International Journal of Science and Mathematics Education
https://doi.org/10.1007/s10763-024-10457-3

How Do Secondary-School Teachers Design STEM Teaching–Learning Sequences? A Mixed Methods Study for Identifying Design Profiles

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Received: 16 January 2023 / Accepted: 14 February 2024

Abstract

Due to the increasing presence of the Science, Technology, Engineering, and Mathematics (STEM) education paradigm in Spain, many teachers have embarked on the design of specific Teaching–Learning Sequences (TLS) to be implemented in schools. Understanding the views and perceptions about STEM that take shape in specific teachers' designs should enrich the way in which STEM education is designed based on a more focused approach. This study aims to characterise how secondary school teachers from Catalonia (Spain) design STEM TLS, to identify specific design profiles that can be related to different understandings of STEM education based on a mixed-method analytical approach. We collected 345 canvases from teachers participating in a national STEM education training programme, outlining STEM TLS. The canvases were analysed with an assessment rubric consisting of 8 instructional components (Interdisciplinarity, STEM practices, Information and Communications Technology tools, Formalisation, Openness, Alignment, Authenticity and Values). We identified patterns in teachers' designs while implementing a hierarchical cluster analysis of the results, obtaining 6 different clusters of 39, 36, 66, 49, 90, and 65 TLS, respectively. The diverse components prioritised or balanced in each cluster suggest how STEM education can be conceived of differently by participating teachers through the lens of component analysis. While authenticity appears to be a major force in the clustering process, direct relationships between components can be found (i.e., between Formalisation and Alignment), as well as inverse relationships (i.e., between Openness and Practices). These findings provide important clues to understand STEM TLS design and recognise the rubric and the cluster definition as powerful tools for teacher training and evaluation in STEM education.

Keywords Cluster analysis · STEM · Mixed methods · Secondary school teachers

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Introduction

In recent decades, in the educational community, there has been widespread adoption of a STEM paradigm (acronym for Science, Technology, Engineering, and Mathematics). Within this context, institutional programmes, research projects, and private initiatives have developed and implemented an extensive array of alleged STEM educational activities, projects, and research in formal and non-formal contexts (Li et al., 2020; Martín-Páez et al., 2019). Hence, a quick search on STEM education will demonstrate the wide variety of educational proposals that cohabit under the STEM umbrella. For example, some STEM activities focus on the use of elements of robotics (Thibaut et al., 2018), others focus on laboratory practices (Daher & Shahbari, 2020), or even tackle global challenges such as climate action (Zeidler, 2016), as constitutive (and sometimes incompatible) elements. Hence, while STEM can refer to a collection of separate disciplines, for others, STEM activities can refer to lessons where all disciplines are all integrated into one cohesive whole. Moreover, the purposes or aims of these STEM educational activities are also diverse, because while many of these proposals seek to promote students' STEM literacy, various others mainly seek to foster STEM career paths among a wider number of students (Bybee, 2010).

When teachers design STEM activities, they need to not only address this conceptual ambiguity but also address curricular demands, issues related to facilitation and assessment, especially in secondary education, where the need to address educational standards is significant (Wang et al., 2020). All of these aspects, together with their own personal beliefs about education, teachers' disciplinary knowledge, and the broader organisational and institutional contexts of secondary-school teachers' professional work, creates highly complex educational contexts that teachers have to manage (Fang & Fan, 2023). Therefore, when teachers need to design concrete STEM classroom activities, they need to take all those aspects into account. The result of this can be studied through educational artifacts such as Teaching–Learning Sequences (TLS). Hence, although STEM education can be diversely defined at a theoretical level, the study of how STEM activities can actually take shape in secondary school classrooms from the study of TLSs can enrich the understanding of how secondary-school teachers handle these complex educational environments, helping shape responses to those complexities, and better understand their contributions to STEM education and to the learning of disciplinary knowledge in the areas involved, as Berisha and Vula (2023) also describe in their study.

In response to these questions, some authors have tried to characterise STEM TLS through the analysis of the instructional components of different STEM TLSs implemented in classrooms. However, previous studies usually focused on the extensive characterisation of one instructional component, such as the type of relationship between disciplines (Ring-Whalen et al., 2018) or the instructional approach used (Thibaut et al., 2018), on two components such as in the case of Bergsten and Frejd (2019) and Daher and Shahbari (2020), or in the characterisation of several components at a qualitative level in a few teachers' productions, as is the case in Berisha and Vula (2023). These studies provide interesting analyses, but only a partial picture of how STEM education can be shaped differently through TLSs due to teachers' negotiations between educational components. Therefore, this analysis could be enriched by considering other key components of STEM TLSs and a bigger sample, leading to a more comprehensive understanding of teachers' views on STEM education.

This study uses a mixed-methods approach to understand how secondary-school teachers conceive the horizon of STEM classroom education by analysing their TLSs designs. The study contributes to the field by identifying what teachers most value in STEM education based on the analysis of the level of development of the eight components in the overall sample, developing methodological artifacts that allow an extensive analysis of the TLSs, and finding "major forces" acting as possible predetermined design paths based on the analysis of the different profiles of STEM TLS found.

Instructional Components of STEM TLSs

According to Méheut and Psillos (2004), when designing a TLS, four elements must be considered: knowledge, teacher, students, and the material world, as well as the main relationships among them. Particularly, the relationship between knowledge and the material world represents the epistemic dimension, whereas the relationship between teacher and students represents the pedagogical dimension (Méheut & Psillos, 2004). Regarding the epistemic dimension, we can find assumptions about STEM practices, processes of elaboration, and validation of STEM knowledge (Méheut & Psillos, 2004). Within the pedagogical dimension, these same authors describe choices about a teacher's role, types of interactions between teacher and students, as well as the outcome of the activity (Walker et al., 2018). Drawing from this approach, for this study we have synthesised several relevant elements influencing STEM TLSs designs in secondary school into eight components, prioritising those related to the construction of STEM-related knowledge and the use of educational instruments or artifacts for this specific type of knowledge construction. This selection was also undertaken based on an extensive literature review while considering the impact of these elements on our educational and research context to produce a final manageable number of components. For this reason, we have excluded other possible elements that are less specific to STEM knowledge construction, such as the social organisation of the group/s of students, evaluation and feedback strategies, and strategies for promoting inclusion.

The components considered for this study, represented in Fig. 1, are: (1) STEM interdisciplinarity, which refers to the extent of the incorporation of different aspects of STEM domain-specific knowledge; (2) STEM practices, which refer to the concrete STEM practices that are included within the TLS; (3) STEM ICT tools, which refer to the role of digital technology; (4) Alignment, which refers to the connection between students' activity and learning goals; (5) Formalisation, which refers to the formalisation of STEM knowledge by using the different semiotic registers; (6) Openness, which refers to students' agency in terms of creating products and

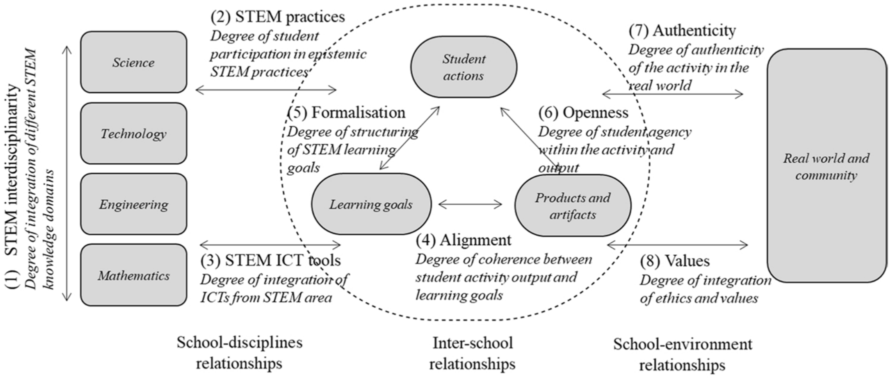

Fig. 1 Diagram of the eight instructional components of STEM Teaching–Learning Sequences

artifacts; (7) Authenticity, which refers to the authenticity of the activity; and (8) Values, which refers to the incorporation of social and ecological values. Although each STEM TLS can be characterised by all these eight instructional components, the way in which each component is introduced into each TLS can vary from one TLS to another. Hence, a deeper analysis of each component is required to define this range within components and, in turn, better characterise the diversity of how teachers can conceive the horizon of STEM classroom education based on the analysis of their TLS.

STEM Interdisciplinarity

The degree of interdisciplinarity or integration of STEM domain-specific knowledge or disciplines (biology, physics, etc.) is one instructional component which has attracted attention in the literature. Some authors argue that STEM is not a "real" or "single" construct with a unique nature (Akerson et al., 2018), but rather a socially constructed label to focus on a particular STEM knowledge domain while making connections with other STEM-specific domains. Other authors have proposed an overarching view where STEM education is seen as an approach that highlights the convergence of STEM fields in addressing problems that demand science, technology, engineering, and mathematics (STEM), rather than viewing each field separately (Fang & Fan, 2023; Pleasants, 2020). Although the interdisciplinary approach seems to be most prominent in the literature, the nature of the inter-relationship between domains in interdisciplinary work represents a significant challenge for teachers (Berisha & Vula, 2023; Margot & Kettler, 2019).

STEM Practices

STEM TLSs might engage students in epistemic practices that univocally characterise how each STEM domain produces knowledge (Ortiz-Revilla et al., 2020).

Hence, scientific practices are aimed at producing knowledge through a combination of observations, experimental evidence, and argumentation (Lederman et al., 2002), which are defined in the Framework for K-12 Science Education (National Research Council, 2012): asking scientific questions; developing and using models; planning and carrying out investigations; analysing and interpreting data; using mathematics and computational thinking; constructing scientific explanations; engaging in argument based on evidence; obtaining, evaluating, and communicating information.

The objective of knowledge in terms of engineering is human-made artifacts (i.e., technological tools), their study in functional terms, and their construction (Couso & Simarro, 2020). For this reason, we understand technology as the product of engineering practices, in line with Simarro and Couso (2021). Based on the NRC definition of engineering practices, Simarro and Couso (2021) describe nine engineering practices: defining and delimiting engineering problems; developing and using prototypes and simulations; planning and carrying out tests; analysing and interpreting data to identify points for improvement; using mathematics and computational thinking, scientific models and available technologies; identifying and/or developing multiple solutions and selecting the optimal one; materialising the solution; engaging in argument based on evidence; obtaining, evaluating, and communicating information.

Mathematical practices are actions or expressions that are produced during the solution of a problematic situation in mathematics (Font et al., 2010), in which different mathematical objects (material or immaterial entities, such as representations) intervene (de Gamboa et al., 2021). These practices have been described in the (NGACBP, 2010) framework: making sense of problems and persevering in solving them; reasoning both abstractly and quantitatively; constructing viable arguments and critiquing the reasoning of others; modelling using mathematics; using appropriate tools strategically; focusing on precision; looking for and making use of structure; and looking for and expressing regularity through repeated reasoning. We see the relationships between the knowledge produced in STEM domains as a "seamless web" between interdisciplinary STEM TLSs, where the different practices in STEM domains focus on the "larger" purpose of cognitively and socially relevant problem-solving, in line with Ortiz-Revilla et al. (2020).

STEM ICT Tools

STEM TLSs usually include the use of certain technological tools, such as robotics, sensors, virtual labs, simulations, etc. (Bozzo et al., 2015; Martín-Páez et al., 2019). These ICT might support the development of STEM practices, including aspects such as the degree of interactivity with the tool, the communication formats used, and the role they play in cognitive processes (data collection — from data sources or from phenomena — such as prototyping, modelling, etc.). Regarding the adoption of ICT, some critical voices have tried to raise awareness about the financial pressures behind the introduction of (digital) technology in schools (McComas & Burgin, 2020), while others argue for its promotion as a necessary element of twenty-first-century skills (Ananiadou & Claro, 2008; Schleicher, 2012).

Alignment

STEM TLSs usually present students with a petition (challenging problem, intriguing question, or multi-sided issue) which is materialised into specific products or artifacts (exhibitions, prototypes, portfolios, etc.) (Mergendoller, 2018). This petition acts as a didactic strategy to achieve the learning goals. Although the products/artifacts should be associated with the specific learning goals of the TLS, sometimes there can be a potential mismatch between them, especially when the product/artifact of the TLS requires only a very superficial level of knowledge. The existence of this potential mismatch between the learning goals and the products/artifacts (students' activity) leads us to define the instructional component Alignment (Domènech-Casal, 2018b).

Formalisation

The learning goals associated with STEM TLSs (especially when they are focused on a target model) can be introduced and represented with different degrees of formality, that is different levels of communication modes that can include abstract scientific modes of communication or not (e.g. graphic representations or incorporating domain-specific lexical elements or codes, such as chemical formulation, vectors, or formulas) (Buty et al., 2004). Generally, in TLSs, students start by using more simple communication modes, and are invited to use progressively more sophisticated and abstract communication modes as the TLS moves forward (Anggraeni & Suratno, 2021). In TLSs, this formality is usually mediated by knowledge-structuring events that can take on a wide range of forms (e.g. summarising, diagrams, conceptual maps…) (Singer & Moscovici, 2008). Sometimes, these events challenge teachers because they might feel they do not have enough information or expertise about domain-specific STEM knowledge, or they feel they do not have enough time to develop it (Diana et al., 2021).

Openness

Students' agency, seen as the "intention and capability to take action regarding one's learning in educational activities, in order to change the trajectory of theirs and their peers' learning" (Clarke et al., 2016, p. 29) can be promoted in STEM TLS if students understand what is going on, and are given some significant role in helping to design and bring about the desired activity outcomes (Claxton, 2007). Therefore, in order to foster the exercise of that agency, when designing TLSs, teachers need to create tasks which allow students' familiarity with and competent use of STEM practices (Engeness, 2020), for example, in students' engagement in the definition of the products/artifacts, the investigation (or inquiry) (Thibaut et al., 2018), and/or the learning assessment (Engeness, 2020). Promoting students' agency involves sharing power (Cook-Sather, 2020), which ultimately reflects the degree of openness of a TLSs. Similarly, as with other instructional components, the degree of openness also poses a challenge related to the complexity of the activity in which students are involved and the time consumed in the classroom (Riga et al., 2017).

Authenticity

The degree of authenticity can be understood as how the context, the students' roles, or what students do are realistic or connected to "real life", for example using real-world problems or questions, or having an actual impact on or application in the real world (Tytler et al., 2021). This authenticity might start from TLSs focusing on non-context specific problems where the activity is conceptualised as purely abstract academic work that only makes sense within the classroom. At the other end, some TLSs can be conceptualised as an arena for developing connections to real, concrete, and complex world problems to provide relevance and student engagement (Pleasants, 2020). However, some topics related to particular STEM specific-domain knowledge, such as mathematics, can be highly abstract and teachers might not find the appropriate contextual example or application of that topic in real life (Diana et al., 2021), thus failing to offer authentic learning experiences (Maiorca & Mohr-Schroeder, 2020).

Values

The incorporation of ethics and values into STEM education is based on the understanding that many personal and collective decisions or innovations are not made using STEM knowledge alone, but rather rely on social and cultural contexts (Pleasants, 2020). Hence, when considering that STEM TLSs should promote STEM literacy, the discussion of ethics and values should play an important role in STEM education (Zeidler, 2016). There is a large tradition in STEM-related domains regarding the introduction of these aspects, such as the Socio-Scientific Issues Framework (Zeidler, 2016), and it has also received attention in the latest PISA frameworks (Organization for Economic Co-operation and Development [OECD], 2023). Although there is no consensus about which specific values should be promoted within STEM education, different authors argue for the development of values related to students' personal health, energy efficiency, environmental quality, resource use, and national security (Bybee, 2010), sustainability (Maass et al., 2019), or related to gender inclusion and social justice (Ortiz-Revilla et al., 2020).

Research Objectives

When designing a TLS, teachers must make decisions about which learning goals are planned for, which activities should be included, and how students' actions should be related to STEM disciplines and to the real world, etc. Through these decisions, the eight instructional components always operate implicitly or explicitly. Analysing TLS design through these eight components can be helpful to understand the horizon of STEM classroom education that teachers "imagine" as a result of all these factors (Maiorca & Mohr-Schroeder, 2020) and, particularly, better understand what teachers most value about STEM education. This negotiation was reflected in the wide variety of STEM TLS proposals made by secondary-school teachers participating in a training programme. The training programme became an opportunity to understand and discuss teachers' ideas about STEM education, and potential barriers and opportunities related to STEM educational teaching practices. In this context, this aim behind this article is to answer the following two research questions:

1. What is the level of development of the eight instructional components in STEM TLSs by secondary-school teachers?
2. Which different profiles can be identified in the STEM TLS analysis, based on the level of development of the eight instructional components?

Answering these questions can enhance our understanding of practical knowledge in STEM education, rather than relying solely on theoretical statements and also expand it, since having eight components presents a more inclusive viewpoint in this context. Moreover, by identifying three "major forces" in the design of STEM TLSs, we can infer the presence of specific design paths leading to the final product.

Methods

This research follows a mixed methods approach and, particularly, an exploratory sequential design as described in Dawadi et al. (2021). Hence, our study begins with a qualitative exploration and analysis of the data collected, followed by a quantitative stage to test findings with the aim of providing more generalisable results.

Context, Data Collection, and Participants

This research was performed in the framework of a collaboration between the Universitat Autònoma de Barcelona (UAB) and the Departament d'Educació de Catalunya. STEM education experts from the UAB participated in the design of the training activities within the STEAMCat[1] teacher training programme. As part of their training, teachers were asked to outline a STEM TLS proposal by filling in a canvas (see "Instruments and Materials" subsection). This training programme was implemented in different editions over three academic years (2017–2021) (Table 1), involving secondary-school in-service teachers from different STEM domains (Mathematics, Science and Technology), and pre-service teacher training activities. All participant teachers had no previous experience in STEM education, which was the reason they enrolled for this training programme.

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[1] STEAMCat is an institutional programme set up by the regional government of Catalonia (Spain) devoted to enhancing STEM education, and it included different initiatives such as support for schools and training courses for teachers.

Table 1 Data collection settings. Trainees from D, E and F editions were pre-service teachers. Trainees from A, B, and C editions were in-service teachers with 3 to 25 years of teaching experience, but with no previous experience in STEM education

Training (sub-sample)	Date	Number of participants, gender, and profile	Background and teaching area	Number of TLSs collected*
A	May 2017	52 female, 30 male in-service teachers	Science, Engineering, Mathematics	87
B	May 2019	43 female, 9 male in-service teachers	Science	49
C	May 2019	60 female, 35 male in-service teachers	Science, Engineering, Mathematics	68
D	June 2019	38 female, 20 male pre-service teachers	Science	90
E	June 2020	18 female, 14 male pre-service teachers	Science	20
F	May 2021	14 female, 17 male pre-service teachers	Science	31

*A few other TLSs were discarded as they were incomplete, the handwriting was unintelligible, or they had very low-quality writing

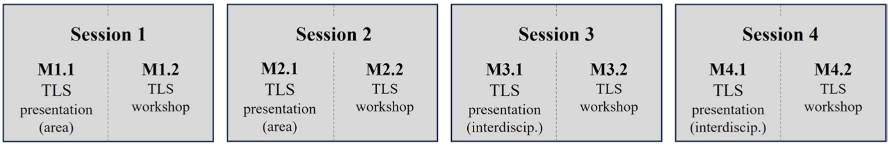


Fig. 2 Diagram of the training process, where the number of sessions and the distribution of modules is detailed

The training programme aimed to familiarise teachers with the STEM education paradigm and its application to secondary school classrooms. That is, the goal of the training was not to promote one valid approach to STEM education, nor a single ideal STEM TLS profile. On the contrary, the objective of the training programme was to provide teachers with tools to analyse the diversity that can be found under the umbrella of STEM education and develop a critical view of its educational implications in the classroom.

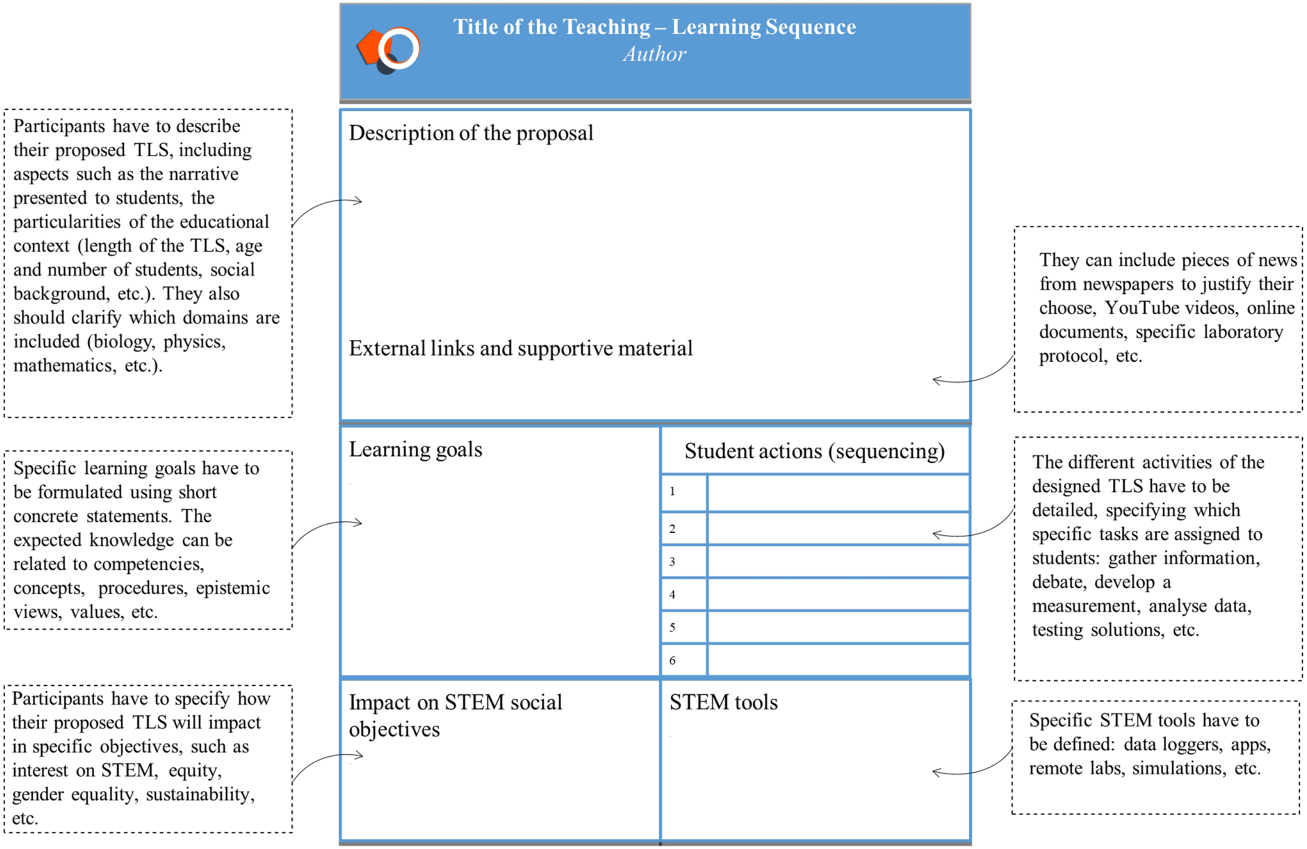
The training was divided into four sessions, and each session divided into two modules: TLS presentations and TLS workshops (Fig. 2). In the first module (M1.1, M2.1, M3.1, and M4.1), different experts in the field presented 4 STEM TLS that had been already applied in the classroom with their results. Participants were encouraged to discuss and analyse these different STEM TLSs through the lens of the eight instructional components. The first two sessions (M1.1 and M2.1) focused on area TLS (Mathematics, Science or Technology), while the third and the fourth ones (M3.1, M4.1) focused on interdisciplinary TLS. Throughout session 1 to session 3, in the second module (M1.2, M2.2, and M3.2), participants were asked to outline (individually, in pairs, or in small groups) one STEM TLS detailing the learning goals, teaching sequence, tools, and scaffolds, as if they were to implement this TLS in their classrooms. To this end, an ad hoc designed canvas was introduced based on the instructional components (Fig. 3). In the last session and module (M4.2), participants were asked to present their designs and discuss them with their classmates.

We gathered a total of 345 TLSs outlined in the canvases which were used as data in this research. TLS were named according to the training event in which they were outlined, that is: #A1, #A2…, #A87, #B1…, #F31.

Instruments and Materials

We created the STEM TLS rubric (Table 2) to analyse the collected STEM TLS. This rubric includes eight rows corresponding to each of the eight components mentioned above, and four columns representing a scale with four levels of development (null, weak, moderate, high), being the optimal compromise between providing enough detail of the development of the components and ensuring a good reliability in the scoring, in accordance with Wolf and Stevens (2007).

The creation process of the rubric included four different steps: (1) Conceptualisation: The first version of the STEM TLS rubric was created in 2017 and tested with 5 physics and chemistry TLSs designed and implemented in school year



Participants have to describe their proposed TLS, including aspects such as the narrative presented to students, the particularities of the educational context (length of the TLS, age and number of students, social background, etc.). They also should clarify which domains are included (biology, physics, mathematics, etc.).

They can include pieces of news from newspapers to justify their choose, YouTube videos, online documents, specific laboratory protocol, etc.

Specific learning goals have to be formulated using short concrete statements. The expected knowledge can be related to competencies, concepts, procedures, epistemic views, values, etc.

The different activities of the designed TLS have to be detailed, specifying which specific tasks are assigned to students: gather information, debate, develop a measurement, analyse data, testing solutions, etc.

Participants have to specify how their proposed TLS will impact in specific objectives, such as interest on STEM, equity, gender equality, sustainability, etc.

Specific STEM tools have to be defined: data loggers, apps, remote labs, simulations, etc.

Fig. 3 Summarised template of the canvas used by (pre- / in-service) teachers to design their STEM TLS (see expanded version at https://bit.ly/3vGE55i)

Table 2 STEM TLS rubric. Definition of the levels of development of the instructional components

	Null	Weak	Moderate	High
(1) STEM Interdisciplinarity Degree of integration of different STEM knowledge domains	One STEM domain	Two STEM domains	Three STEM domains	More than three domains
(2) STEM Practices Degree of student participation in epistemic STEM practices	Students are just involved in reproducing information	Students are involved in low complexity STEM practices (observe, measure, test…)	Students participate in explicitly formulated high-complexity STEM practices (inquiry, conjecture, prototyping…)	Students perform entire epistemic practices, including the community components (argumentation, consensus…)
(3) STEM ICT tools Degree of integration of ICTs	Students undertake the entire activity without using any ICT	Students use ICTs to search for and synthesise information in non-interactive formats	Students use ICTs to visualise and observe phenomena in formats, allowing them to change perspectives (i.e., zooms, plotting)	Students use ICTs to interact with, programme or construct representations or digital artifacts
(4) Alignment Degree of coherence between student activity output and learning goals	Learning goals are not necessary at all to reach the activity output	Learning goals are slightly necessary to reach the activity output	Learning goals are necessary (but not sufficient) to reach the activity output	Learning goals are fully identified with the activity output
(5) Formalisation Degree of structuring of STEM learning goals	STEM knowledge associated with the learning goals (especially when they are target models) is not represented anywhere in the activity. It can be constructed, but it is not made explicit	STEM knowledge associated with the learning goals may explicitly appear somewhere during the activity, but in isolation, and playing a minor role	STEM knowledge associated with the learning goals is considerably formalised at some point in the activity (e.g. equations, laws, definitions…), but without an exhaustive and explicit manner	STEM knowledge associated with the learning goals is made completely explicit and highlighted by means of structured external representations (e.g. diagrams, conceptual maps, taxonomies…)
(6) Openness Degree of student agency within the activity and output	Students follow a set of closed tasks regulated by the teacher's instruction	Students are self-regulated following a sequence of tasks proposed by the teacher	Students take some decisions in a general frame set by the teacher	Students choose major goals and strategies to reach the output

Table 2 (continued)

	Null	Weak	Moderate	High
(7) Authenticity Degree of authenticity of the activity in the real world	Students' roles only make sense within the classroom	Students' roles have few connections with the real world (stories, voices, scenarios…)	Students' roles make sense in the real world, but they are fictional	Students' roles are real; they have an impact on the real world
(8) Values Degree of integration of ethics and values	Learning goals and activities do not mention values implicitly or explicitly	Learning goals and activities include lemmas or prompts without promoting explicit reflection on values	Learning goals and activities explicitly demand judgment and reflection on values	Learning goals and activities explicitly demand reflection on values and their relationship with general critic frames

Note. An extended version of this table with examples can be found as Electronic Supplemental Material, ESM

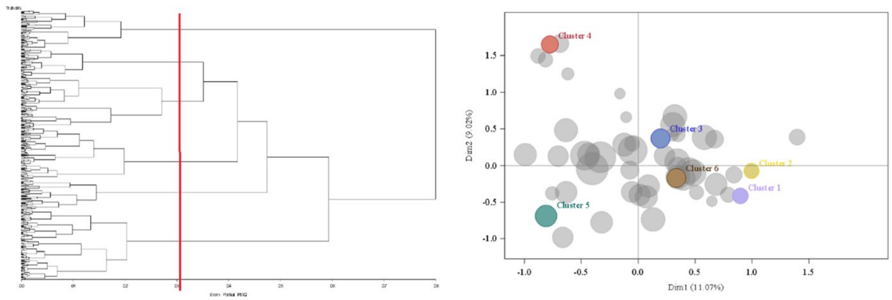
2017–2018. Preliminary results were presented at a national conference (Domènech-Casal, 2018a); (2) Piloting: The tool was refined by including three more TLS (one focused on geology, other on mathematics, and other on biology), and published their results in Domènech-Casal (2018b). (3) Expert assessment: in 2019, two experts from Biology and Mathematics Education (both with over 25 years of experience as secondary-school teachers) assessed the rubric by analysing sub-sample A (Table 1). The resulting version of the rubric was published in Domènech-Casal et al. (2019); (4) Refinement: In 2020, authors 1, 2 and 3 joined Domènech-Casal in a process of revision and refinement of the rubric by incorporating additional theoretical underpinning and new data (B-F sub-samples). This refinement led to the inclusion of two new components (STEM ICT tools and Values), and minor adjustments regarding the definition of the levels of development of the previous six components. Through this process, the validity of the rubric (particularly its construct validity) was ensured, following the guidelines provided by Jonsson and Svingby (2007) to build scoring rubrics.

Analysis Procedure

Due to the descriptive nature of this study, the novelty of STEM education for the participants, and the limitations of the sample, all collected STEM TLS were treated as a single sample without considering the impact of personal variables such as teachers' background, gender or teaching experience (pre-service and in-service) on the final products. We are aware of the possible effects of those personal variables but, as is explained in the "Limitations and Implications" section, looking for potential design differences according to those variables would lead to a risk of incurring spurious relationships: for example, pre-service teachers have the same background, while in-service teachers have more diverse backgrounds. Despite these limitations, the analysis of the overall picture can be a valuable and innovative contribution to understanding teachers' design processes in STEM education.

Phase 1: Qualitative Analysis of TLSs

A first qualitative analytical approach through directed content analysis was undertaken to obtain a detailed characterisation of each TLS submitted by participant teachers, in accordance with Hsieh and Shannon (2005). Each TLS was independently analysed as a unit by the three researchers involved in writing this article using the rubric provided in Table 2. To ensure the reliability of the process, each researcher coded a subsample (Table 1) and contrasted their own analysis with the participants' self-analysis, who had also been asked to self-evaluate their own TLS with the rubric and justify their evaluation, similarly to Berisha and Vula (2023). After the same subsample was coded, the three researchers contrasted their coding in a group discussion to identify the divergences. The aim of this discussion was to identify possible misinterpretations of the meaning of the codes and reach a consensus. Hence, after the discussion, a single negotiated code was agreed upon. This procedure was repeated for each subsample.



Note. Left: Dendrogram used for the selection of the optimal number of clusters (6). Right: Representation of the distribution of TLSs and the 6 clusters according to two dimensions defined for a simplified representation of the variables in the analysis.

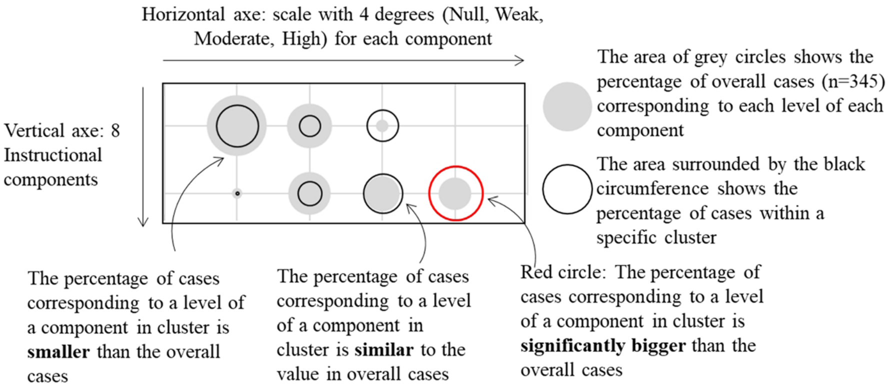
Fig. 4 Two representations are used for Cluster definition

The negotiated interpretation of the TLS lessened the individual coding bias and guaranteed the appropriate reliability of the procedure. Hence, due to the qualitative nature of this part of this stage of the research, and in accordance with Golafshani (2003), reliability was conceptualised as trustworthiness, rigour and quality. For this reason, researchers did not set an inter-coder reliability index threshold, but sought to reach unanimity in all coding results using a triangulation method. As a result of the qualitative analysis, we obtained a database composed of 345 columns (one per TLS) and 8 rows (one per instructional component), into which the 2760 cells were coded at 4 levels.

Phase 2: Cluster Analysis of TLSs (Quantitative Analysis)

We determined the most frequent levels for each component in the database through a descriptive statistical analysis. Afterwards, a hierarchical cluster analysis was performed to identify the most relevant TLS profiles, according to Everitt et al. (2011). A multiple correspondence analysis was performed to group together all the features of the TLSs based on their similarity and to obtain a simplified representation of them in a smaller number of dimensions (Greenacre, 2017). The differences between the groups or clusters formed in each grouping step and the subsequent one until all cases were merged hierarchically were calculated using Ward's method. The optimal number of clusters was selected using a dendrogram and homogeneity criteria, such as Pseudo T-square, and Cubic Clustering Criteria among others were used, to increase reliability, thus obtaining a total of six clusters (Fig. 4). During this process, personal variables such as gender (male, female, and mixed groups) and teaching status (pre-service and in-service groups) were not included, as justified at the beginning of the analysis subsection.

The main traits of each cluster were assessed by comparing the distribution of the values of each component (variable) in each cluster with all the levels of all TLSs as a group, considering a hypergeometric distribution of each value, according to



Note. Gray circles represent the percentage of overall TLSs corresponding to each level for each instructional component. Black circumferences show the percentage of TLSs for each cluster.

Fig. 5 Representation of the quantitative data for cluster characterisation

Lebart et al. (2006). This final step aimed to find which component displayed significantly high or low values in each cluster. The analysis was carried out using SAS v9.4 software, and the significance level was fixed at 0.0001. The results of the main features of each identified cluster are represented in a bi-dimensional graph formed by grey circles with black circumferences (Fig. 5) to better identify the differences between each cluster and the overall sample.

Results

The representation of the six clusters and their main features can be found in Fig. 6.

Cluster 1 (N = 39) Real-World Engineering and Environmental TLSs

This cluster is characterised by TLSs with a strong development of Authenticity, usually leading to an impact in the real world. The use of ICTs to transform or create ideas and a moderate development of Values are also of relevance. TLSs from this cluster tend to develop topics related to engineering, bioengineering, and environmental issues.

TLS #F17 is an example of this cluster: students are asked to select the appropriate plants for landscaping the entourage of a new road to be sent to the town council (See annex 2 in the Supplementary Information). To this end, students consider taxonomic, aesthetic, climatic, and ecological constraints together with surveys and interviews to report inhabitants' requirements in relation to the topic. Throughout

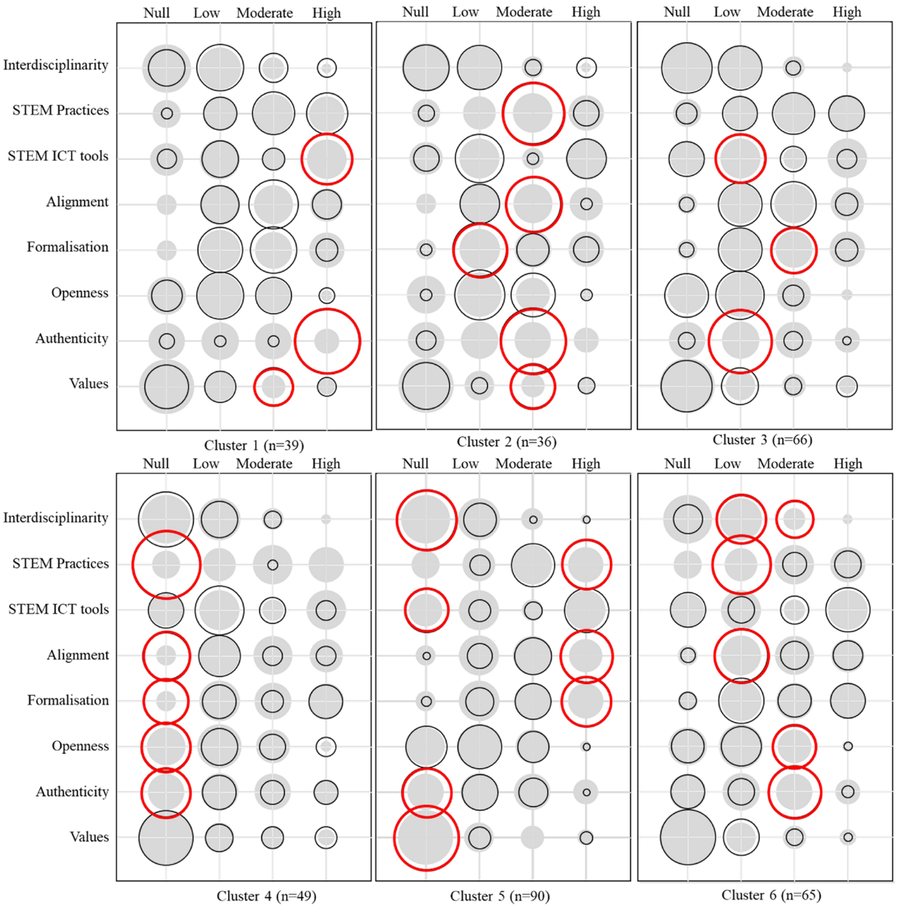


Fig. 6 Representation of the level of development of the eight instructional components for the six clusters of STEM TLSs identified

the activity, debates, the search for information, and the collection of samples established strong connections with the real world (Authenticity).

Cluster 2 (N = 36) Realistic School Scenarios for Research and Engineering

TLSs grouped in this cluster tend to emulate scholarly versions of real-world conflicts to promote learning, with moderate levels of Authenticity and Alignment. These TLSs are also defined by a moderate level of the Practices of STEM domains (research, design…) and Values. In contrast, the cluster is determined by a significantly low level of Formalisation of STEM contents, compared to the overall mean among the TLSs. TLSs from this cluster usually deal with topics related to technology, inquiry, and the environment.

As an example, TLS #D12 begins with a simulated demand for students to construct a solar collector able to furnish all the energy needed to heat water for a house (specific temperature and water flow petition). The fictional scenario locates the demand in a low-industrial development region, resulting in a limitation of the materials required for the construction that must be recycled (See annex 3 in the Supplementary Information). Different activities of the TLS are suggested (design and drawing, calculations, construction, testing, and assessment), but Formalisation events (i.e., conceptual maps, summaries, glossaries…) are not set.

Cluster 3 (N = 66) Low Context Formal Disciplinary School Proposals

TLSs from this cluster tend to problematise learning with low levels of Authenticity. A moderate Formalisation is also characteristic of this cluster, although ICT Tools are used mainly to search for information (low level). TLSs focus on a few STEM domains, with a preference for inquiry and health topics.

TLS #B1 proposes a gamified activity (escape room) where students have a limited amount of time to solve decontextualised enigmas on a periodic table, chemical formulation, and a history of science (See annex 4 in the Supplementary Information). Students receive questions in a particular order and have to use concepts or processes learnt previously, hints and clues to solve them.

Cluster 4 (N = 49). Just Search-and-Reproduce Information TLSs

TLSs in this cluster usually require students to reproduce or represent mainly scientific information (e.g. oriented towards science popularisation), but without developing any ideas, practices, or context related to STEM in any depth. TLSs from this cluster tend to be closed and not consider students' decisions, and do not develop Practices from STEM domains. As a result, this cluster is characterised by null levels of Practices, Alignment, Formalisation, Openness and Authenticity.

In TLS #C3, students are asked to produce a leaflet and a poster to raise awareness about the environmental impact of plastic (See annex 5 in the Supplementary Information). To this end, students only watch videos and read generic information about the topic, but they do not connect it to scientific ideas such as biogeochemical ecologic cycles of the plastics, the concept of ecosystem, or develop sampling or data-based research.

Cluster 5 (N = 90). Disciplinary-Based Minds-on Challenges

This cluster includes TLSs that tend to develop high levels of problematisation and STEM approaches (Practices, Alignment, and Formalisation). Null levels of Interdisciplinarity, ICTs, Authenticity and Values are characteristic of this cluster. Hence, inquiry, modelling, and engineering approaches are frequent in this cluster.

In TLS #A21, students face the challenge of measuring the exact height of a tower using mathematical strategies (See annex 6 in the Supplementary Information). Along with the different activities, students are taught explicitly geometrical concepts to undertake the challenge and several application problems are solved, leading to the construction of a clinometer.

Cluster 6 (N = 65). Open Interdisciplinary Contexts with Low-Level Demands

These TLSs tend to develop low-level skills or concepts from several STEM domains to fulfil a demand that is usually technological or digital and is open-ended. Moderate levels of Interdisciplinarity, Openness and Authenticity are characteristic of this cluster, together with low levels of Alignment and Practices. TLSs grouped in this cluster do not have any specific outstanding topics, but instead a high diversity of topics is found.

In TLS #D31, students use recycled materials to build a musical instrument chosen by them (See annex 7 in the Supplementary Information). Students' need to apply knowledge from several domains (physics, engineering, music, and arts) but concepts and domain practices play a minor role in the Alignment (i.e., students develop their ideas about sound waves during the TLS, but they do not use them to build the product). Several events of Formalisation (e.g. debates, assessment rubrics) conduct the sequence, that mainly focus on the products rather than on the learning goals.

Discussion

Development of Eight Instructional Components in STEM TLSs

Observing the overall sample of outlined TLSs through the lenses of the rubric, we can see that the diversity of the levels of the instructional components was broad, making it evident that many combinations would fit in with what STEM TLS would mean for teachers. Acknowledging the many factors that can influence teachers' designs (e.g. the need to address curricular objectives or issues related to facilitation and assessment, as Wang et al. (2020) describe in their study, we interpreted these results as teachers having significantly diverse and rich conceptions about STEM education. This myriad of teachers' views contributes to expand previous findings in the literature, as previous studies have addressed this issue through the lenses of a few components or a small sample offering a detailed but partial picture.

We observed a combination of components that were exceptionally underrepresented in the general sample (below 10% of the sample). These infrequent TLSs display high levels of Interdisciplinarity, Values and Openness, but null levels of Formalisation and Alignment. We interpreted our findings by understanding that teachers might struggle when integrating two or more STEM subjects with at least two dominant subjects when designing TLSs, according to Berisha and Vula (2023) and Dare et al. (2018), and how this integrated nature of STEM education is usually perceived as a challenge by high school teachers (Margot & Kettler, 2019). Open-ended TLSs can also be challenging for both students and teachers, who might feel confused because of the complexity of inquiry (Riga et al., 2017), and face difficulties in finding genuinely open-ended problems suitable for investigation in school classrooms or in providing adequate support (Akuma & Callaghan, 2019).

Conversely, two novel conclusions can be drawn. First, although different authors argue for the development of values (Bybee, 2010), our analysis show that this is not a fundamental element in teachers' TLS and, subsequently, in their views about STEM education. This mismatch between theoretical and practical instructional models of STEM made evident a need to address how (and which) values are operationalised within TLS designs as a way to help students become STEM literate citizens who can deal with the challenges of future society (Zeidler, 2016). Second, we interpreted the near absence of TLS with null levels of Formalisation and Alignment as evidence for the existence of a certain consensus among teachers. Participants might consider that a good TLS should be coherent between the products/artifacts and the specific learning goals, as Berisha and Vula (2023) also describe in their research, as well as that an important part of these learning goals might entail the mastering of semiotic registers.

Profiles of STEM TLSs

Looking into the clusters to identify patterns, we observed that some clusters reached the maximum level for some components, but that none of them reached the maximum level for many components simultaneously. For example, TLSs in clusters 1 and 5 pushed their design to the maximum level in ICT tools and Authenticity for cluster 1 and Practices, Alignment and Formalisation for cluster 5. TLSs in clusters 2 and 6 did not stand out for certain specific components but rather showed a balance between component levels, avoiding the lowest levels for several components. Hence, we observed that in some cases, the high development of very few components implied the underdevelopment of the others (Polarised design), and that sometimes intermediate levels of the majority of components were developed rather than stressing just a few (Balanced design). This might suggest that when teachers design STEM activities, they adopt either a polarised design, or a balanced design in the development of the instructional components to strengthen the added value of their TLSs as a negotiating strategy between their beliefs and/or other external influences or tensions.

Among these two designing strategies, we identified three aspects that seem to act as "major forces" in the clustering process. The first "major force" would be Authenticity. Particularly, we found that the distribution of other components seemed to be according to a particular level of Authenticity. For example, when comparing clusters 2, 3 and 5 (Fig. 6), the higher the Authenticity is, the lower the Formalisation, and vice versa. When comparing clusters 1 and 6, the higher the Authenticity is, the lower is the Interdisciplinarity, and vice versa. Authenticity, as the connection with the real world, has been seen in the literature as an asset of STEM education, as it has the potential to engage students in deeper understanding of a given topic, see

STEM connections, or as a context to foster engineering design (Dare et al., 2021; Wang et al., 2020). Clusters 1, 2 and 6 would also confirm teachers' value of this component. However, we argue that authenticity could be also acting as a limiting factor in STEM TLS design. Although authentic problems may encourage students to focus on solutions that work pragmatically, more authentic contexts would be perceived as more complex and demanding for students, following Lehrer and Schauble (2021), and drawing from our results, teachers would balance the development of other also perceived complex components in TLS that would be carried in a reasonable amount of time, such as formalisation and/or interdisciplinarity.

We observed a positive interrelation between Formalisation and Alignment that could also be acting as a second "major force": Higher levels of Formalisation were associated with higher levels of Alignment (e.g. clusters 2, 4 and 5). Hence, devoting time to formalise the knowledge and practices developed can contribute to better support the products/artifacts that students create with the specific learning goals of the TLS. An optimal adjustment between the final products and the learning goals cannot occur without students' explicit practice of the different levels of communication modes (e.g. visual representations or domain-specific lexical elements or codes) (Buty et al., 2004), as these communication modes are an intrinsic part of the knowledge involved in the STEM areas, in line with Tang and Williams (2019). Therefore, reflecting about how communication modes can be gradually stretched into forms that are increasingly formal can help teachers to design more coherent STEM TLS with the demand, as well as increase the potential to raise students' epistemological knowledge about the different practices within STEM education.

Finally, a third identified association, especially manifested in cluster 6, is that increasing levels of Openness could be related to decreasing levels of Practices and Alignment. Research has shown that teachers struggle to promote students' agency when giving them significant roles in the design and achievement of the desired activity outcomes (Daher & Shahbari, 2020). Our research not only supports these previous findings, but found that teachers might find it difficult to promote STEM practices coherently with the development of the final products if students are given the capacity to influence in the development of the sequence and/or the final products. This may seem reasonable, because the teacher might need to deal with the variability of proposed solutions, strategies, or proposals, which may deviate from the development of initially targeted particular practices (Lehrer & Schauble, 2021).

Limitations and Implications

There are two major limitations to our study. Firstly, our data does not come from a real school scenario, but from a training programme, and therefore, the analysis focused on which TLS teachers would ideally implement from the canvases collected. Despite being able to bring to the surface teachers' conceptions about STEM education, we assume the existence of the influence of logistical, material, and other factors (e.g. time, resources, and organisation and coordination with other teachers) affecting the actual implementation of each STEM TLS in real school scenarios. In other words, the clusters show patterns about what teachers would like to do, not patterns about what they actually do in class.

Secondly, our study does not provide evidence about the relationships between the distribution of components within the clusters and personal variables, such as gender, teaching status (pre-service and in-service groups), background and teaching area, and other personal variables that have been not measured such as their beliefs and identities, or their different interpretations of the curriculum. Furthermore, although teachers provided the self-evaluations of their TLSs, it would have been worthwhile to include teachers' voices through personal interviews, focus groups, or questionnaires. We are aware of this limitation, but our research was mainly descriptive, not explanatory. For this reason, we aimed to identify profiles of TLSs considering a single sample of TLSs, including a combination of different personal variables. Since we wanted to identify the relationship of personal variables with TLSs profiles, we would have needed a different sampling method (e.g. stratification, randomisation…). For example, running different analyses for pre-service and in-service teachers separately, while looking for potential design differences would be at risk of incurring spurious relationships, as pre-service teachers only have a science background, while some in-service teachers also have a mathematics and engineering background. A similar situation occurs with gender distribution, since the existence of mixed design groups within the training programme, made the interpretation of the impact of this variable on the results particularly difficult.

These two main limitations open up two paths for continuing to develop our research by studying how these personal variables influence the design of STEM TLSs, in line with Daher and Shahbari (2020), and how early outlines for TLSs are modified when teachers implement them in their classrooms based on the teachers' different experiences. Furthermore, and beyond these limitations, we consider that our analysis approach (the STEM TLS rubric and profile identification) can be a powerful tool for teacher training and evaluation. These tools can provide support in an initial or final diagnosis as a way of identifying participants' difficulties and good examples of TLSs in current practices. Moreover, the rubric can be used as a self-reflection tool to promote metacognitive skills in teaching practices, helping teachers to comprehensively reflect on their own views about STEM education. Finally, the definition of STEM TLSs profiles can also open up a way of designing higher quality teacher training, targeting the particular needs of the different design profiles.

Conclusions

A study of how secondary-school teachers outline STEM TLSs in order to understand how teachers operationalise STEM education and potential barriers and opportunities related to STEM educational teaching was carried out. Specifically, we analysed 345 STEM TLSs following a mixed-methods approach to assess the level of development of eight different instructional components and identify STEM TLS profiles.

From our study, we can conclude that a wide variety of horizons of STEM classroom education, in accordance with Maiorca & Mohr-Schroeder (2020) underlie the materialisation of teachers' STEM proposals. This variety is not distributed homogeneously, but rather seems to respond to implicit tensions that lead to different similarities and allow the proposals to be grouped into a few well-determined profiles. In addition, we have observed that the development of certain instructional components enters into conflict with the development of other components, leaving the ideal STEM proposal, in which all the components would achieve their maximum development, stranded at a theoretical level. Hence, our research demonstrates how secondary-school teachers prioritise particular components and decide whether they need to be stressed or balanced in their design, thus suggesting that STEM education can be differently operationalised by participant teachers through the analysis of diversity among TLSs.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10763-024-10457-3.

Acknowledgements The authors are deeply grateful for the contributions and teachings of Dr Jordi Domènech-Casal, who unfortunately passed away in 2023 while working on this study. Unfortunately, our colleague will not read this final published work, but we would like to homage his contribution to the field in this publication.

Funding Open Access Funding provided by Universitat Autonoma de Barcelona. This research has been funded by the Ministerio de Ciencia e Innovación (PID2022-138166NB-C22b) and carried out within the SGR ACELEC research group (2021SGR00647).

Data Availability Additional data and materials supporting findings can be accessed at Zenodo through the following link: https://zenodo.org/uploads/5815218.g

Declarations

Competing Interests The authors have no competing interests to declare that are relevant to the content of this article.

Ethics approval and consent to participate This study was conducted under the recommendations of BERA's *Ethical Guidelines for Educational Research, and the Code of Good Practices in Research of the Universitat Autònoma de Barcelona. All participants gave voluntary informed consent* under the Declaration of Helsinki.

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