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Research paper

Supporting in-service teachers' STEM design practices

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ABSTRACT

Design plays a central role in integrated STEM approaches. However, there is limited knowledge of how teachers from different S-T-E-M disciplinary backgrounds practice STEM design. To address this knowledge gap, we examined the STEM design practices of a convenience sample of 26 in-service teachers who voluntarily participated in a 7-month-long STEM professional development programme, divided into 4 Learning Community (LC) groups. As part of this programme, teachers designed STEM modules in the context of Nanoscience-Nanotechnology. Qualitative analysis of the LC discussions (synchronous), forum posts (asynchronous), and the designed artefacts provided insights both in terms of ideas/themes that teachers mostly discussed, as well as the design activity of the individual teachers. Frequencies of teachers' inductively coded design actions during the LC meetings were noted, described through design visualisations and were used to infer the centrality of ideas discussed and the centrality of members' activity. This analysis showcased that modelling, technicalities, robotics, and sensors were some common themes discussed among the four cases. Regarding the impact of teachers' backgrounds on the nature of their practices, it was found that STEM design centrality was not restricted to any disciplinary background. However, the activity of most mathematics teachers appeared peripheral. Finally, teachers tended to contribute to parts of the artefact that were closer to their disciplinary expertise, while a few boundary-crossing design practices were noted.

Keywords: STEM design, integrated STEM, learning communities, STEM artefacts, design visualisations, multiple case study, nanotechnology

Introduction Educational reports stress the importance of cultivating design practices among teachers (European Commission, 2021), especially since the introduction of technology, engineering, and integrated STEM in school education (NRC, 2014). Design generally refers to solving problems in real-world contexts (Zhou et al., 2022). However, few teachers have the competencies and confidence to become designers, while there appears to be a lack of teacher preparation in the area of design (Kim, 2019).

Involving teachers in the open-ended and complex environment of designing and developing prototypes allows them to foster their own 'adaptive expertise', articulate their practical knowledge, generate and integrate new ideas, and move beyond their practices (Bannan-Ritland, 2014). Moreover, design gains much importance in STEM education since it facilitates the conceptualisation and development of integrated STEM in schools (English, 2016).

In this study, we adopt a definition of STEM as "a teaching approach that integrates content and skills specific to science, technology, engineering and mathematics" (Martín-Páez et al., 2019); hence it is regarded as an integrative approach by definition. Therefore, for the purpose of this study, we use the term *STEM design* to signify the design of teaching material for integrated STEM, i.e. STEM modules and related artefacts.

Regarding STEM artefacts, Aranda et al. (2020) support that using artefacts such as physical models and analogies can assist in the connection between physical models and abstract conceptual models used in science. Especially in microworld phenomena, modelling can lead to learning gains (Geelan, 2012). However, research shows that when teachers use curriculum materials and artefacts such as physical models, differences appear in their verbal explanations and discussions, as well as the connections between the physical and conceptual models (Aranda et al., 2020). Similarly, differences appear at the disciplinary level, and concerning the particular project (Berland et al., 2014). Therefore, it becomes critical to investigate the design practices of teachers from different disciplinary backgrounds and experiences.

Specifically, by studying teachers' design practices on artefacts and curriculum materials, we can gain an understanding of how these materials, and curriculum reforms in general, are actually understood and implemented in school classrooms by the teachers, while we can also access the way teachers develop and transform knowledge. Therefore, findings can improve the effectiveness of designing curriculum materials and can inform our knowledge about teacher practices (Davis et al., 2016). However, the design process is often not reported or overlooked by researchers who mostly report empirical results instead (Kim, 2019).

Hence, the present study aims to investigate the STEM design practices of in-service secondary teachers under three lenses: the developed STEM modules and artefacts, the conceptual themes and ideas discussed, and the design practices of individual teachers from diverse disciplines. This initiative aims to respond to the gap in the literature about the differences and the peculiarities that agents coming from all S-T-E-M disciplines bring to STEM design. The study was implemented during a STEM Professional Development (PD) programme, in which teachers work in diverse groups to develop STEM teaching material from scratch.

In terms of the content topic, Bannan-Ritland (2014) suggests the introduction of complex topics that promote deep learning and challenge teachers to reconsider their beliefs about teaching practice. Hence, the development and implementation of new teaching strategies can take place, in contrast to strategies crystallised by experience. In this light, NanoScience-NanoTechnology (NST) was chosen as a topic due to its real-world relevance and intrinsically interdisciplinary nature (Manou et al., 2022). It was deemed that such a topic would promote an integrated STEM approach and would assist teachers in developing STEM practices.

Therefore, the scope of this study was to examine how S-T-E-M teachers design and develop STEM teaching material in the context of Nanoscience-Nanotechnology. The research questions were the following:

- RQ1) What STEM modules and STEM artefacts do teachers design and develop?
- RQ2) What are the central ideas/themes that teachers engage with when designing and developing STEM teaching material?
- RQ3) What is the nature of the teachers' design activity when designing and developing STEM teaching material?

Responses to these questions will add significantly to the growing literature on teachers' design practices and could be used as input for the design of teacher education and professional development programs.

LITERATURE REVIEW

It is well documented in the literature that implementing design activities in teaching can contribute to several benefits, such as increased science content knowledge and promotion of students' computational thinking engagement (Kelley & Sung, 2017). Moreover, design activities can also foster students' creativity in STEM education contexts (Kim, 2019; Zhang et al., 2024). Furthermore, engaging students in design activities can positively affect students' attitudes towards research and design, can empower underrepresented groups in STEM such as girls, and can aspire students to pursue careers related to research or design (Vossen et al., 2018).

However, challenges appear when engineering design is integrated in K-12 classrooms, since students tend to undervalue the opportunities for applying and exploring the relevant science and mathematical content knowledge (Berland et al., 2014). Also, students often find difficulties in transferring content knowledge into new situations, therefore teacher preparation is needed to provide scaffolds and guidance to students in design-based instruction (Kelley & Sung, 2017).

Regarding teacher education, STEM design, especially through integrating engineering practices, is new to science teachers (Aranda et al., 2020). Hence, they often lack an understanding of engineering practices as well as the skills to implement engineering design (Nipyrakis et al., 2024b). However, the benefits of implementing design practices to educate teachers are numerous. It allows teachers to go through the same process as students, while it also provides an intellectual and organisation mechanism for teachers to develop curriculum design, monitor, assess, and revise the designed approach or materials (Billiar et al., 2014).

Generally, an overlap of design practices appears across disciplines (Sevian & Talanquer, 2014). Vossen et al. (2018) identify some main phases of design, including the clarification of the problem, assembling a programme of requirements, planning design, constructing a prototype, testing and optimising the prototype, analysis of the product, and communication. Similarly, Billiar et al. (2014) describe a general STEM curriculum design framework, inspired by engineering design.

However, some variances appear in the design process regarding discipline and project (Berland et al., 2014). For example, in the context of engineering, 4 core components of engineering design identified by Berland et al. (2014) include: a) the definition of the problem, b) the systematic approach to many possible solutions and making choices about them, c) modelling and analysis, and d) the iterative nature of the process. In the context of technology, definitions of design are closely linked with engineering. However, design is mostly connected with the engineering profession, while technology is perceived as performing more deterministic work (Murphy et al., 2015).

In the context of chemistry, design relates to the creation and implementation of strategies for analysing, synthesising, or transforming substances to address relevant problems (Sevian & Talanquer, 2014). Regarding mathematics, it is quite common to use applied mathematics in the design processes of related disciplines (Wittmann, 1995), often in a rather instrumental way, a practice that often neglects the deep interactions among the disciplines (Tzanakis, 2016). This confirms the general tendency of underrepresenting mathematics in STEM (Nipyrakis et al., 2024c; English, 2016). Teachers often integrate mathematics in a practical way without making deep connections (Nipyrakis et al., 2024b), while they underestimate the collaboration with mathematics teachers because they regard mathematical knowledge as fundamental that they already possess themselves (Nipyrakis et al., 2024c). Contrastingly, Branchetti and Levrini (2025) propose critical encounters with other disciplinary knowledge and practices through historical-epistemological approaches in order to highlight the role of mathematics. Concerning design, Wittmann (1995) suggests that mathematics education be considered into the larger class of design sciences, in which the constructed 'artificial objects' are teaching units, curricula and investigations of their effectiveness. Therefore, in the context of science and mathematics education, attention rather focuses on the development of conceptual systems instead of physical artefacts or tools (Lesh & Sriraman, 2005). Nevertheless, traditional views on science and mathematics in schools do not regard these as disciplines in which students design (Li et al., 2019). A generic differentiation considers science and mathematics as 'natural' sciences, while engineering and technology as 'design' sciences (Nathan et al., 2013). However, Nathan et al. (2013) regard this differentiation as insufficient and inappropriate in the context of integrated STEM, while crossing disciplinary boundaries is needed, a process that creates a learning potential (Barelli et al., 2022). Specifically, boundary crossing offers a potential continuity across sites (Akkerman & Bakker, 2011) and is commonly defined as "a person's transition and interactions across different sites" (Suchman, 1994), which in our case relates to S-T-E-M design practices for STEM teaching.

Building upon these findings, it becomes imperative to investigate the design practices of different S-T-E-M agents when engaged in integrated STEM design in order to trace peculiarities and commonalities among them. Moreover, for the purpose of facilitating integration, the use of interdisciplinary topics such as NST appears promising, while a collaborative framework can better frame disciplinary interactions. In this light, STEM design in the present study is situated in a collaborative Learning Communities (LC) framework (Couso, 2016), hence it is studied as a teamwork process. Particularly, LCs are groups of teachers, academics and experts who work together in a way that constructive discussion, criticism, reflection and an inquiry stance are pursued. LCs can be effective in teacher education contexts (Nipyrakis et al., 2024a) and can facilitate the effective adoption of educational innovations (Couso, 2016), such as integrated STEM in our study. Specifically, its dialogical nature can foster interdisciplinary collaboration instead of antagonism (Torres-Olave & Bravo González 2021).

METHODS

Context

The study was implemented during a 7-month-long STEM PD programme for in-service teachers in Greece, and it was co-designed by researchers and local educational stakeholders. The programme has been ethically approved by the committee of the academic department. The aim of the programme was to educate teachers in STEM teaching. **Table 1** shows the different phases of the PD programme. Specifically, the present study focuses on the phase of designing STEM modules and artefacts, i.e. sessions 4-10. Particularly, each designed STEM module was deemed to be entangled with the design and development of the STEM artefact; therefore the design and the development of the two were both explored in an integrated way.

The content topic of the PD programme was chosen to be NST, hence, the teachers were assigned the parameter to include some NST concept/phenomenon/ application into their designed module.

Table 1

Outline of the STEM PD Programme

Session number	Modality	Description
1	in-person	Introductory meeting, groups formation
2	online	Lecture on NST content/phenomena/applications
3	online	Lecture on STEM Education and STEM integration principles
4-10	LC groups: online/in-person	Design & Development of STEM modules & artefacts
11-12	LC groups: online	Development of STEM lesson plans on the module
13	LC groups: in-person	Sharing and exhibition of the finalised STEM artefact
Implementation of the STEM teaching material in schools		

The PD programme included both in-person and online LC meetings. Additionally, an online forum was used for each LC group to facilitate asynchronous communication and sharing of resources.

The part of the PD programme after the 8-9th session took place under rigorous Covid restrictions, therefore the development of the STEM artefact was carried out either sequentially, i.e. each teacher contributed to some part of the artefact and passed it to another LC member, or in parallel, i.e. LC members worked on different parts of the artefact and then combined them.

Participants

The sample of the study consisted of 26 in-service secondary teachers who voluntarily participated in the study after being informed by the educational stakeholders. The researchers informed the participants about the purpose of the study through a debriefing session. The disciplinary background of the teachers was science (n=10), technology (n=5), engineering (n=6) and mathematics (n=5). 14 of them were females and 12 of them were males. **Table 2** provides further information. Particularly, STEM experience was coded according to three scales based on teachers' responses: a) no experience in STEM, b) little experience, i.e. previous participation in one STEM school project or reference on practising interdisciplinary 'episodes'/sessions in their own teaching practice in a rather implicit way, c) adequate experience, i.e. previous participation in more than one STEM school projects.

Table 2

Participants' attributes

node	teaching experience (years)	STEM experience	node	teaching experience (years)	STEM experience
LC group A			LC group C		
AS1	25	adequate	CS1	16	no
AS2	5	little	CS2	11	no
AT1	24	adequate	CT1	19	little
AE1	19	little	CE1	12	little
AE2	10	no	CE2	23	adequate
AM1	22	little	CM1	18	little
LC group B			LC group D		
BS1	7	no	DS1	13,5	little
BS2	-	-	DS2	19	no
BS3	33	little	DT1	14	adequate
BS4	20	no	DT2	20	little
BT1	-	-	DE1	20	adequate
BE1	8	adequate	DM1	8	no
BM1	10	little	DM2	20	little

In terms of reference, the first letter in the name of each node represents the LC group assigned and the second letter their disciplinary background, e.g. CS1 is a science teacher who participated in LC group C. BS2 and BT1 quitted the programme after having participated in 5 LC meetings, due to the pandemic period.

The participating teachers were divided into four Learning Community (LC) groups by aiming to include at least one representative from each S-T-E-M discipline in each group. This setting was intentionally chosen in order to leverage the contribution of all disciplines and to foster cross-disciplinary collaboration. A science education researcher (R1) and partly a second researcher (R2) acted as the moderators of the discussion through their roles as the STEM experts in the LCs.

Data collection

Data sources of the present study consist of: a) the transcribed LC meetings of design phase, i.e. LC meetings 4-10 in Table 1, b) the online forum posts, c) the finalised STEM artefacts, as discussed and presented in the last session, i.e. LC meeting 13 in Table 1, d) reflection interviews at the end of the PD programme concerning the STEM design process and collaboration preferences.

Data analysis

The transcripts from the LC meetings were analysed by using qualitative content methods (Mayring, 2015). Specifically, inductive coding was deemed appropriate due to the exploratory nature of the research questions. The design was examined through the examination of *design ideas*, which were concepts, methods, physical objects or questions/suggestions related to designing the module. Notably, all ideas were coded regardless of their efficiency or their scientific accuracy. Subsequently, the analysis unit used to examine the nodes' activity was the *design action* i.e. an action carried out by a node in terms of designing the module. The design actions were identified and coded according to the following inductively made categories:

- Node A *introduces* idea B: when a node initiates a new idea/theme concerning STEM design
- Node A *supports* the idea C: when a node supports or approves an existing idea/theme or s/he provides additional information/resources about it
- Node A *extends* to idea D: when a node extends a previous idea/theme to another idea/theme which is related to the previous one. In this case, the link between the two ideas was also noted.
- Node A *criticises* the idea E: when a node disapproves/criticises an idea/theme
- Node A *debates* about idea F: when a node defends or further supports an idea/theme against the criticism expressed before towards it
- Node A *agrees* about idea G: when a node relents in her/his initial criticism or support on an idea/theme and agrees with the view of another peer LC member
- Node A *connects* the idea H: when a node connects an already expressed idea/theme with another already expressed idea/theme. In this case, the link between the two ideas was also noted.

First, the data from the discussions were analysed in order to familiarise ourselves with the process. Inductively-made criteria were developed, reviewed and agreed upon by another two researchers, and they were kept for the coding of the design actions with the use of Atlas.ti software. The coding scheme which includes descriptions of codes and indicative examples is included in the Appendix. Notably, the same design action from the same node to an idea was not coded twice in the same session/LC meeting. Hence, frequencies were used to indicate the number of sessions in which this design action took place, and not to the numerical sum of the times that it was verbally expressed in total. Similarly, a matrix of the expressed ideas in each LC meeting was created by including the nodes who acted on them. Therefore, summative matrices were created both for the 'nodes activity' and the 'ideas activity'.

In parallel, STEM design was also visually represented by what we shall call *design visualisations*. Design visualisations are schematic representations which include the nodes, the ideas and the linking words that connect them. As occurs with concept maps, the aim of the design visualisations is to represent the structure and the connections of abstract notions, i.e. design ideas in our case. Specifically, each design visualisation included a) the expressed ideas, b) the nodes who interacted with these ideas and c) the evolution of the interactions between nodes and ideas in relation to time. An example of a part of a design visualisation is represented in **Figure 1**.

Similarly, the activity that took place asynchronously through the online forum was coded following the same process as described previously. The analysis of the forum posts was used to a) complement the analysis of the LC transcripts, and b) triangulate the findings from the LC transcripts.

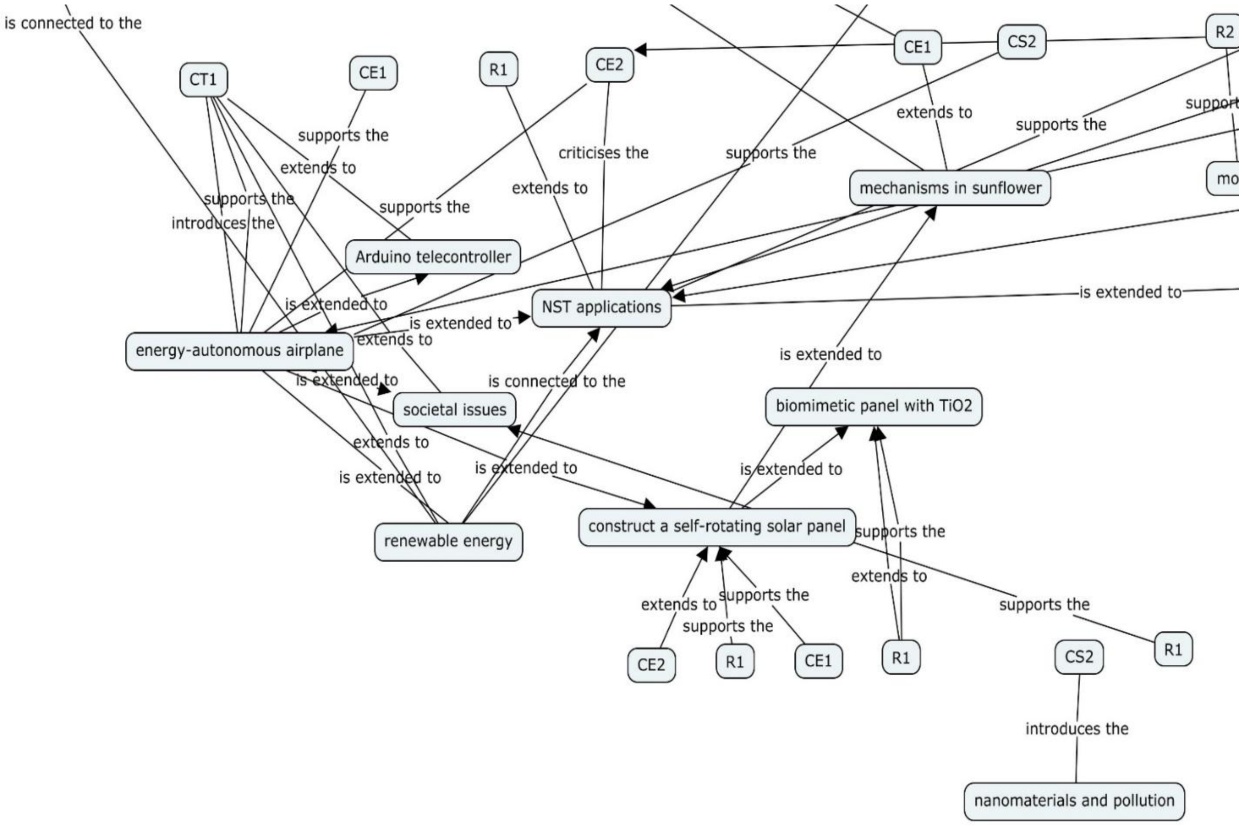
RQ1) The qualitative analysis of the designed STEM modules and the related STEM artefacts was carried out by reducing techniques. Specifically, brief descriptions of the modules & artefacts were developed based on the discussions and descriptions during the LC meetings. The media resources (photos & videos of artefacts), and the exhibition & sharing session (n.13 in Table 1) were used for triangulation, when needed.

RQ2) In order to answer RQ1 concerning the STEM modules and artefacts developed, the set of ideas with the maximum centrality was inspected. Particularly, the centrality of ideas was assumed by a) consideration of the number of LC meetings where these ideas were discussed, b) the engagement and/or support that they drew from the LC members, and c) the number of other concepts that this idea was linked to (extended to or connected with). A threshold of $n=4$ LC meetings where an idea was discussed was set in order to distinguish the ideas that could be considered central. Exceptions were considered in cases where that idea had $n \geq 5$ in some category (e.g.

supported by 5 members). Also, the ideas/themes communicated by teachers in asynchronous ways through the forum were noted. Additionally, the finalised artefacts were used to triangulate findings. Specifically, we examined what ideas were finally implemented in the constructed artefact. Therefore, key ideas' were deemed to be the ideas that were actually implemented in the finalised artefact. The analyses from all three data sources were used to increase concurrent trustworthiness (Cohen et al., 2009). Specifically, we examined the extent to which an idea was discussed in LC meetings and to how many of them, in forum post sessions (i.e. between two LC meetings) and in how many of them, and whether it was finally decided to be included in the artefact and in what manner, i.e. whether that was presented as a central feature in the artefact discussion and final presentation.

Figure 1

Design visualisation example



RQ3) In order to answer RQ3 regarding teachers' design roles, the summative frequencies from the analysis of the LC transcripts and the forum posts were used. Therefore, the LC members' activity was analysed by considering both the overall engagement of each member and the contribution to the development of the artefact.

Similarly with RQ2, the finalised artefact was used for triangulating the findings. The centrality of the nodes was defined by considering the nodes' activity and contribution in developing the artefact and the application of the ideas introduced. Since STEM design is a complex endeavour, and given the small number of members per group, we treated design centrality through a mixed-methods approach, rather than a purely quantitative or network analysis approach. Particularly, we qualitatively inferred the centrality of nodes through the summative frequencies of design actions, but also the overall contribution to central ideas and in developing the physical/digital artefact. We regard such a mixed approach as multidimensional and accurate enough to infer the nodes' design centrality. Moreover, an analysis of the reflection interviews regarding the STEM design process and the collaboration preferences was used from Nipyrakis, Stavrou, and Avraamidou (2024c) to triangulate the findings regarding the centrality of the nodes and to provide additional insights about each teacher's design roles.

Each LC group was analysed independently as an individual case. A comparative analysis of the four independent cases was subsequently carried out to investigate: a) transversal patterns related to design ideas/themes, and b) patterns related to teacher attributes (e.g. disciplinary background, teaching experience, STEM experience) that seemed to correlate with nodes' centrality. Hence, a cross-case synthesis technique (Yin, 2018) was used to analyse the multiple-case studies.

FINDINGS

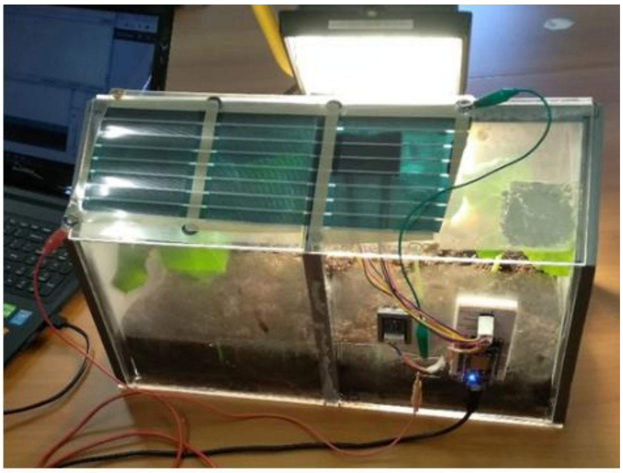
RQ1) The STEM modules

LC group A: the 'smart' greenhouse

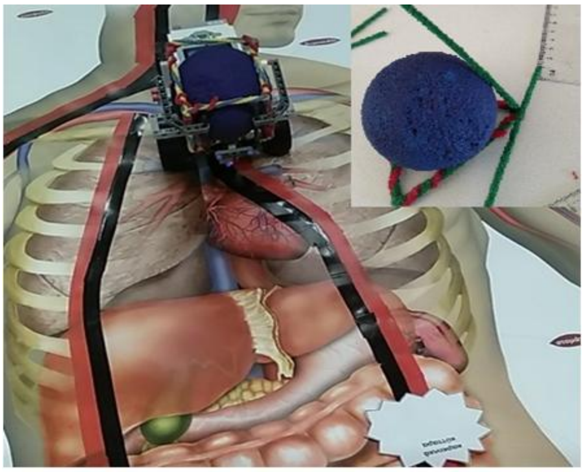
LC A decided to develop a module related to a 'smart' greenhouse, i.e. a greenhouse artefact in which sensors of temperature, humidity, and light were collecting data in and out of the greenhouse for comparison. As shown in **Figure 2** (Picture 1), the smart greenhouse was partly covered with transparent and flexible organic solar cells which are 3rd generation solar cells based on organic polymers. A teacher-manufactured sample of Dye-Sensitised Solar Cell (DSSC) and two samples of thermochromic glass i.e. glass that changes colour and hence its reflectance according to the external temperature, were also used for demonstration of how NST can contribute to energy saving and sustainability. Small plant nurseries (e.g. pepper, pumpkin, tomato, etc.) were used inside the greenhouse. The collected sensor and solar cell data were shared in real time through a platform that students could access online. Automation that could open the window according to a threshold on the data was added, while students could also remotely open the window.

Figure 2

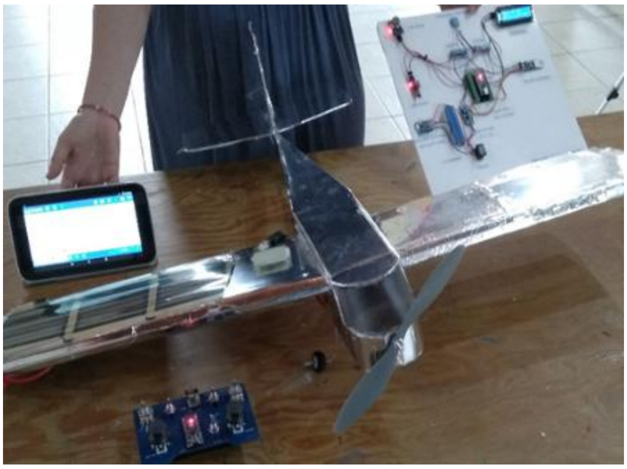
The developed STEM artefacts



Picture 1. The Smart Greenhouse



Picture 2. DNA origami and nanorobots for drug delivery



Picture 3. The Energy-Autonomous Aeroplane for Fire Risk Assessment

Picture 4. The flash-memory drive model based on spintronics

LC group B: DNA origami and nanorobots for drug delivery

This group, inspired by an article in the Nature journal about DNA origami, decided to develop a model representation of DNA origami that included pharmaceutical substances by using pipe cleaners and styrofoam. The students could use scissors as CRISPR-Cas 9 to cut 'DNA strands' and make the 3D geometrical shapes needed. Moreover, a robotic model used a light/colour sensor to circulate in an artery-like path on a human body map, stopped at specific body parts where students could stamp as having cancer cells, and released the DNA origami. The process modelled a drug delivery, and selective targeting cells process from nanorobots. **Figure 2** (Picture 2) provides a glimpse of the artefact.

LC group C: the energy-autonomous aeroplane for fire risk assessment

LC C designed and developed an aerodynamic model of an aeroplane by using an Arduino-based telecontrolling navigation system with a brushless motor and servomotors for drifting, while depron techniques were used to bend the wings and increase the lift force. The aeroplane model was using an organic solar panel and a DSSC sample to simulate a scenario of an aeroplane/drone that operates by using only solar energy, which teachers found in a news article. Moreover, the group contextualised its use for fire risk assessment by collecting data from several sensors (temperature, pressure, gas, fire, etc.). The sensor system was installed on an external board for better demonstration, as shown in **Figure 2** (Picture 3).

LC group D: the flash-memory drive based on Spintronics

Figure 2 (Picture 4) demonstrates the artefact of a STEM module on flash-memory drives which represents the translation of letters to binary code and vice versa. The model represented the use of electrons' spin in ferromagnets to store information in modern spintronics applications. Specifically, 4 octets of wooden balls were placed in the interior of the flash model. The balls were painted with two different colours, one on each side, representing 'up' and 'down' spin. A robotic vehicle 'read' the spin by using a colour sensor and displayed the information in binary mode. In parallel, an Arduino circuit represented the word that the user provided as input with a set of blinking LEDs according to the ASCII code. Additionally, a teacher-developed cell phone app used an App Inventor code to translate letters to binary code, contributing to representing the process with multiple representations.

RQ2) The central ideas/themes

Table 3 (see appendix) provides an overview of the central ideas/concepts discussed. **Table 3** presents the central ideas discussed in ≥ 4 LC meetings, or ideas discussed in 3 LC meetings but had $n \geq 5$ engaged nodes/ideas.

Transversal themes

A general inspection of the themes discussed in all 4 LCs can lead to identifying some common patterns in this multiple-case study. First, since teachers are engaged with the STEM design of physical artefacts, it should be expected that technicalities and practicals would be a common topic, especially at the stage of constructing the artefact, i.e. in follow-up LC meetings. Examples from the 4 case studies included discussions about geometry, such as shape (in n=4 LC groups) and dimensions (n=4) of the artefact. Furthermore, contextual factors about the availability of materials (n=3) and cost (n=2) were also taken into account. Using the artefact for data collection (n=4) and the creation and analysis of graphs (n=2) was also a common theme. Nevertheless, there were cases in which mathematics was involved in the artefact, even though no graphs were used; geometrical shapes (LC B) and number systems (LC D) were implemented instead.

Designing the artefact was an important topic and something that a part of teachers discussed in all 4 LCs. Specifically, discussions about using 3D-printed objects appeared to be a common theme in all groups, while in 2 groups, an idea stated was the construction of a 3D printer. It seems that 3D printing was something that has drawn the interest of teachers, even though few teachers stated that they had knowledge of using a 3D printer.

Robotics was also a common theme, a result that should be expected, since a common trivialisation is that STEM is relevant or even identical to robotics, as revealed in the excerpt below.

> AE1: 'The truth is, yes, that by starting the project maybe I took 'STEM' wrong by connecting it with educational robotics, as most of us let's say, and so Nanotechnology was an unpleasant surprise for me, the fact that we should, yes, to be honest' (LC meeting A2).

All teachers in the study who were engaged in robotics stated that they were more familiar with Arduino robotics and not Lego robotics. Specifically, Lego robotics was discussed in 2 groups, while Arduino was discussed in all groups. Preference for low-cost and open-source technologies was mentioned as reasons for preferring Arduino.

A quite common theme in all four groups was modelling, i.e. making a representation of a concept/phenomenon/application. In other words, a STEM artefact for teachers was contextualised as a didactical instrument, an object to be used for teaching; therefore perfection in constructing or operating it, as well as using authentic materials was marginalised. Hence, in many cases, a representation of a process (e.g. flying aeroplane model, translation of letters to bits) or just a small sample of a nanomaterial (e.g. thermochromic glass, DSSC) was deemed as an adequate starting point to teach about the phenomena. In addition, all 4 LCs discussed aspects of how to better demonstrate/exhibit the artefact, such as what size it should have, what different colours, what artistic interventions should be made to assist students to better understand the phenomenon, etc. Consequently, the teaching aspect of using the artefact was apparent in the discussions.

Finally, regarding NST, all groups engaged in discussing NST, either by explicitly talking about NST or by discussing some particular 'big ideas' of NST. However, in many cases, such as in LCs A and C, discussions concerning NST were subsequently marginalised when the technicalities and practical parts came into play.

RQ3) The central nodes

Switching the focus to the node level, i.e. the LC members, we can inspect in **Table 4** (see appendix) the total design activity of the LC members during the LC discussions and forum sessions.

LC group A

As we can infer from the nodes' design activity in Table 4 and the centrality of the introduced ideas in Table 3, AT1 and AS1 could be regarded as the most central members in this group, the expert excluded. Specifically, AT1 introduced the main alternative idea of the Arduino-based meteorological station, and he introduced using the datalogging system of the meteorological station for other non-meteorological purposes, a key idea which led AE2 to contextualise using the datalogger for monitoring a greenhouse, and R1 to an NST-enhanced 'smart' greenhouse. On the other hand, AS1 introduced and supported central ideas related to data collection, the physical magnitudes to measure, and the artefact's dimensions. However, AS1 did not use the forum to exert design activity. In total, AS1 and AT1 introduced 9 and 5 central ideas, respectively, while R1 introduced 8 central ideas.

Regarding the development of the STEM artefact, AT1 designed the 3D printed frame, developed and installed the Arduino electronics and the window automation. AT1 was also the one who set up the online platform for sharing data and tested the prototype. AE2 contributed to elaborating plastic parts for the greenhouse, an idea which was abandoned for technical and aesthetic reasons. AS1 constructed a DSSC sample with the assistance of R1. Finally, R1 cut and assembled the plexiglass, the solar panels and the thermochromic glass on the greenhouse, and also placed the plants inside the greenhouse model. Consequently, we may infer that AT1 was the most central member, while AS2 and AM1 were rather peripheral members. Teachers' reflections during the post-interviews confirm this result as AT1 was deemed an experienced and skilled member whose skillset matched the proposed goals of this project.

LC group B

The main idea in this STEM module was introduced and supported by BS4, while BS4 introduced 3 central ideas. R1 introduced 4 central ideas, including the use of Lego robotics and discussions concerning the map of the human body. However, BS4 had average activity in the LC meetings; his absence in 3 out of 7 group meetings has inevitably affected this result. BT1 was a member who introduced or extended several new ideas; however, these ideas did not attain applicability in the artefact, while some of them were criticised for their scientific validity and applicability. BE1, BS3 and BS1 were nodes that exerted average activity in the group.

Regarding the development of the artefact, BS4 initially contributed to developing and demonstrating a prototype of DNA origami based on his ideas on using models of pipe-cleaners and styrofoam, while BS1 also subsequently followed this practice. BE1 contributed to programming the robotic vehicle in collaboration with his students. BS3 performed research about the map of the human body. R1 assembled the socket in the robot, developed similar DNA origami models and tested the prototype. Consequently, we may infer that BS4 was the main contributor in the group, while BM1 was rather a peripheral member. Teachers' reflections during the post-interviews confirm the centrality of BS4 (n=2), due to his knowledge, engagement and relevance to the topic. However, most teachers (n=3) preferred to collaborate with BE1 because of his STEM experience and technological expertise.

LC group C

The main idea of the energy-autonomous aeroplane and the telecontrolling system was introduced by CT1, while CT1 also introduced alternative ideas that also gained attention. However, centrality in this group was also shared with CE2, who was also a very active member. Those two nodes were also very active in both synchronous and asynchronous ways. Other members were also engaging as well. Despite the low participation of CM1, she was the one who introduced 3 central concepts. Particularly, she was the one who contextualised the artefact for environmental purposes and for fire risk assessment, an idea which gained immediate acceptance. Similarly to BS4, CM1's absence in 4 LC meetings affected these low frequencies. Other central ideas were also introduced by CE2 (n=12), R1 (n=11), CT1 (n=9), and CE1 (n=1).

As concerns the development of the artefact, CE1 was the one who designed and developed the physical artefact of the aeroplane model, and also initially tested the installation of the electronics in the plane, with the guidance of CE2. CE2 developed the external board for data collection and revised the prototype with the electronics. CE2 also designed and printed the telecontrollers and provided guidance to CT1 in developing an additional telecontroller. CT1 developed a telecontroller and tested it in class. R1 provided a ready DSSC sample, and a sharkskin surface, which was not implemented in the final artefact. Therefore, we could infer that CE2 and CT1 could be regarded as central LC members. Reflections during the interviews confirm the central role of CE2 (n=3) due to his knowledge, engagement, STEM experience and collaborative stance, while 2 teachers highlighted the role of CE1 due to her niche expertise in designing and constructing models.

LC group D

In LC D, the main idea of the artefact was introduced by DS1, who also introduced 9 central ideas. However, major contributions also came from DM2, who was rather the most active member of the forum, despite the small number of central ideas she introduced (n=1). DE1 also actively engaged, especially in issues regarding the development of the artefact, despite the number of his introduced central ideas being limited (n=2). R1 introduced several central ideas in this group (n=16), while 1 central idea was introduced by DT1 and DS2.

Concerning the development of the artefact, DM2 initiated in developing a preliminary artefact with magnets and a GeoGebra animation representing the binary coding in different spin orientations of the ferromagnets. She also developed several versions of prototypes such as prototypes with KNEX sticks and pulleys, balls of Styrofoam, pattern paper and wood, and magnets. In all cases, she demonstrated them using the forum and asked the LC group to reflect on them. Concerning the robotic vehicle, DE1 was the one who developed and programmed the robot, while R1 revised and tested it. DT1 developed the Arduino circuit setting which was using a system of phonetic transcription and a representation of the bits with blinking LEDs. DT2 developed the AppInventor translation app for smartphones. DM1 elaborated on the physical prototype of the flash memory box, which was subsequently revised by R1. Consequently, many LC members contributed to STEM artefact development. Summarising, without having a centralised pattern in this group, we could infer that DM2, DS1 and DE1 shared centrality in this group, while DS2 and DM1 were more in the periphery. Post-interview reflections confirm the central roles of DE1 (n=2) for his STEM knowledge and collaborative stance, DS1 (n=2) for contributing to the main idea and content knowledge and for being collaborative, and DM2 (n=1) for her engagement and artefact contribution. Moreover, DT1 was also preferred (n=2) because of her knowledge and contribution to Arduino.

Transversal patterns

A general overview of nodes' activity reveals that in a non-negligible number of teachers, there was quite a decline in activity both during the LC meetings and the forum sessions. Although the moderator of the discussion was posing questions to all LC members in turns, some members (typically 1 or 2 per group) participated peripherally in the process. Contrastingly, some members were substantially more motivated and engaging. Investigating the above results in relation to teaching experience, as depicted in Table 1, we cannot identify a pattern between these two. The lack of integrated STEM training in teacher preparation programmes of previous decades, as the teachers reported, might have impacted this finding. On the other side, we could infer that, apart from the case of BS4, most central members did have adequate or little experience in STEM, a result which is in accordance with the analysis of their interviews (Nipyrakis et al., 2024c). However, the existence of central members without having prior STEM experience, such as BS4, reveals that there are other factors, such as background knowledge, design thinking and intrinsic motivation that might have impacted design centrality.

Regarding their forum activity, we can infer that, generally, the asynchronous way of communication was not used to a great extent by the teachers. Concerning centrality in the forum activity, we can see that the central nodes in the groups often were the central nodes in the forum sessions as well, increasing the trustworthiness of the results. However, exceptions did occur with some members who were quite active during the LC meetings but did not participate at all in the forum sessions, such as AS1 and DE1.

As regards patterns related to gender, the findings of this study revealed that gender did not affect design centrality, since it appeared common, especially in groups C and D, that central members were females. We could hypothesise that the implementation of a collaborative LC approach and embracing a participatory approach and a dialogical environment would balance gender inequalities, an argument which needs to be examined.

Disciplines & STEM design

Implementing a disciplinary lens of analysing nodes' activity, we claim, based on the analysis of the present study, that centrality in STEM design was not disciplinary-dependent. Specifically, we can see that central LC members had a background in science (BS3, DS1), technology (AT1, CT1), engineering (CE2, DE1), as well as mathematics (DM2). Therefore, results from this case study support that STEM design centrality cannot be restricted in relation to teachers' disciplinary backgrounds.

Despite the centrality of a mathematics peer, there seemed to be a pattern that most mathematicians often exerted low activity or were the least active members, e.g. AM1, BM1, CM1 and DM1.

> DM2: 'As a mathematician, I feel like the weakest link, in terms of not knowing the scientific phenomena, coding, all these. I know the mathematical knowledge that everybody knows (laughs). So I wonder how important is the role of the mathematician in STEM teaching? Is it needed? Or inversely, if the mathematician attempts to teach STEM, does s/he need more knowledge and training? That is a question that I am problematised with during the whole programme' (LC D, 8th meeting).

However, some central ideas adopted by LC C did come from CM1, whereas DM2 was actually a core member in LC D. Interestingly, though, DM2 still did not identify herself or her discipline as something important for STEM design. Subsequent reflections from her LC peers disagreed with this view and showed support to her. Besides, mathematics was meaningfully integrated in LC D concerning number systems, translating and storing data in drives, as well as in LC B concerning geometrical shapes and structures of DNA origamis; hence they were not restricted to data analysis of graphs which is a commonplace in STEM (Ring-Whalen et al., 2018). Nevertheless, there seem to be deeper and cultural barriers against promoting STEM identity to mathematics teachers, even regarding the ones who were meaningfully contributing to the design. Overall, the peripheral activity of most mathematicians should be interpreted with caution due to the counterexample of DM2 and the meaningful integration of mathematics in some modules.

Some patterns can also be identified concerning teachers having a natural sciences background and a design sciences background. Specifically, NST-related ideas were mostly supported by natural sciences teachers, such as AS1, BS3, CS1, CS2, DS1, and DM2, while some design teachers were more sceptical towards NST, such as AE1, AE2, and CE2. However, exceptions also took place with individuals such as CT1 who highly supported NST applications and extended the discussion about NST concerning innovative entrepreneurship. Contrastingly, in discussions related to technicalities such as the use of electronics, hardware settings, coding, etc., it was the design teachers who were more engaged.

A disciplinary pattern was also apparent in the construction process. LC groups tended to distribute some parts of the construction to LC members, because of time restrictions but also due to Covid restrictions that hindered group meetings. Although the moderator generally provided space for teachers to decide and undertake parts themselves, teachers tended to undertake parts related to their expertise. Hence, the robotic and electronics parts were developed by design teachers, the aeroplane model was designed and developed by the architect teacher and the 3D printing parts were designed by the technology teacher. On the contrary, the experimental construction of a DSSC and models about electrons and DNA were developed by natural sciences teachers. Again, exceptions of 'boundary crossing' did occur, since DM2 developed a KNEX mechanism for representing electrons' spin as well as a GeoGebra digital animation, etc. Also, DM1 undertook the development of the physical flash memory box because, as she said, she liked the artistic part.

The role of experts

Regarding the role of the researchers in STEM education, we can see in Tables 2 and 4 that R1 was one of the most active members, often the most active one. Apart from moderating the discussion, the researchers' role was to support the reflection and the expressed ideas, but also to introduce ideas in multiple domains. Some common patterns about their role concern a) the support in didactical methodologies, for example in discussions about modelling a process in the artefact as occurred in 3 LCs, b) supporting the adoption of the educational innovation of NST, i.e. through explicit reference to NST applications, introducing and supporting the use of NST-related solar cells and thermochromic glass, etc., especially in cases in which teachers were sceptical or even reluctant about implementing NST, such as in group A, and c) introducing and supporting the use of robotics, as occurred in group B and D in order to support the integration of technological tools. Also, key interventions of the researchers included criticism against alternative ideas that were considered not scientifically supported enough in the literature (Group B), lacked innovation (Group A) and moved far in terms of representing the phenomenon (Group D).

Moreover, knowledge and resources from external experts, e.g. researchers in NST were also valued as critical in sharing knowledge and applicability of the phenomena in all LCs, as well as sharing resources (e.g. organic solar panel samples). Therefore, assistance from academic personnel could be characterised as multifaceted and critical.

DISCUSSION

This multiple-case study aimed to investigate the STEM design process of STEM modules and artefacts from 4 independent LC groups of in-service teachers coming from diverse S-T-E-M disciplinary backgrounds. Given the importance of designing and developing STEM artefacts for students' STEM learning (NRC, 2014), it becomes valuable to examine the STEM modules and the design process that teachers go through to provide enhanced STEM learning environments to students. Findings revealed some common patterns of themes that teachers focused on. One common theme discussed was modelling phenomena through the artefact. That theme could relate to the fact that NST was set as a topic and modelling is an effective practice in the microworld (Geelan, 2012). On the other hand, we consider that modelling represents a broader theme when designing STEM artefacts, since the main artefact goal is to represent core content ideas and processes −contrasting the goals of artefacts of another use, e.g. commercial ones.

Other common themes relate to dimensions and technicalities of the physical artefact, especially in latter LC meetings. These were not just procedural or marginal themes, since they actually affected or even restricted the whole artefact design, as occurred in all 4 LCs of this study; hence, they should be taken into consideration from earlier design phases.

Using robotics was also a common theme in all groups, something that should be expected since realisations of STEM often include misleadingly being restricted to robotics or makerspaces (McComas & Burgin, 2020). 3D printing also attracted teachers' attention as a tool that would facilitate manufacturing custom objects and models. Furthermore, using sensors was quite discussed in all groups, especially to 2 groups which used sensors for datalogging, making graphs and analysis.

Regarding NST, 2 groups integrated NST concepts more integrally, while 2 groups adopted NST applications such as NST solar panels in a less central role. However, we consider it useful to promote a contemporary topic such as NST in STEM design since a) it can drive the discussion away from purely technical topics and connect science content-related goals, b) it persuades teachers to move to innovative design of artefacts, moving away from trivial and ordinary artefacts, c) it allows teachers to develop new teaching approaches, away from topics that have been crystallised due to their extended teaching experience.

On the other side, focusing the analysis at the teacher level, we can see that divergencies took place regarding teachers' engagement and activity both during the design and the development of the STEM module and artefact, which aligns with divergencies found in their lesson planning practices (Nipyrakis et al., 2024b; Grimalt-Álvaro et al., 2024). First, regarding the disciplinary background of the teachers, some divergence was found among teachers with a 'natural' sciences background and a 'design' sciences background. The former tended to introduce and contribute more to discussions about NST phenomena and applications, real-world contextualisation of the idea/problem and modelling phenomena, while the latter contributed more to discussions about the setting and use of electronics, robotics, and designing the prototype. This result was also reflected in the artefact development phase, in which most teachers tended to undertake parts of the artefact that were closer to their disciplinary expertise and knowledge. However, some exceptions did take place, since some teachers did practice boundary crossing into quite different disciplines. Nevertheless, we can conclude that disciplinary background and stereotypes played a role in teachers' STEM design practices, corroborating their influence on designing STEM lesson plans found in Nipyrakis et al. (2024b).

Second, concerning the LC members that exerted substantial STEM design and development activity and engagement in the LCs, i.e. what we defined as STEM design centrality, it was found that prior STEM experience was a good predictor of design centrality, in accordance with Nipyrakis et al. (2024c). On the contrary, teachers' disciplinary background was not found as a restriction to design centrality, since central LC members coming from all S-T-E-M backgrounds arose in the present study. Therefore, the findings of this study support that disciplinary roots cannot predict or restrict whether an LC member would be a central STEM designer and developer or not.

Third, some disciplinary patterns did appear in analysing the overview of teachers' design activity nevertheless. Specifically, a pattern found in our previous analysis of teachers' post-reflections revealed that teachers tended to highvalue collaboration with the technological expert (Nipyrakis et al., 2024c), even in LC groups where this member was not substantially the most central one. It seems from teachers' reflections that teachers perceive it as quite important to collaborate with a technological expert, which confirms the difficulties that technology poses for non-experts (Nipyrakis & Stavrou, 2022; Waight & Abd-El-Khalick, 2012). Furthermore, this study reveals that even among technology teachers, it was found difficult to adopt a technological tool that they were not familiar with (e.g. moving from Arduino to Lego robotics) or that costs more. Many barriers in terms of knowledge, skills, and attitudes arise, which confirm the need for expertise as well as the role of culture and values in integrating technology (Waight & Abd-El-Khalick, 2012).

A second disciplinary pattern relates to the finding that most mathematics teachers of the study tended to have rather low design activity in the LCs, which, to some extent, supports the marginalised role of mathematics in STEM (English, 2016). Interestingly, even the minority of mathematics teachers who, as counter-examples, did provide some central contributions in their LC groups, still underestimated their role in STEM design, even though mathematics were actually involved in the STEM modules. This paradox highlights the difficulties of mathematics teachers in cultivating STEM identities (Pulsawad et al, 2024).

Finally, the findings highlight the facilitating role of collaboration among teachers and academics, as recommended in the literature (Kim, 2019). Particularly, science education researchers assisted STEM design in the LCs, both in terms of introducing, supporting or criticising ideas, but also in promoting the adoption of educational innovations, such as the cutting-edge topic of NST.

Limitations of this study include the fact that the vast majority of LC meetings took place in distance mode, not only because of Covid restrictions but also because of teachers' limited availability. We assume that the distance modality of the LC meetings could well have affected the form of LC discussions and the artefact development phase, which needs further investigation. For example, we could hypothesise that discussions in online meetings were mostly dominated by the facilitator or fewer members than in in-person meetings. Furthermore, some LC members were absent in some meetings (13% average absence) which affected the frequencies matrix of their design activity.

Implications of the study relate to informing the literature on in-service teacher STEM design practices in the context of NST through the presentation of four case studies in parallel. Findings also speak to the feasibility of introducing NST in STEM classroom practice. Such an approach has the potential to highlight integrative STEM approaches while bridging knowledge and skills from the existing curricula.

Moreover, the study aims to provide guidelines for developing STEM PD programmes. Specifically, common patterns found at the disciplinary level can lead to more personalised PD programmes about design practices based on teachers' needs, or the provision of special discipline-based workshops. Finally, the present study advocates the facilitating role of collaboration among teachers of diverse expertise in STEM design. Under a collaborative LC approach, design groups of teachers and researchers can benefit from the specific traits and affordances that each agent brings due to their disciplinary background, while empowering teachers from marginalised domains in STEM, such as mathematicians, to highlight their role and develop stronger identities in STEM.

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Ethical statement

The present study met the ethics/human subject requirements of our institution at the time the data were collected.

Competing Interests

No potential conflict of interest was reported by the authors.

Author Contributions

All authors contributed to the study conception and design. The first author collected, organised and transcribed the textual/audio/video data of the study. All authors participated in data analysis and in writing and reviewing the manuscript.

AI disclosure

The authors did not use generative Artificial Intelligence (AI) tools to generate, collect or analyse the data of the study or to prepare the manuscript.

Data availability

The data that support the findings of this study are available from the corresponding author [A.N.], upon reasonable request. The paper has been published in the PhD thesis repository of the University of Groningen according to the regulations of the University of Groningen (article 4.7.4, https://www.rug.nl/about-ug/organization/rules-and-regulations/onderzoek/promotiereglement-18-en.pdf).

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APPENDIX

Table 3

Indicative Central Ideas Discussed in the LC Meetings

Number	LC meetings	introduced by*	supported by*	extended by*	extended to**	criticised by*	debated by*	agreed by*	connected by*	connected to**
LC group A										
humidity	5	R2	3						1	1
temperature	5	AS1	4						2	2
constructing an artefact	4	AS1	4	3	3				1	1
using NST	4	AT1	4	2	2	3			6	7
datalogger	4	AT1	4	3	3				2	5
data collection	4	AS1	4	5	7				1	1
cost of materials	4	AS1	4			1			2	2
smart greenhouse	4	R1	5	5	10	1			5	10
availability of materials	3	AE1	5	2	2				2	4
Arduino-based meteo station	3	AT1	7	5	10	5	2		2	4
dimensions	3	AS1	5	3	5				2	2
thermochromic glass	3	R1	3	3	10				2	3
LC group B										
DNA structures/folds that include drugs	5	BS4	6	3	12	3	5	1	3	3
lego robotics	4	R1	1	3	10	1	1	1	1	1
use of colour sensor, follow line	4	R1	2	1	3					
map of the human body	3	R1	4	3	9				1	1

LC group C										
model	7	R1	3						2	5
external board for data collection	6	CE2	4	2	10			1	1	5
data collection	5	CT1	6	4	5	2			1	1
energy-autonomous airplane	5	CT1	7	5	30	1			3	5
data collection on the plane	5	CE2	4	1	1	1	2	1	2	2
graphs and statistical analysis of data	5	CM1	4	1	1				1	2
making the airplane fly	5	R1	3	2	2	6	5	1		
comparing solar panels	4	R1	3	1	1				1	1
arduino tele-controller	4	CT1	4	3	13				2	3
construct an airplane model	4	CE1	4	3	6	1			1	1
use for environmental purposes	4	CM1	2						2	3
fire sensor	4	CT1	4	1	3	2				
NST applications	4	R1	2	1	1	2	1		3	4
flex/organic solar cells	4	CT1	4	3	3				3	7
produced output voltage	4	R1	5	1	1	2			2	5
use of electronics	4	CE2	4	4	11	3	1	1	2	2
use for fire risk assessment	4	CM1	4	1	1				3	4
DSSC	4	CE1	2			2	1	1		
thermometer sensor	3	R1	5						1	1
3D printing	3	CE2	5	3	4	4			1	1
plane dimensions	3	CE2	6	2	2	2	1	1	2	3
Aristotle university lab sources	3	CT1	2	2	5	1				
LC group D										
flash memory drive spintronics	6	DS1	8	4	30	1			3	6
electrons representation	5	DS1	2	3	5				1	1
representation with magnets	5	R1	4	3	6	3			3	5
number of letters	5	DS1	6						1	1
robot which scans the digits	5	R1	3	2	5	2				
translation of letters to bits	5	DS1	3	3	3				2	2
tunnelling effect	5	DS1	5	2	2	1			2	5
translator app	5	R1	5	4	9				2	2
use of robotics	5	R1	3	3	6	2			1	2
using robotic arm	4	DS1	3	3	5	2			1	1
time needed	4	R1	2						4	6
electrons' spin	4	R1	2			3			1	1
dimensions	4	R1	2	1	3				3	4
translation of bits to letters	4	R1	3			2				
LEDs on and off representing bits	4	DT1	3	2	4	1			2	2

Note: *Numbers represent the number of different LC members.
**Numbers represent links to other ideas/concepts
R1 and R2 represent the science education researchers.

Table 4

Nodes' design activity

ID	LC meetings activity (synchronous)							Forum activity (asynchronous)						
	Introduces	Supports	Extends	Criticises	Debates with	Agrees with	Connects	Introduces	Supports	Extends	Criticises	Debates with	Agrees with	Connects
LC group A														
AS1	3	61	36	7	8	1	6	0	0	0	0	0	0	0
AS2	0	3	0	0	0	0	0	0	0	0	0	0	0	0
AT1	2	53	28	10	2	0	13	1	2	2	0	0	0	3
AE1	1	12	14	4	1	0	7	0	2	3	0	0	0	0
AE2	3	35	12	8	1	1	4	0	3	5	3	0	0	6
AM1	2	5	7	2	0	0	2	0	0	0	0	0	0	0
R1	2	97	54	14	7	1	17	0	3	2	1	0	0	0
R2	1	12	4	1	0	0	1	0	0	0	0	0	0	0
LC group B														
BS1	3	20	12	4	1	0	1	0	0	0	0	0	0	0
BS2	3	1	2	2	1	3	0	0	0	0	0	0	0	0
BS3	2	18	18	5	1	0	0	1	1	0	0	0	0	0
BS4	1	12	11	2	3	0	5	3	3	1	1	0	0	0
BT1	8	7	21	2	2	0	12	0	0	0	0	0	0	0
BE1	1	18	9	6	1	2	0	0	0	0	0	0	0	0
BM1	0	6	2	2	0	0	0	0	0	0	0	0	0	0
R1	5	65	63	24	6	0	4	2	0	1	0	0	0	0
R2	1	1	0	0	1	0	0	0	0	0	0	0	0	0
LC group C														
CS1	3	27	9	11	3	1	0	0	0	0	0	0	0	0
CS2	1	37	2	8	9	2	3	0	0	0	0	0	0	0
CT1	3	73	38	18	9	1	14	10	10	23	1	0	0	1
CE1	3	38	26	6	6	1	4	4	17	8	5	0	0	0
CE2	12	116	66	50	10	5	16	3	26	1	4	1	0	0
CM1	0	6	8	0	0	0	2	0	0	0	0	0	0	0
R1	2	112	36	34	10	4	19	1	12	1	3	0	0	0
R2	1	7	0	0	5	0	3	0	0	0	0	0	0	0
LC group D														
DS1	5	44	20	13	0	0	5	0	12	3	3	0	0	2
DS2	0	6	1	5	0	0	0	0	1	0	2	0	0	0
DT1	5	15	14	3	0	0	6	0	0	0	0	0	0	0
DT2	0	13	6	4	0	0	1	0	2	2	0	0	0	0
DE1	0	46	21	13	1	0	3	0	0	0	0	0	0	0
DM1	0	7	1	1	0	0	1	0	1	1	0	0	0	0
DM2	3	36	20	12	0	0	10	7	24	24	2	0	0	3
R1	7	104	49	18	1	0	11	1	9	9	2	0	0	1
R2	0	2	6	0	0	0	0	0	0	0	0	0	0	0