal education (IE, ES, PT, DE, RS) and formal education (NO, RO, SK, GR), while 2 SLEs were set up by governmental organizations (CY, MT) and another SLE was launched by a civil society organization (IT). With regard to learners' ages, SLEs covered all educational levels, from lower primary education to higher education (Table 1). Table 2 shows the representation of different types of stakeholders across SLEs, for instance, providers of formal education (e.g., primary and secondary schools, universities) and non-formal education (e.g., research institutes), governmental organizations (e.g., Ministries), civil society organizations (e.g., non-governmental organizations), and industry partners. Overall, there were 96 stakeholders engaged, with a median of 7.5 stakeholders per SLE (min across the 12 SLEs = 4; max = 13). Most numerous were formal education providers (n = 28; Mdn = 2; min = 1; max = 4) followed by industry partners (n = 23; Mdn = 1; min = 0; max = 11), non-formal education providers (n = 20; Mdn = 1; min = 0; max = 4), governmental organizations (n = 18; Mdn = 1; min = 0; max = 3), and civil society organizations (n = 7; Mdn = 1; min = 0; max = 1)[1]. SLEs engaged 1079 learners, overall (min = 11; max = 450). There was considerable heterogeneity in the number of learners across SLEs, with three SLEs, hosting a much higher number of learners than the median of 30 (RS = 450; PT = 188; GR = 175).

2.2 Procedure

The establishment and operation of SLEs closely followed the life cycle presented in Section 1.1. Initiators were either project partners themselves (see, for example, the SLEs in NO, IT, DE, and GR) or stakeholders connected with project partners who served as initiators (see, for instance, the SLEs in IE, ES, CY, and SK). After initiators outlined the challenge to be addressed in the SLE and formulated some preliminary learning objectives, they proceeded with building the partnership through stakeholder mapping and contacting potential stakeholders. A core group of stakeholders was set up in each location, which took over co-creating the SLE, specifically, identifying learning resources, arranging them along learning paths, and describing the LPs to be expected from learners and the support to be provided to learners for creating these products. All SLEs had a minimum learner engagement duration of approximately 40 hours. As each SLE developed and learner engagement advanced, more stakeholders would be invited to join based on learner and stakeholder needs and desires. During the implementation of each SLE, stakeholders worked with a template for participatory pedagogical design to plan and formatively assess learner engagement, as well as a participatory scenario development template to evaluate stakeholder engagement. Project partners acted as initiators or as national coordinators maintaining close contact with all stakeholders in SLEs, providing guidance anytime needed and informing stakeholders about the progress of the SLEs project. The process concluded with documenting each SLE, which involved collecting: (1) participatory pedagogical design templates, (2) participatory scenario development templates, (3) LPs created by learners, (4) stakeholder interviews, (5) questionnaires completed by national coordinators.

2.3 Data Sources

We used the items delivered to document SLEs as our data sources. The template for participatory pedagogical design was completed for each SLE with stakeholder input (Appendix A). Stakeholders described learning resources, arranged them along learning paths, and outlined LPs expected from learners (Authors, 2023a). This template also included a curriculum mapping of LPs based on the knowledge and skills necessary for their creation, the support learners would need from stakeholders, and the total duration of learner engagement. Finally, stakeholders commented on the attractiveness of the learning paths to both male and female learners and related career opportunities. The template for participatory scenario development was also completed with stakeholder input (Appendix B) and referred to stakeholder synthesis and interaction, the learning resources available and learner support. This template enabled stakeholders to allocate resources efficiently and take corrective action whenever needed (Authors, 2023b). Business-as-usual scenarios portrayed baseline conditions under no additional stakeholder investment; small-effort scenarios outlined desirable results under minimal input; best-case scenarios depicted ideal futures under optimal investment. Moreover, we detailed metadata of all LPs gathered in each SLE to document the creative outcomes of learner engagement (see Data analysis). Stakeholder interviews concentrated on the local context, the stakeholders engaged, their prior experience with open schooling, the challenges encountered, the benefits and added value of the SLE, learner engagement, SLEs' sustainability, and suggestions for improvement. The questionnaire completed by national coordinators focused on learning outcomes, how stakeholders facilitated learning, female participation, educators' experiences, impact of the policy framework, challenges encountered, and stakeholder collaboration.

2.4 Ethics, data protection, and ethical approval

All stakeholders who were interviewed provided their informed consent before the interviews started and after they were briefed about the SLEs project, data collection and data processing. The participation in the interviews was voluntary and anonymous and interviews lasted, on average, about 30min. All data were pseudonymized and kept in a digital repository. Access to the data repository was provided to members of project partners involved in the research for pursuing the objectives of the project, namely, for processing data to draft the deliverables of the project and scientific publications. Interviewees were informed that all personal data would be destroyed 5 years after the completion of the project, until the period eligible for a full audit by the Granting Authority has expired. They were also informed that they had the right to withdraw their participation at any time without having any consequences. All procedures followed by project partners with regard to ethics and data protection were described in detail in a deliverable of the SLEs project titled Ethics Monitoring Mechanism (Deliverable D1.2). This deliverable is EU Classified and includes the procedures followed for each country to secure an ethical clearance, including informed consent forms. For instance, data collection and processing in Cyprus, which was undertaken in the frame of the SLEs project, received approval from the Department of Secondary General Education of Cyprus' Ministry of Education, Sport and Youth (Reference number 07.15.004.015.004/5 October 2023), while ethical clearance for data collection and processing in Norway received approval from the Norwegian Agency for Shared Services in Education and Research – Sikt (Reference number 415352/25 May 2023). Although there were interviewees in this research from two countries which are not EU Members States (Norway; Serbia), there was no transfer of personal data of interviewees in any EU Member States to these two countries. Personal data of minors were not collected in this research.

2.5 Data Analysis

We first analyzed the templates for participatory pedagogical design completed with stakeholder input and the LPs delivered by learners in each SLE. This allowed us to develop a typology of SLEs based on design characteristics and the main outcomes of learner engagement. The first author went multiple times through all templates and LPs and initiated a categorization of SLEs based on the template and metadata identification based on the characteristics of the LPs. More specifically, the coding criteria at this stage were the learning paths including learning resources and learning products, sequencing of learning activities, flexibility in pedagogical design, and trade-offs (e.g. incompatible features in pedagogical design and potential compromises between them; see Table 3). Initial categories of SLEs were reconsidered as data analyses proceeded, and the coding process concluded with a final set of SLEs types. A second coder, who is a researcher at the University of Cyprus, Research in Science and Technology Education Group, and has considerable experience in STEM teaching and participation in several STEM projects funded by the EU, and who did not participate in drafting the initial SLEs categories and metadata, repeated the coding process, with a Cohen’s kappa greater than 0.85. In the present paper we will refer mainly to the typology of SLEs and present some characteristic LPs in each category, without delving deeper on their metadata. In the second stage of data analysis, we processed the templates for participatory scenario development, interviews, and questionnaires, to explore if there were any major trends across types of SLEs in terms of stakeholder engagement. In this case, the coding criteria were determined by the structure of the participatory scenario development template, the interview protocol and the questionnaire. These involved, for instance, stakeholder synthesis, learning objectives, potential for change (e.g. departure from business-as-usual conditions based on varying stakeholder input and contribution), challenges related to establishing and operating SLEs, and sustainability of SLEs. This second coding process was undertaken again by the first author, who developed and refined codes after repeated readings of the data sources. Inter-rater reliability was calculated in this case as well with the aid of the second same coder at the University of Cyprus, with a Cohen's kappa greater than 0.85. Before the second coder repeated the coding process, for both the first and second stage of analysis, there was an initial discussion between the first and second coder focusing on coding criteria and procedures for all data sources as well as research objectives. After the second coder completed the coding process and Cohen's kappa was computed, mismatches between the two coders were identified and these divergences were settled through a discussion between the two coders. Given that the Cohen's kapa in our coding processes was quite high (>0.85), mismatches were not numerous, so there was no need to develop any elaborate resolution protocol for coder disagreements.

3. Results

3.1 Typology of STE(A)M Learning Ecologies

Table 3 presents the typology of SLEs in the pilot cycle of the project. The aspects addressed for each type include the learning path including learning resources and

LPs, sequencing of learning activities, flexibility in pedagogical design, and trade-offs in design aspects. Learner-experience oriented SLEs comprised the majority of STE(A)M Learning Ecologies (IE; IT; PT; RO; DE; MT) in the pilot phase. Learners in this type of SLE delivered a rich portfolio of diverse LPs making use of dedicated learning resources offered by stakeholders (see examples in Figures 1 & 2 from the Learner-experience oriented SLE titled "Steaming up with nature's wonders"; RO, Ramnicu Valcea). With regard to sequencing of learning activities, SLEs in this category were quite modular, because learning activities did not presuppose each other or did not follow a strict serial sequence and their order could be switched. Flexibility of the pedagogical design was further promoted by the fact that learning activities and LPs could be skipped or new activities could be added without any major impact on the learning path or the overall learner experience. A trade-off in Learner-experience oriented SLEs, however, was that the addition of learning activities and products, which could obviously enhance learner experience in the short term, could compromise the coherence of learner engagement and long-term learning outcomes.

A second type of SLE was Master-product oriented SLEs (ES; SK). Here, all learner work converged on a master LP, which was delivered at the end of the learning path. This master LP integrated all prior LPs or needed them to be created (Figure 3 presents an example from the Master-product oriented SLE titled "AI in ecology – ecology in AI"; SK, Poprad). Sequencing of LPs was organized around the master-product, which could be presented to various audiences to demonstrate learners' delivery, and which could also be used to propose and launch policy initiatives. Flexibility of the pedagogical design was fostered by the fact that prior LPs could be adapted to suit different learning contexts, provided that the overall structure as determined by the features of the master product was maintained. Trade-offs in this case were related to allocation of time and workload between all necessary prior LPs and the master product.

End-user oriented SLEs were the third type of SLE (NO; RS). In these cases, learners were tasked to design and create a key LP that addressed end-user needs and desires (Figure 4 displays an example from the End-user oriented SLE titled “Student software solutions for real clients”; NO, Trondheim). To do so, learners followed a number of iterations, which involved a pronounced co-creation dimension in direct contact to stakeholders in the SLE, who acted as the end-users. The co-creation process marked the sequencing of learning activities, which unfolded as a product development lifecycle having considerable resemblance to an iterative engineering design process. In terms of flexibility, each design in this type of SLE was unique, in the sense that key products had to meet different end-user needs and desires. A major trade-off was that the innovation and creativity of learners and end-users needed to be weighed against narrowing down their options so that realism (i.e., what was doable given available resources) was maintained along the learning path.

The fourth and final category of SLEs was Citizen-science oriented SLEs (CY; GR). Learners in these SLEs used a pre-determined data collection methodology to contribute to a wider process building on such data, which was supported by multiple social actors in multiple locations (An example from the Citizen-science oriented SLE titled “Studying earthquakes”; Greece, Athens, is shown in Figure 5). As far as the learning activity sequence is concerned, learners first got familiarized with the methodology. Then, they collected data, inserted them into a broader database, analyzed data, and concluded with policy implications. Flexibility was added to the pedagogical design by the fact that policy recommendations and initiatives provided further opportunities for stakeholder engagement and extension of the SLE. The trade-offs encountered mostly referred to an optimal balance that needed to be found between the rigidity of the methodology, on the one hand, and innovation in terms of policy recommendations and initiatives, on the other.

In Figure 6, we present the four types of SLEs in a visual depiction, where dark rhombuses represent LPs, and the dark line running through LPs represents the learning path and activity sequence. In Learner-experience oriented SLEs (1), learning activities and the delivery of LPs do not follow any strict serial sequence but can be switched in order, without that having any impact on the learning path. This is indicated by the cyclical arrangement of LPs. In Master-product oriented SLEs (2), one final LP is singled out (master-product), which is delivered at the end of the learning activity sequence, and which integrates all prior LPs or needs them to be created. This configuration is portrayed by arrows starting from all LPs and heading towards the master-product. In End-user oriented SLEs (3), the learning path evolves along an iterative process, where learners co-design and optimize in close collaboration with end-users a key LP, which addresses concrete end-user needs and desires. This is represented by the helix-shaped learning activity sequence. In Citizen-science oriented SLEs (4), the learning activity sequence involves two phases: First, learners follow a pre-specified methodology to collect and analyze data (continuous cycle on the top); second, they formulate policy recommendations based on their data, and invite new stakeholders in the SLE to pursue these initiatives (dashed cycle at the bottom). Overall, the different types of SLEs seem to correspond to different strategies employed to address real-world problems in open schooling projects, for instance, studying different dimension of a problem (Learner-experience oriented SLEs), developing and presenting a solution to a problem to raise awareness (Master-product oriented SLEs), following a product development lifecycle to address specific needs and desires of end-users (End-user oriented SLEs), and co-designing policy recommendations with stakeholders and launching participatory initiatives (Citizen-science oriented SLEs).

3.2 Similarities and Differences between Types of STE(A)M Learning Ecologies

3.2.1 Stakeholder and learner engagement

The average total number of stakeholders engaged was least in the Master-product oriented SLEs (*Mdn* = 4.5) and maximum in the End-user oriented SLEs (*Mdn* = 10.5) (see also Table 2 for an overview of all SLEs). The latter category also had the most industry partners (*Mdn* = 7), who acted as end-users of the key LPs delivered by learners. Citizen-science oriented SLEs were the most diverse type in terms of stakeholder synthesis (number of different categories of stakeholders engaged) (*Mdn* = 4.5), while Learner-experience oriented SLEs was the least diverse (*Mdn* = 3.5). For Citizen-science oriented SLEs, policy recommendations and initiatives capitalizing on citizen science data could increase stakeholder heterogeneity substantially during the lifecycle of the SLE. Learner-experience oriented SLEs included the most formal education providers (*Mdn* = 3) and non-formal education providers (*Mdn* = 3), despite their relatively lower stakeholder diversity. This should be carefully considered and weighed for scaling up STE(A)M learning ecologies. As far as number of learners are concerned, there was quite high variation across and within SLE types. More data from the mature phase of our project will be needed to see if there are any differences in the number and age of learners across types of SLEs.

3.2.2 Learning objectives

All SLEs targeted 21st century skills (e.g., communication, collaboration, critical thinking and problem solving, creativity and innovation), implying the importance of this skillset for all challenges to be addressed and for open schooling, overall. Such references were widespread in both the interviews with stakeholders and the responses of national coordinators to the questionnaire. The following extracts describe how bridging formal learning settings with non-formal learning environments as well as learners' collaborative work in SLEs could promote 21st century skills:

> *Stepping out of the box of the usual work of the school and the teaching process brings teachers and students to a more informal form of communication…Also, creativity, communication, collaboration skills, organization of work and the ability to perform in public crystallize as important skills that young people develop in this way of collaboration…* (Interview with representative of non-formal education provider; RS, Belgrade)

> *Collaborative work allowed students to improve team building skills, collaboration and management of contrasting ideas.* (Questionnaire completed by the national coordinator; MT, Pembroke)

Most SLEs (10 out of 12) included data collection and interpretation skills among their desirable learning objectives. Furthermore, some Learner-experience oriented SLEs targeted digital skills (IE; DE; MT), computational thinking skills (PT; RO;

MT), and experimentation skills (PT; RO; DE). End-used oriented SLEs (NO; RS) noted entrepreneurial skills among their learning objectives, while Citizen-science SLEs (CY; GR) prioritized modelling skills. All SLEs relied on female role models to attract and sustain the participation of female learners. This was primarily operationalized through female representatives or stakeholder spokespersons. These are two characteristic extracts from questionnaires referring to female role models:

> *During this process, all those who worked with the students in leadership roles were female – scientists, teachers, workshop leaders, librarians, artists etc. This was a conscious decision to use the principle of 'See it – Be it'.* (Questionnaire completed by the national coordinator; IE, Galway)

> *During the pathway, stakeholders presented the list of five Italian excellent female scientists who are on the list of the 100 most influential female scientists. Contrary to other situations where the male component tends to strive more to be in the spotlight and impose itself on the female component, in this context, instead, boys and girls worked on a parity basis.* (Questionnaire completed by the national coordinator; IT, Rome)

End-user oriented SLEs (NO; RS) included an elaborate co-creation process engaging learners and end-users (industry partners) in iterations before the final version of the key LP was delivered. Such an arrangement proved quite instrumental for promoting career opportunities. In other types of SLEs, career opportunities were usually linked with the contributions of stakeholder spokespersons.

3.2.3 Change

Templates for participatory scenario development conveyed stakeholder input on three different scenarios: (1) current conditions (business-as-usual scenarios), including gaps and inconsistencies to address when implementing SLEs; (2) small-scale inputs that could prove crucial for achieving considerable progress in the short term (small-effort scenarios); and (3) ideal conditions for SLEs to flourish and achieve long-term sustainability (best-case scenarios). Stakeholders in each SLE started with business-as-usual and then indicated changes in the other two scenarios. A key finding across all types of SLEs was that small-effort scenarios marked a departure from business-as-usual, indicating a qualitative change in prior conditions that promoted all aspects of stakeholder engagement in SLEs (i.e., stakeholder synthesis, stakeholder interaction, learning resources available, support provided to learners). Such qualitative change was transformative in character because it signified progression beyond business-as-usual. This finding implies that open schooling can be initiated with small-scale inputs only, which may nonetheless have decisive impact. It also points to small wins as drivers for scaling up open schooling. Indeed, adding even a small number of stakeholders in an SLE for the realization of small-effort scenarios seems to have initiated a positive feedback loop, where an increase in stakeholder synthesis enhanced stakeholder interaction, which led to increased availability of learning resources for learner engagement (Learner-experience oriented SLEs) and increased support offered to learners (all types of SLEs). This catalytic response addressed certain bottleneck effects described in business-as-usual scenarios, where teachers working alone could not always be ready to provide all of the quality feedback needed by learners. Here are excerpts from the participatory scenario development in the German SLE, laying out the change from business-as-usual to small-effort scenarios in terms of learning resources and support provided to learners:

> *Students work with easily accessible resources to complete their projects. For some ideas, only theoretical models are available to them.* (Participatory scenario development, Learning resources available, Business-as-usual scenario; DE, Berlin)

> *Students can work with researchers to conduct small experiments with real materials and in real scenarios. They gain new knowledge and practical skills to implement their research ideas.* (Participatory scenario development, Learning resources available, Small-effort scenario; DE, Berlin)

> *The teacher supports the students according to their possibilities. However, it is not always possible to meet all needs as this requires a lot of work and time.* (Participatory scenario development, Support provided to learners, Business-as-usual scenario; DE, Berlin)

> *Supervisors are available at the individual learning stations to support the teacher and help the students carry out their research projects.* (Participatory scenario development, Support provided to learners, Small-effort scenario; DE, Berlin)

In some cases, the qualitative change from business-as-usual to small-effort scenarios was accompanied by quantitative change from small-effort to best-case scenarios.

This was often observed for Learner-experience oriented SLEs and Master-product oriented SLEs, specifically, in terms of stakeholder synthesis and stakeholder interaction. This indicates that these types of SLEs had an increased likelihood of growing further, provided that more stakeholders joined and propelled their interaction. This was exemplified in the example below from the SLE in Spain, showcasing the transition in stakeholder synthesis from the business-as-usual scenario, through the small-effort scenario, to the best-case scenario:

> *A science museum initiates a collaboration with educational, research, science school club, youth association and industry stakeholders to create an SLE on artificial intelligence.* (Participatory scenario development, Stakeholder synthesis, Business-as-usual scenario; ES, A Coruña)

> *The incorporation of an audiovisual content company linked to artificial intelligence brings a different perspective that enriched and provided the key to the design of the SLE.* (Participatory scenario development, Stakeholder synthesis, Small-effort scenario; ES, A Coruña)

> *The partnership is maintained and incorporates new actors to enable the SLE to be implemented in new contexts.* (Participatory scenario development, Stakeholder synthesis, Best-case scenario; ES, A Coruña)

Other transitions involved the same initial qualitative change as above, from business-as-usual to small-effort scenarios, followed by another qualitative change from small-effort to best-case scenarios. This is illustrated in the sequence below from the

Norwegian SLE, showing the continuous qualitative change in terms of stakeholder interaction from business-as-usual, through small-effort, to best-case scenarios:

> *Professors and teacher assistants guide students, but the focus is primarily on academic knowledge, with limited exposure to real-life experiences.* (Participatory scenario development, Stakeholder interaction, Business-as-usual scenario; NO, Trondheim)

> *Occasional workshops and guest lectures by industry professionals provide insights into real-life applications and current trends.* (Participatory scenario development, Stakeholder interaction, Small-effort scenario; NO, Trondheim)

> *Regular meetings between students, teacher assistants, and industry representatives enable the discussion of project progress and overcoming any potential obstacle.* (Participatory scenario development, Stakeholder interaction, Best-case scenario; NO, Trondheim)

Qualitative change was reflected in a second form of positive feedback loop, which was more expressed in Citizen-science oriented SLEs. In these cases, best-case scenarios concentrated on peer interaction of either teachers, stakeholders, or learners, which fostered both the availability of learning resources and the support provided to learners (teacher, expert, or peer support). Developments of that kind revealed an orientation towards SLE growth based on developing and sustaining communities of practice. Overall, qualitative transitions in participatory scenario development indicated that the transformative potential for change and innovation in SLEs was considerable. Here is a characteristic example of that from the Cypriot SLE, showcasing a qualitative transition from one scenario category to the next as far as availability of learning resources is concerned:

> *Resources available mainly stem from the Open University of Cyprus and include: (1) A guide with the methodology for butterfly data collection; (2) an application for identifying butterfly species; (3) a database for storing butterfly data.* (Participatory scenario development, Learning resources available, Business-as-usual scenario; CY, Nicosia)

> *Stakeholders "inherit" the learning products of student projects and make them available to other students, who can use them as learning resources; this is currently facilitated through the contribution of the Natural Museum of Dali, which hosts learning products of the butterfly project.* (Participatory scenario development, Learning resources available, Small-effort scenario; CY, Nicosia)

> *Provided that more stakeholders join, especially the Department of Forests in Cyprus and firms offering gardener services, these are expected to offer additional learning resources and increase the variety of learning products, which can be expected from the butterfly project.* (Participatory scenario development, Learning resources available, Best-case scenario; CY, Nicosia)

3.2.4 Challenges

A series of challenges related to establishing and operating SLEs were stressed for Learner-experience oriented SLEs and Master-product oriented SLEs. These predominantly included constraints on the time that could be invested in SLEs, lack of resources necessary to undertake implementation, curriculum constraints, and other constraints imposed by the wider policy framework. Such challenges were typical of formal education settings anytime educational interventions deviated from what was typically prescribed in the curriculum. There were also a few contradictions identified, which mainly referred to a gap between declarations by policymakers and policy influencers, on the one hand, and what was finally allowed or possible to happen on the ground, on the other. Here are two extracts of that kind, concentrating on the contradictions of the policy framework in Romania and Slovakia:

> *The current policy framework…can both support and constrain the implementation of SLEs, depending on various factors such as funding, regulations, and educational priorities…School leadership encourages the participation in such initiatives, offering all the equipment needed. Unfortunately, primary schools cannot readily access science or ICT labs, so it is only within the frame of such projects that we can benefit from them.* (Questionnaire completed by the national coordinator; RO, Ramnicu Valcea)

> *The current policy framework in the context of implementing the SLE can have both positive and negative impacts on its implementation… Policies that prioritize and support STEAM education initiatives can provide a conducive environment for the implementation of the SLE, as it aligns with the goals of promoting interdisciplinary learning and real-world applications…Insufficient*

funding or budget constraints within the policy framework can hinder the successful implementation of the SLE, limiting resources for educational activities, materials, and teacher training… (Questionnaire completed by the national coordinator; SK, Poprad)

Challenges for End-user oriented SLEs and Citizen-science oriented SLEs mainly related to sustaining or renewing the stakeholder network.

3.2.5 Sustainability

Sustainability of SLEs was primarily supply-driven in Learner-experience oriented SLEs and Master-product oriented SLEs, while it seemed to be demand-driven in End-user oriented SLEs and Citizen-science oriented SLEs. Supply-driven sustainability relied on the readiness of stakeholders to join and offer learning resources or on their ability and willingness to reaffirm their participation, delivery, and support. Demand-driven sustainability built on the iterative co-creation process of learners with industry partners in the case of End-user oriented SLEs, which seemed to create additional demand for end-user LPs on the part of industry partners. For Citizen-science oriented SLEs, demand-driven sustainability depended upon peer networks wishing to extend data collection and the potential impact on relevant policy. The following interview extracts highlight how additional demand catalyzed the sustainability of End-user oriented SLEs (examples from Norway and Serbia) and how peer networks and policy implications promoted the sustainability of Citizen-science oriented SLEs (two examples from Cyprus):

This SLE … is expected to run the following years too. Collaborations with the customers are initiated and sustained in the future, for example some customers may have project proposals for the students every year (Interview with instructor at a higher education institute; NO, Trondheim)

For now, as far as the construction of the physical school gym is concerned, there are indications that our partner could be the city and local authorities… (Interview with representative of non-formal education provider; RS, Belgrade)

The Butterfly project is implemented for a second subsequent year in the school. The students who took part last year were kindly requested to inform the students who joined this year about…the methodology followed to identify butterflies. This way, students are much better able to grasp the methodology… (Interview with teacher; CY, Nicosia)

Students were concerned about the fact that we did not find many butterfly species along the transect and formulated their own hypotheses why this was the case, for instance, that…there were not too many flowering plant species to attract butterflies…this is how the need emerged to contact the Forest Service. (Interview with teacher; CY, Nicosia)

4. Discussion and implications

Based on the data sources we used, we were able to classify SLEs into four types: (1) Learner-experience oriented, (2) Master-product oriented, (3) End-user oriented, and

(4) Citizen-science oriented. Table 4 summarizes the main features for each SLE type. Learner-experience oriented SLEs were the most frequent but least diverse type; however, they hosted the maximum number of formal and non-formal education providers. Master-product oriented SLEs had the least stakeholders and End-user oriented SLE the most, primarily industry partners. Citizen-science oriented SLEs were the most diverse type of SLE. All SLEs included 21st century skills among their learning objectives and all types involved data analysis and interpretation skills; Learner-experience oriented SLEs presented the most extensive list of additional skills targeted (e.g., digital, computational thinking, experimentation skills), while End-user oriented SLEs specialized in entrepreneurial skills and Citizen-science oriented SLEs in modelling skills. Across SLE types, female participation was promoted by means of female role models as stakeholder spokespersons. Career opportunities were mostly facilitated through stakeholder spokespersons, as well. In End-user oriented SLEs, career opportunities were particularly pronounced through the iterative co-creation process followed by learners in collaboration with industry partners who acted as end-users of key LPs. Challenges in Learner-experience oriented SLEs and Master-product oriented SLEs pertained to formal education-related constraints, while sustainability in these two types was supply-driven. Challenges in End-user oriented SLEs and Citizen-science oriented SLEs converged on sustaining their stakeholder networks, while they displayed demand-driven sustainability. This was related to the additional demand for end-user LPs by industry partners for End-user oriented SLEs or to peer networks wishing to extend data collection and analysis in Citizen-science oriented SLEs.

Overall, the different types of SLEs we were able to identify largely correspond to different strategies employed to address real-world problems in open schooling projects (see Tables 3 and 4, in this regard). Learner-experience oriented SLEs offered opportunities to study different dimension of a problem, which was reflected in their diversity of learning objectives. An increased number of formal education providers in this SLE type was obviously related to the formal education constraints confronted. Master-product oriented SLEs may have been more suited for developing and presenting a solution to a problem to raise awareness. This is because in this SLE type a final product was singled out (master-product), which was delivered at the end of the learning path, and which constructively “consumed” all other prior LPs. This master-product can serve to highlight the unique selling point of the solution that learners would propose. End-user oriented SLEs followed a product development lifecycle to address specific needs and desires of end-users. This SLE type revealed the maximum number of stakeholders, especially, industry partners. Therefore, it seems quite appropriate to promote career opportunities, which can be particularly pronounced through the iterative co-creation process enacted by learners in close collaboration with end-users. Citizen-science oriented SLEs involved a first round of learning activities, where a pre-specified methodology was employed to collect and analyze data, and a second round, where new stakeholders were invited for formulating policy recommendations based on the data analyzed and pursuing such initiatives. Indeed, this SLE type presented the maximum number of stakeholder types, which reflected a quite inclusionary approach for co-designing policy recommendations with stakeholders and launching participatory initiatives.

Participatory scenario development exemplified the transformative potential of SLEs (STE(A)M Learning Ecologies, 2024). This was most evident in the transition from business-as-usual to small-effort scenarios. Indeed, the addition of just one stakeholder in the SLE network could have initiated positive domino effects in the form of a positive feedback loop, such that increased stakeholder synthesis and interaction could lead to increased availability of learning resources and learner support. Such a development would address potential bottleneck effects described in business-as-usual scenarios, where teachers alone could not have effectively provided all of the quality support and feedback needed by learners. A small-wins approach based on such small-effort scenarios may prove decisive for scaling up open schooling in the form of STE(A)M Learning Ecologies, because it exemplifies how change can be possible with a relatively confined investment of time and workload. Attracting even one new stakeholder can be pivotal for the dynamics in Learner-experience oriented SLEs, which had the minimum number of stakeholder types as well as for Master-product oriented SLEs, which had the minimum number of stakeholders across SLE types. As implied by quantitative change in scenario transitions in these two types of SLEs (business-as-usual to small-effort; small-effort to best-case), the entry of new stakeholders should be also critical for their supply-driven sustainability, which is dependent upon the provision of learning resources and learner support. In End-user oriented SLEs and Citizen-science oriented SLEs, however, best-case scenarios described ongoing qualitative change, related to consolidated interaction between learners and end-users in the first case, and peer interaction of learners and/or educators in the second. This latter change signified another instance of a positive feedback loop, where peer interaction facilitated the availability of learning resources and learner or peer support.

Building on our findings, we would like to highlight two main dimensions for future research. What was observed in Citizen-science oriented SLEs may refer to distributed leadership, where leadership tasks involving responsibility and decision-making are no longer the privilege of school principals but are decentralized to engage as many teachers as possible (see Daniëls et al., 2019). As we already mentioned, citizen-science oriented SLEs favored stakeholder diversity and teacher collaboration, which may reinforce their sustainability (see in this regard Wu, 2022). In the same vein, distributed leadership presupposes shared ownership of initiatives to promote innovation and can be fostered by both stakeholder diversity and teacher collaboration. Given that peer interaction in teacher networks operating as communities of practice may empower participants (Author, 2016b), it would be insightful if future research examines how SLEs, Citizen-science oriented SLEs in particular, can foster distributed leadership and empower teachers in planning and implementing open schooling projects. This empowerment dimension is linked with the second suggestion we would like to propose for future research. Stakeholders in SLEs can plan their next iterations by following the same format or opting to "evolve" by integrating distinguishing features of other types of SLEs. For instance, if a master product is added to a Learner-experience oriented SLE, and if the participatory pedagogical design is adapted accordingly (e.g., the master product is designed to constructively "consume" prior LPs), then such an SLE may evolve into a Master-product oriented SLE. Another example would be the evolution of a Citizen-science oriented SLE into an End-user oriented SLE. In that case, the policy implications of citizen science could initiate a solution-driven iteration with a co-creation process between learners and stakeholders acting as end-users.

The pool of SLEs in the pilot phase of our project was quite confined (12SLEs) and pertained to the European context, which we need to acknowledge as a limitation of our study. In addition, a richer collection of metadata of learning products may add insights in terms of learner creativity as well as offer the opportunity to explore learner trajectories in more detail (e.g., through lag sequential analysis), which would add a longitudinal perspective. The mature phase of the SLEs project will offer much more data to validate and optimize the typology of SLEs. However, learner and stakeholder engagement have illustrated, already in the pilot phase, how SLEs can promote the creativity of all actors. They have showcased, moreover, that creativity is not just leisure (see here Henriksen et al., 2017) but can be materialized in pedagogical designs and LPs, which can bridge formal and non-formal learning settings. SLEs can provide a delicate balance between structure and guidance, on the one hand, which are the norm in formal education, and agency and freedom, on the other, allowing students, their teachers, and multiple stakeholders to benefit from heterogeneous resources and co-create novel and useful solutions to address real-world problems (see Author et al., 2017). Teachers can employ the concept of SLEs as a robust instructional strategy to support students in developing 21st century skills (see in this regard Varas et al., 2023). Artefacts constructed by learners when using learning resources provided by stakeholders can be exploited as organizing principles of coherent pedagogical designs and learner experiences in SLEs. There were several implementations of design thinking models in STEM education and open schooling, which all aimed to engage learners in designing, producing, and testing artefacts to address real-world problems (e.g. Authors et al., 2023a; Liu et al., 2023; Wingard et al., 2022). Solutions to these problems were often user-tailored, for which stakeholder input and feedback was sought and elaborated upon. Indeed, outdoor activities and stakeholder engagement were found to enhance student creativity through manufacturing artefacts (Lage-Gómez & Ros, 2024). We believe that there is much potential for delving deeper in the overlap between design thinking and creativity (Gabriel et al., 2016; He et al., 2023). Future research should exploit SLEs with their creative pedagogical design and artefacts to weigh optimal mixes of guidance and freedom across different types of open schooling projects.

Endnotes

[1] Details of the stakeholder synthesis for each SLE can be found in the SLEs portfolio at this link: https://www.steamecologies.eu/wp-content/uploads/2024/06/SLEs-PORTFOLIO-TEMPLATE_v1.2.pdf

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Figure legends

Figure 1
Bird feeders in the Learner-experience oriented STE(A)M Learning Ecology titled "Steaming up with nature's wonders" (Romania, Ramnicu Valcea).

Figure 2
Pollination robotics in the Learner-experience oriented STE(A)M Learning Ecology titled "Steaming up with nature's wonders" (Romania, Ramnicu Valcea).

Figure 3
Drawings of plant species used for learners' botanical e-book in the Master-product oriented STE(A)M Learning Ecology titled "AI in ecology – ecology in AI" (Slovakia, Poprad).

Figure 4
Demo of a solution for digitalizing port management (map client for displaying port data) in the End-user oriented STE(A)M Learning Ecology titled "Student software solutions for real clients" (Norway, Trondheim).

Figure 5
Testing a seismograph in the Citizen-science oriented STE(A)M Learning Ecology titled "Studying earthquakes" (Greece, Athens).

Figure 6

Figure 6. Types of STE(A)M Learning Ecologies (open schooling projects). Dark rhombuses represent learning products delivered by learners (i.e. artefacts constructed by learners themselves, anytime they used learning resources to enact learning activities); the dark line running through learning products represents the learning path and activity sequence. In Learner-experience oriented SLEs (1), learning activities and the delivery of learning products do not follow any strict serial sequence but can be switched in order, without that having any impact on the learning path. This is depicted visually by the cyclical arrangement of learning products. In Master-product oriented SLEs (2), one final learning product is singled out (master-product), which is delivered at the end of the learning activity sequence, and which integrates all prior learning products or needs them to be created. This configuration is portrayed by arrows starting from all learning products and heading towards the master-product. In End-user oriented SLEs (3), the learning path evolves along an iterative process, where learners co-create and optimize in close collaboration with end-users 0a key learning product, which addresses concrete end-user needs and desires. This is represented by the helix-shaped learning activity sequence. In Citizen-science oriented SLEs (4), the learning activity sequence involves two phases: First, learners follow a pre-specified methodology to collect and analyze data (continuous cycle on the top); second, they formulate policy recommendations based on their data, and invite new stakeholders in the SLE to pursue these initiatives (dashed cycle at the bottom).

Appendix A. Template for participatory pedagogical design*

Main themes for participatory pedagogical design	Tasks	Examples
(1) Learning products to be created by students themselves along learning paths	Please describe artefacts that are expected by learners in the above learning sequence; can you please give texts, graphs, drawings, sketches, demos, mockups, etc., for these learning products?	Any artefact that will be created by learners during enacting learning activities, e.g., texts, graphs, models, digital artefacts, and any other product manufactured by learners using learning resources.
(2) Potential learning paths; how learning resources can be arranged to form learning paths	Please describe the sequence of learning activities in the SLE pilot. Which learning resources are necessary for these learning activities? Is there one path to take only or can learners have alternative learning paths? Please explain.	Which learning products are expected first and which next? Is any learning product necessary for creating another learning product in the learning activity sequence?
(3) Curriculum mapping of knowledge and skills as	Which targeted knowledge and skills are	Correspondence of knowledge and skills

reflected by learning products	reflected in these learning products? Please match knowledge and skills reflected in these learning products to curriculum standards	reflected by learning products to curriculum standards for corresponding subjects
(4) Support and guidance to be provided by stakeholders to students along learning paths	Please describe how stakeholders can guide and support students while using learning resources to enact learning activities	E.g., Elaborate on the usability of certain apps; scaffold data collection and analysis
(5) Opportunities for female engagement	Please describe how the learning path may attract both males and females	E.g., Selection of topics; female representatives or spokespersons acting as role models
(6) Career opportunities	Please describe how stakeholders involved in the SLE pilot can inspire learners' career paths	E.g., Career opportunities promoted through stakeholder representatives in key positions (public, private, and civil society organizations)

*Note: A completed participatory pedagogical design template from the STE(A)M Learning Ecology in Cyprus is provided as Supplemental Online Material.

Appendix B. Participatory scenario development for the Butterfly project (CY)

	Business-as-usual scenario (Baseline conditions, crucial gaps and inconsistencies to address when implementing SLEs)	Small-effort scenario (Small-scale inputs potentially decisive for achieving considerable progress in the short-term)	Best-case scenario (Ideal conditions for SLEs to flourish and secure long-term sustainability)
Stakeholder synthesis	The Butterfly project is part of a European initiative which employs the same methodology to gather and analyze butterfly data from multiple European locations. In Cyprus, the project was initiated by the Ministry of Education, Sport and Youth (Unit for Education for the Environment and Sustainable Development) under the support of the Open University of Cyprus. A secondary	The University of Cyprus (Research in Science and Technology Education Group) joined the project as National Coordinator in the SLEs project and the Butterfly project was the pilot SLE selected in Cyprus. Additional stakeholders, which joined the stakeholder coalition, are the Local Municipality of Pera Chorio and the Museum of Natural History in Dali,	Other stakeholders sought to join the network and foster its strengths and sustainability were: (1) The Department of Forests in Cyprus, which may adopt student recommendations to enhance flora and butterfly diversity and support butterfly pollination; (2) firms offering gardener services in the wider area of Nicosia may provide additional learning resources and integrate student

	school teacher in a school near Nicosia adopted it from a colleague of hers.	which hosts an exhibition of the butterfly project.	recommendations in their business model.
Stakeholder interaction	The teacher tries to bring additional stakeholders in the project through personal initiatives and interpersonal relationships, which is restricted by time constraints, lack of resources, and total workload. A main barrier for scaling up the project is that it is perceived as an extracurricular initiative.	Stakeholder collaboration is currently concentrating on the local scale, around the neighborhood. Stakeholders start integrating parts of the butterfly project in their planning. The Local Municipality has offered considerable funding for the construction of a park, which will be supported by the SLE.	Provided that quality control is maintained in data collection and processing, the project may mature into a fully-fledged citizen science initiative with considerable implications for spatial planning and the overall aim to increase flora and butterfly diversity for butterfly pollination.
Learning resources available	Resources available mainly stem from the Open University of Cyprus and include: (1) A guide with the methodology for butterfly data	Stakeholders “inherit” the learning products of student projects and make them available to other students, who can use them as learning resources; this	Provided that more stakeholders join, especially the Department of Forests in Cyprus and firms offering gardener services, these are expected to offer

	collection; (2) a digital tool for identifying butterfly species; (3) a database for storing butterfly data.	is currently facilitated through the contribution of the Natural Museum of Dali, which hosts learning products of the butterfly project	additional learning resources and increase the variety of learning products, which can be expected from the butterfly project.
Support provided to learners	The teacher works mostly on her own to support students in data collection and processing. Support by the Open University of Cyprus is crucial bot not enough to account for all learner needs and desires.	Learners are supported by two higher education institutes, the Local Municipality and the Museum of Natural History in data collection and processing and in formulating policy implications based on their data analysis.	Learners connect with other SLEs in the wider European “Butterfly” initiative; they exchange knowledge, experiences, and learning products; peer and teacher support from other SLEs is available and a community of practice is formed.

Table 1. Descriptive characteristics of STE(A0M Learning Ecologies

STE(A)M Learning Ecology	Challenge	Initiator; National Coordinator (when different from Initiator)	Country, city	Learners' age
Intertwined – Mosaic of the community brain	Teenagers' lack of engagement with the local library and its maker space	Ballybane Community Library; National University of Ireland Galway	Ireland (IE), Galway	15
Student software solutions for real clients	Support university students transition from academic settings to the professional world	Norwegian University of Science and Technology	Norway (NO), Trondheim	21-24
Imagining the world in 2030	Raising awareness on the ethical and environmental opportunities and threats of AI	Domus - Museos Científicos Coruñeses	Spain (ES), A Coruña	15-16
The butterfly project	Contribute to data collection and analysis of butterfly species in local ecosystems	Cyprus Ministry of Education, Sport and Youth; University of Cyprus	Cyprus (CY), Nicosia	16
Green citizenship in action	Need for new practical models for more sustainable schools and communities	Agency for the Promotion of European Research	Italy (IT), Rome	11

Ecosystem services from land to sea	Need to increase students' awareness on UN Sustainable Development Goals	Centro Ciência Viva do Algarve	Portugal (PT), Faro	9-10
Steaming up with nature's wonders	Need for students to reconnect with nature, especially local nature	Mircea ceL Batran National College; European Schoolnet	Romania (RO), Ramnicu Valcea	6-7
AI in ecology – ecology in AI	Lack of students' engagement in the conservation of the local ecosystem	Poprad Primary School; European Schoolnet	Slovakia (SK), Poprad	13
Energies for the future	Need for younger generations to be aware about climate change and renewable energy	WISTA Management GmBH and Humboldt-Universität zu Berlin	Germany (DE), Berlin	12-16
Psychological health and wellbeing	Create a gym for physical education in the Patrijarh Pavle Gymnasium	Center for the Promotion of Science	Serbia (RS), Belgrade	5-19
Studying earthquakes	Understand earthquakes and increase awareness of civic protection	Ellinogermaniki Agogi	Greece (GR), Pallini-Athens	13-16
GIRLS4STEM	Counteract gender stereotypes with female STEM professionals acting as role models	Directorate for STEM & VET Programmes	Malta (MT), Pembroke	12-13

Table 2. Stakeholders and learners in STE(A0M Learning Ecologies

STE(A)M Learning Ecology	Formal education providers	Non-formal education providers	Governmental organizations	Civil society organizations	Industry partners	Total number of stakeholders	No of stakeholder types	No of learners
Intertwined – Mosaic of the community brain (IE)	2	3	0	0	1	6	3	37
Student software solutions for real clients (NO)	1	0	1	0	11	13	3	65
Imagining the world in 2030 (ES)	1	1	1	1	1	5	5	11
The butterfly project (CY)	3	1	3	0	2	9	4	23
Green citizenship in action (IT)	2	0	3	1	0	6	3	11

Ecosystem services from land to sea (PT)	4	4	1	1	1	11	5	188
Steaming up with nature’s wonders (RO)	3	3	1	0	0	7	3	21
AI in ecology – ecology in AI (SK)	2	1	0	1	0	4	3	20
Energies for the future (DE)	3	3	3	0	3	12	4	15
Psychological health and wellbeing (RS)	2	1	1	1	3	8	5	450
Studying earthquakes (GR)	2	1	1	1	1	6	5	175
GIRLS4STEM (MT)	3	2	3	1	0	9	4	60

Table 3. Typology of STE(A)M Learning Ecologies.

	Learner-experience oriented SLEs	Master-product oriented SLEs	End-user oriented SLEs	Citizen-science oriented SLEs
Learning path including learning resources and learning products	Learners deliver a rich portfolio of diverse learning products making use of dedicated learning resources offered by stakeholders in the SLE	Learner work is converging on a master learning product delivered at the end of the learning path, which integrates all prior learning products	Learners follow a number of iterations to deliver a key learning product, which addresses concrete end-user (stakeholder) needs and desires	Learners follow a pre-specified methodology to contribute to data collection and analysis supported by multiple social actors in multiple locations
Sequencing of learning activities	SLEs in this category are quite modular, in the sense that learning activities do not follow any strict serial sequence but can be switched in order	Learner engagement serves the creation of the master product, which can be presented to external audiences and utilized for launching policy initiatives	Product development lifecycle; marked resemblance with iterative engineering design process and analogous approaches (e.g. model-based inquiry)	Learners get familiarized with the methodology, collect data, insert them into a broader database, analyse data, and conclude with policy implications

Flexibility in pedagogical design	Learning activities and learning products can be either skipped or added without any major impact on the learning path and overall learner experience	Overall structure dictated by the features of the master product; prior learning products may be adapted to suit different learning settings	Unique designs focused on end-user needs and desires; learners and end-users maintain contact throughout the duration of the SLE to adapt designs	Further opportunities for stakeholder engagement and extension of the SLE in terms of policy recommendations and initiatives
Trade-offs	More learning activities and products may enhance learner experience in the short term at the expense of coherence and long-term learning outcomes	Time and workload for learners and stakeholders needs to be effectively allocated to all necessary prior learning products as well as the master product	Learners and end-users need to be creative and, at the same time, be able to narrow down options to maintain realism and cost-effectiveness	Stakeholders and learners need to strike an optimal balance between the rigidity of the methodology and innovation in terms of policy initiatives
Examples	IE; IT; PT; RO; DE; MT	ES; SK	NO; RS	CY; GR

Table 4. Similarities and differences between types of STE(A)M Learning Ecologies.

	Learner-experience oriented SLEs	Master-product oriented SLEs	End-user oriented SLEs	Citizen-science oriented SLEs
Stakeholder synthesis	Minimum number of stakeholder types; maximum number of formal and non-formal education providers	Minimum number of stakeholders	Maximum number of stakeholders; maximum number of industry partners	Maximum number of stakeholder types
Learning objectives	21st century skills; data analysis and interpretation skills; digital and/or computational thinking skills and/or experimentation skills	21st century skills; data analysis and interpretation skills	21st century skills; data analysis and interpretation skills; entrepreneurial skills	21st century skills; data analysis and interpretation skills; modelling skills
Female participation	Female role models	Female role models	Female role models	Female role models

Career opportunities	Stakeholder spokespersons	Stakeholder spokespersons	Particularly pronounced through the iterative co-creation process	Stakeholder spokespersons
Change	Transformative change in small-effort scenarios; increasing number of stakeholders increases availability of learning resources and learner support; quantitative change in best-case scenarios	Transformative change in small-effort scenarios; increasing number of stakeholders increases availability of learner support; quantitative change in best-case scenarios	Transformative change in small-effort scenarios; increasing number of stakeholders increases availability of learner support; qualitative change in best-case scenarios	Transformative change in small-effort scenarios; peer interaction increases availability of learning resources and learner support; qualitative change in best-case scenarios
Challenges	Formal education constraints	Formal education constraints	Sustain stakeholder network	Sustain stakeholder network
Sustainability	Supply-driven	Supply-driven	Demand-driven	Demand-driven
Examples	IE; IT; PT; RO; DE; MT	ES; SK	NO; RS	CY; GR


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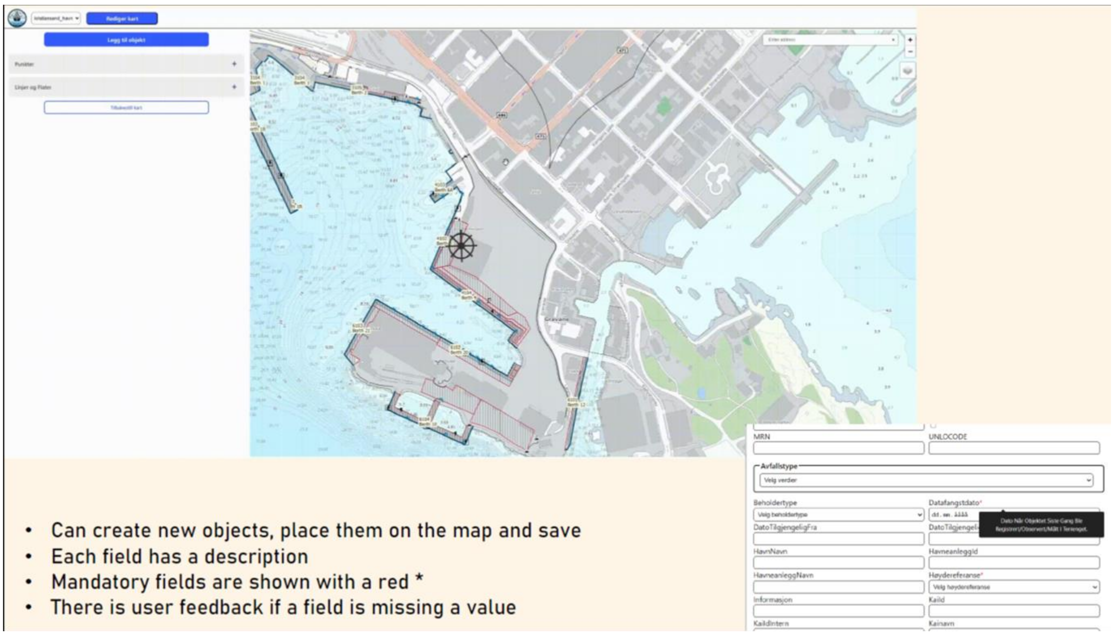

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• Mandatory fields are shown with a red *
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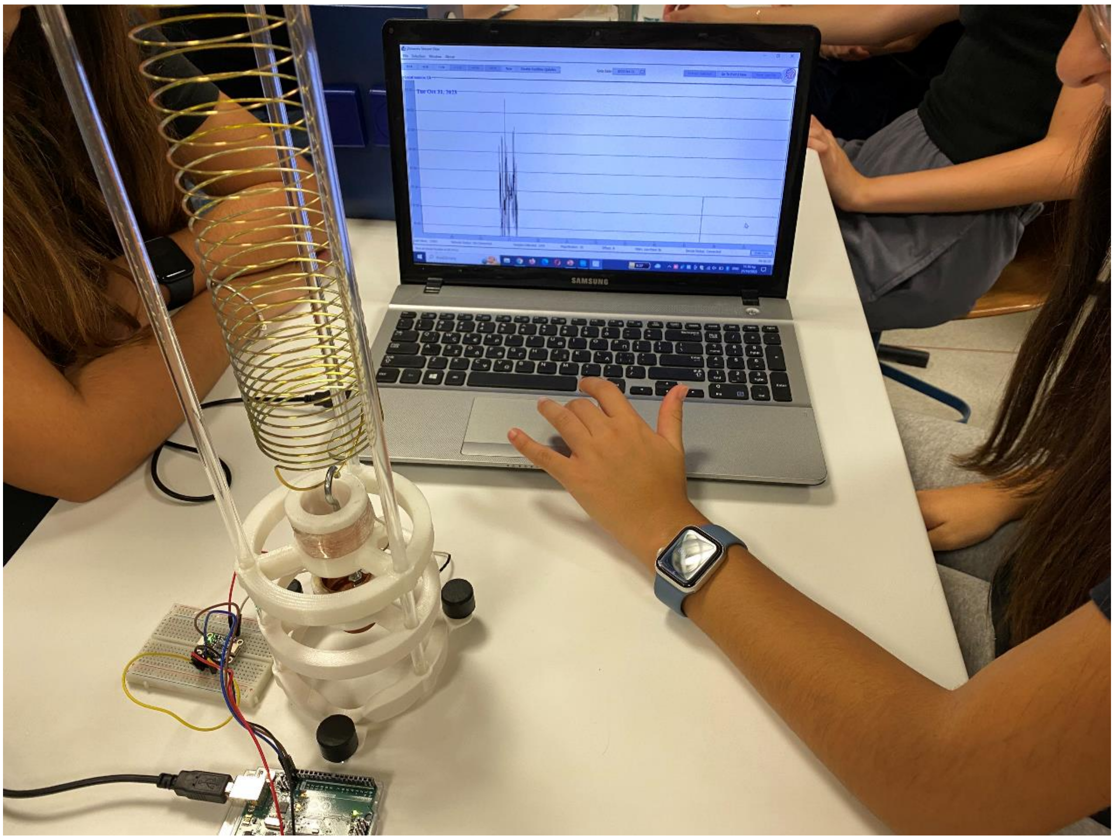
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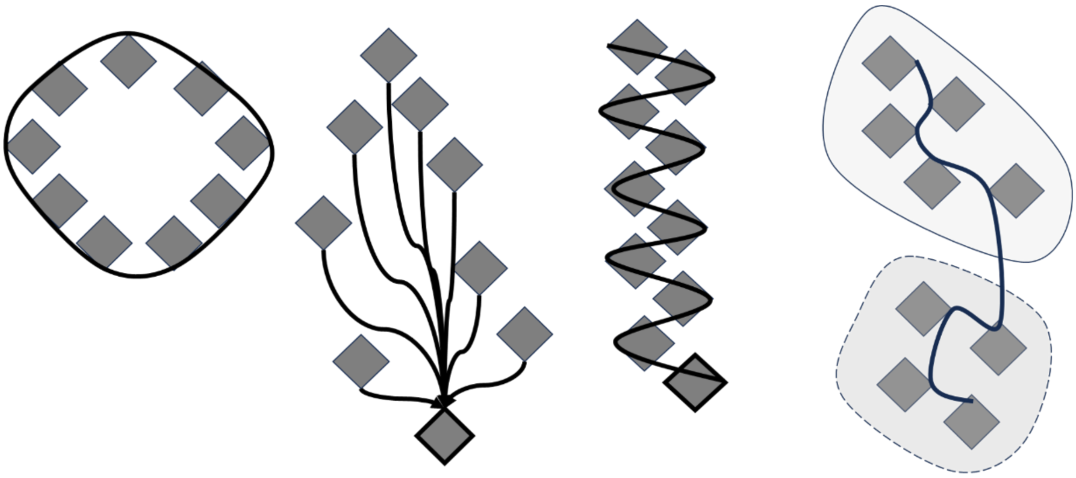

(1) Learner-experience oriented SLEs | (2) Master-product oriented SLEs | (3) End-user oriented SLEs | (4) Citizen-science oriented SLEs