CHAPTER 7

7. GENERAL DISCUSSION, REFLECTIONS, AND RECOMMENDATIONS
General Discussion, Reflections, and Recommendations

7.1 General discussion

The main motivation for carrying out this PhD study was to explore new pathways of teaching, by explicitly integrating knowledge and skills from several disciplines, which appears as ‘STEM’ in the literature. I consider this initiative as revolutionary and promising, since it can have both cognitive gains and wider benefits for the development of the personality and the career of future students.

Without neglecting the fact that integrative teaching approaches were historically also been pursued previously (Millar, 2020), STEM education as a research domain has received increasing attention the last two decades (Li et al., 2020). However, there appears to be vagueness regarding definitions of what is STEM, as well as models on how to apply STEM teaching (Martin-Páez et al., 2019).

First, one of the reasons for this vagueness I assume to be the fact that different disciplines and disciplinary agents come into play, each of them having distinct and unique content, methods, epistemologies and practices. In parallel, apart from their differences, they also have common grounds due to their epistemological ‘vicinities’. Therefore, there is a space of both differences and similarities among S-T-E-M disciplines and disciplinary agents.

Second, another source for this vagueness I consider to be that initiatives for STEM initially appeared having different goals, such as to ‘feed the workforce pipeline’. Efforts in ‘immigrating’ STEM into science educational goals such as teaching and learning as well as the holistic development of a student’s personality in general, brings up discontinuities, which often lead to incompatibilities.

Third, the particular complexity of technology contributes to this vagueness, since technology as a ‘discipline’ in the wider sense evolves with an accelerated rate and bidirectionally affects and is been affected not only by the other S-E-M disciplines, but also by the society in general. Therefore, integrating technology has always been a ‘wicked’ problem (Warr et al., 2019).

Last but not least, the well-documented discontinuity between research and practice, i.e. that there is a gap between what is been proposed from researchers in education and what is been or could be implemented in practice by the agents of this innovation, the teachers.

Therefore, this study aimed to explore STEM in two ways, both from what is been theoretically proposed in the literature, but also regarding to how teachers conceptualise it and implement it. For this reason, we included participants from all S-T-E-M backgrounds in order to explore on the one hand their specific peculiarities and traits, and on the other hand the effect of collaboration among them.

Particularly, in my thesis, we carried out analyses from two main empirical studies. The first study (Chapters 2, 3, 4) explored secondary in-service teachers’ views and practices on integrated
STEM during a 7-month-long STEM Professional Development (PD) programme. Participating teachers come from all S-T-E-M backgrounds and collaborate in four Learning Community (LC) groups. In specific, we analysed teachers’ STEM design of teaching material, i.e. STEM modules and artefacts in the context of NanoScience-NanoTechnology (NST) (Chapter 2). Subsequently, we analysed the STEM teaching that they design, through their STEM lesson plans and LC group discussions about them (Chapter 3). The analysis of teachers’ post-interview reflections complements the previous two chapters by exploring teachers’ views on STEM, STEM integration models, as well as their collaboration preferences (Chapter 4).

Based on the complexity of integrating technology, we complemented the first empirical study with a second study with preservice primary teachers (Chapters 5, 6). In this study, teachers’ disciplinary background was kept the same, while the focus is on how technology is been implemented. Particularly, one chapter relates to teachers’ views and practices in integrating technology, the extent to which they implement technology and in what ways (Chapter 5). The next chapter explores the effect of collaboration among teacher groups in developing technology-enhanced teaching material, both by investigating the content and nature of the LC discussions as well as the design influences among peer groups (Chapter 6).

In this final chapter, we recap the main findings of each chapter, and we discuss about limitations of the study. Subsequently, we present the main contributions of this project and we discuss about implications.

7.2 Main findings

7.2.1) Analysing in-service teachers’ STEM design through four Learning Community group cases.

In this first study, we analysed how do secondary in-service teachers from all S-T-E-M disciplinary backgrounds design and develop STEM teaching material, i.e. modules and artefacts. Participants (n=26) were divided in four separate Learning Community (LC) groups and were called upon to collaboratively develop STEM teaching material in the context of NanoScience-NanoTechnology (NST). The developed STEM modules and artefacts were qualitatively analysed based on the LC discussions (synchronous & asynchronous), as well as the delivered STEM teaching material. Design visualisations were used to represent the STEM design process and frequencies were noted in terms of a) ideas/themes discussed and b) the design activity of the teachers.

Regarding the central ideas that teachers focused on, common patterns among the four groups include modelling processes, technicalities, dimensions, robotics and use of sensors. NST was implemented in all groups in terms of: self-assembly of DNA origamis, size and scale, NST applications in 3rd generation solar cells and using quantum properties in NST applications such as electrons’ spin to store data.
Regarding nodes' design activity, it was found that prior STEM experience played a role in design centrality on the nodes. On the contrary, STEM design centrality appeared not to be discipline-dependent, since central nodes who appeared in the study had diverse S-T-E-M backgrounds. However, most mathematics teachers had peripheral roles in their LC groups and also expressed emphasised self-views on STEM identity.

Divergencies at the disciplinary level occurred, mostly between 'natural' sciences teachers (science, mathematics) and 'design' sciences teachers (technology, engineering). The former tended to engage more in NST-related topics, real-world contextualisation of the idea/problem and modelling phenomena, while the latter focused more on the setting and use of electronics, robotics and designing the prototype. Similarly, teachers tended to undertake the development of parts of the artefact that were more related to their disciplinary expertise.

Support from science education researchers and experts was deemed important and multifaceted, mostly in the domains of adopting NST, robotics and supporting didactical methodologies. Finally, we found that specific expertise was quite important in implementing technology, since design sciences teachers found it difficult to implement technological tools different from the ones that they were familiar with, e.g. Arduino and Lego robotics.

7.2.2) Integrated STEM Design and Implementation: A case with in-service teachers

Following the analysis of teachers’ designed STEM modules and artefacts at the previous study, we examined the individual STEM lesson plans that teachers subsequently designed and developed at the third phase of the PD programme, i.e. after defining the design of the STEM module. The analysis of the STEM teaching material in this phase includes the analysis of the delivered STEM lesson plans as well as the LC group discussions regarding the lesson plans. Qualitative content analysis methods were used through both deductive and inductive techniques in order to explore how Roehrig’s et al. (2021) integrated STEM conceptual framework and theoretical constructs such as boundary objects are been implemented in the designed teaching material.

The findings provide information on the extent to which S-T-E-M teachers implement each key characteristic of STEM, as well as the ways that teachers conceptualised and implemented each characteristic of integrated STEM. Considering content integration, only a limited number of teachers planned activities for explicitly discussing about interdisciplinarity, since most teachers tended to teach interdisciplinarity in a rather implicit manner. Also, a quite limited number of teachers planned activities for promoting STEM careers and STEM identities to students.

Similarly with the previous study, we found some divergencies between natural sciences teachers and design science teachers, mainly in terms of engagement with engineering design and focus of real-world problems. In specific, a considerable number of natural science teachers emphasised engineering design by solely planning to demonstrate the artefact to students. On the contrary, a considerable number of design sciences teachers emphasised or neglected the
real-world relevance in their lesson plans, while all the lesson plans that gave holistic connection with a real-world problem were designed from natural science teachers. Teachers’ disciplinary background also seemed to affect the sequence and the type of the activities, since most natural sciences teachers tended to prioritise theoretical instruction before the artefact sessions, while many design sciences teachers emphasised mostly on artefact sessions.

Analysis of the disciplinary elements that teachers identified in the modules revealed some insights about the ways teachers conceptualise the S-T-E-M disciplines in the light of STEM. Particularly, science in the modules was mostly identified in terms of knowledge, while technology and engineering in terms of skills. Mathematics skills gained importance from teachers, but mostly in terms of data collection, graphs and analysis.

Analysis of the identified interdisciplinary elements revealed an emphasis on science and technology and a rather marginal role of mathematics. In general, teachers tended to identify more disciplinary and interdisciplinary elements regarding their own discipline, with the exception of engineering in which we observed some vagueness concerning what is engineering, even among engineering teachers. Finally, natural sciences teachers conceptualised boundary objects mostly in terms of concepts and artefacts, while design sciences teachers mostly in terms of methods/techniques.

7.2.3) In-Service Teachers’ Views about STEM Integration: A case study

The third study complements the first two studies, since it relates to the reflection interviews of the in-service teachers who participated in the STEM PD programme. In specific, we investigated teachers’ views on a) STEM integration models, b) the benefits and barriers that they identify in STEM, as well as c) their collaboration preferences at the discipline and at the personal level. Data include the interview transcripts of the teachers who accomplished the PD programme (n=24). Qualitative content analysis methods were used through a combination of deductive and inductive coding techniques in order to identify patterns and match them with categories from the literature. In specific, Bronfenbrenner’s systemic model was used in order to analyse teachers’ identified challenges in STEM, while teacher-generated models from Ring’s et al. (2017) were used as a reference point to spur the discussion and argumentation about STEM integration.

Teachers’ reflections about the benefits of STEM focused mostly on cognitive and procedural themes. Regarding challenges in STEM, we identified a variety of systemic factors that affect the implementation of STEM. In relation to the immediate environment of the teachers, i.e. the microsystem, main challenges relate to lack of prior experience, time, resources, and technical difficulties. In relation to other disciplines and peers, i.e. the mesosystem, teachers mentioned lack of knowledge and skills from other disciplines, and convergence on the topic issues. External factors such as the distance modality and lack of availability because of covid were also mentioned. The macrosystemic challenge of the general educational system and culture was also stated, as well as time-related factors concerning the generation gap. Notably, natural sciences
teachers mentioned more difficulties in terms of lack of STEM experience, lack of knowledge and skills in other disciplines, than the design science teachers.

Teachers’ STEM integration models highlighted the engineering design process, content integration and real-world problem contextualisation. Following a disciplinary lens of analysis, as in the previous two studies, we found some divergencies in relation to teachers’ disciplinary background. Many science teachers highlighted the real-world contextualisation, while many engineering teachers focused on models that have engineering as a context or the engineering design cycle. On the other side, mathematics teachers valued STEM models that begin with a problem. Qualitative analysis of their verbal reflections and justifications confirmed the influence from disciplinary epistemologies and background. Moreover, natural sciences teachers mentioned much more challenges in terms of lack of prior experience, knowledge and skills in other disciplines, compared with the design sciences teachers. Therefore, natural sciences teachers seem to enter STEM with more perceived challenges in these issues.

We also traced some collaboration patterns in relation to teachers’ disciplinary backgrounds. Teachers high regarded the role of science teachers in order to contribute to the initial formulation of the idea/problem, while collaboration with mathematics teachers was the least preferred. Notably, in all LC collaboration networks, the mostly preferred persons to collaborate with were the ones who had the technological expertise, which emphasises the crucial role of the ‘translator’ in technology integration studies. Finally, justifications on collaboration preferences mostly highlighted the partnership with a peer that has complementary knowledge and skills from their own.

7.2.4) Integration of ICT in Science Education Laboratories by Primary Student Teachers

In this study we explored the views and practices of primary pre-service teachers in integrating technology. Participating teachers (n=12) pair up in six groups of two along with a science education researcher and design and develop science experiments with the use of digital technology, datalogging systems in particular. The course consists of three design phases, while at the end of each phase there was a cyclical shift of the branches of science assigned to each group. An LC meeting took place between the design phases for presenting the teaching material and reflection, as well as at the end of the course for reflection. Data collection mainly consist of the developed teaching material and transcripts from the LC discussions. Mixed methods were used for the analysis. In specific, a matrix of the total experiments was created in relation to the extent to which they include datalogging and the use of dataloggers in the experiments. The coded experiments were analysed by non-parametric tests. Additionally, qualitative content analysis of the LC discussions provided more in-depth insights about teachers’ views on technology and the difficulties that teachers encountered.

Findings of the study showed that teachers in a non-negligible number of experiments did not implement technology or they did in ways that do not constitute meaningful use. In specific,
teachers mostly used technological tools for measuring data and rarely used them as tools to be used for inquiry purposes, e.g. for prediction of an experiment. Teachers held limited views about technology, for example they tended to relate a sensor with one specific experiment, something that delimited the implementation of these digital tools in subsequent design phases. Qualitative analysis also revealed difficulties in terms of content knowledge and technological content knowledge that hindered the implementation of technology.

Barriers were also found in terms of culture, since teachers felt insecure about confronting errors and damaging the tools and did not feel comfortable in a student-centered and open-ended design challenge; instead they mentioned that they would prefer a more guided and confirmatory process. Teachers also stated that both themselves as well as the students did not initially regarded tablets as educational tools, but they rather regarded them as tools for entertainment. Teachers also had a rather unrealistic view of the applicability of datalogging due to high cost and unavailability of digital tools in schools.

Teachers’ previous experiences with non-digital instructional materials seem to have affected their Pedagogical Content Knowledge (PCK), in which teachers tended to return to when they found difficulties in integrating technology. Moreover, we found from teachers’ reflections and LC discussions that the main priority for teachers was to find an experiment that would assist content goals and subsequently they were seeking to integrate technology, which constitutes a PCK to Technological Pedagogical Content Knowledge (TPACK) process.

7.2.5) Designing technology-enhanced science experiments in elementary teacher preparation: The role of learning communities.

Complementary to the previous study, this chapter examined the content and the nature of teachers’ discussions as well as the effect of collaboration on the design of technology-enhanced science experiments. Data collection consist of the developed teaching materials i.e. science experiments along with indicative lesson plans, transcripts of the LC discussions about the developed teaching material, and researcher’s field notes about the development of the teaching material during the lab sessions for triangulation. Mixed methods were used for the analysis of the discussions, while network analysis was used for analysing interactions among peers. In specific, the coded thematic quotations from the LC discussions were analysed deductively based on Kittleson and Southerland’s (2004) categories, and were further analysed statistically with non-parametric tests. Concerning peer interactions, we analysed teachers’ design influences, i.e. ideas/comments that were expressed by LC members during the LC meetings and were subsequently adopted by peers in designing their teaching material.

The findings of the study revealed that the LC discussions were mostly of negotiating nature and quite on-task (i.e. into conceptual, laboratory skills and technology categories). Most teachers also participated adequately in discussions concerning peers’ teaching material. Regarding the content of the discussion, the discussion about laboratory skills prevailed, while a decrease on
discussions about technology was noted in the second LC meeting (LC2), which was interpreted on the initial difficulties that teachers addressed in the first design phase.

Analysing changes across the design phases, we found that in the second LC meeting (LC2) discussion was significantly more negotiative than the first LC meeting (LC1), and many teachers participated significantly more in discussions related to peer groups’ material than LC1. Concerning the design of science experiments, teachers got influenced from peers’ ideas in a considerable number of experiments, while an increase on the design influences was also noted from the LC1 to LC2. Therefore, we advocate that collaboration did have a mediating effect in the design of teaching material since teachers made use of peers’ design ideas, and participated more in peers’ discussions. Notably, qualitative analysis revealed that teachers were addressing problems in designing non-trivial experiments in latter design phases; therefore, collaboration increased in a more demanding situation in LC2.

We interpreted this increase in collaboration levels according to two reasons, based on the qualitative analysis of teachers’ reflections. First, the teacher groups that had been engaged in a branch of science and in using related digital tools, had developed more knowledge and skills in this domain, i.e. increased Technological Content Knowledge (TCK). This result is been triangulated by the increased network homophily among the groups that shared the same branches of science. Second, these groups who shared the same branches of science had increased task relevance and hence, increased motivation to collaborate.

Finally, findings support that assistance from the expert was deemed important, both through his participation in design influences as well as in scaffolding a participatory and dialogic environment during the LC meetings.

7.3 Limitations

Limitations of the study are described as follows:

First, both the in-service teachers that took part in the first empirical study (Chapters 2,3,4) as well as the pre-service teachers that took part in the second empirical study (Chapters 5,6) could not be regarded as a representative sample. In the former case, teachers voluntarily participated in the study, while in the latter case, students chose to enroll to this course among other courses. Therefore, in both cases we can assume that teachers were more motivated in the topics of STEM and Technology, respectively. Also, the teachers of the first study were teachers working at the four regions of Crete, Greece, with the exception of a teacher working in the island of Kea. The pre-service teachers of the second study were studying in the region of Rethymnon, Crete. Also, all teachers from both studies had Greek ethnicity. Therefore, all participants of the two studies were geographically restricted to a specific context.

Second, the small sample sizes of participants in both empirical studies is a limitation of the study, since tendencies found and/or inferences made in relation to disciplinary backgrounds
could also be to a great extent affected by the personal characteristics of the participants. Third, concerning the second empirical study, findings are limited by the small number of iterations regarding the total number of design phases and LC meetings. A study with more LC meetings and design phases would give us more reliable results about the effect of collaboration.

Fourth, one of the limitations of the first empirical study (Chapters 2,3,4) is that it was partly implemented under the first Covid restrictions period (starting March 2020). Therefore, the design and the development of the STEM teaching material, as well as the format of the meetings had to remain in distant mode. Even though the programme has already been carried out in blended mode up to that point due to teachers’ availability and convenience, we assume that this restriction has inevitably affected the programme. For example, the design of the STEM artefacts took place in parallel or in turns, i.e. a teacher would contribute and pass it to a colleague.

We assume that the aforementioned pandemic issue has also detrimentally affected the implementation of the STEM teaching material in schools, the planned timeline of the programme, as well as the behaviour/attitude of teachers. On the other hand, we acknowledge that the pandemic issue may well have facilitated part of the study since some of the teachers had increased free time.

Fifth, limitations regarding the design of the first empirical study (Chapters 2,3,4), relate to the fact that the study did not include an LC meeting(s) after the implementation of the STEM teaching material in schools in order to give the teachers the opportunity to further reflect on the implementation. Also, the PD programme did not implement a whole-group meeting in order to share and exhibit the STEM teaching material across different LC groups in order to subsequently give teachers the opportunity to interact with other topics and other teacher groups in an additional design iteration of the prototypes. As regards to the second empirical study (Chapters 5,6), the design of the study did not include audio/video recordings of the implementation of the technology-enhanced teaching material in order to gain more in-depth information about teachers’ practices and use of technology during the students’ visit at the science teaching lab. Also, the design of the study did not include more design phases and more LC meetings in order to investigate the evolution of the content and the nature of the discussion as well as the peer interactions and design influences in a longer duration period.

Sixth, the findings of the first empirical study include limitations due to the fact that teachers were not called upon to reflect on the analysis of themes in their lesson plans in order to provide additional triangulation. Similarly, in the second empirical study the teachers did not triangulate the results of the analysis regarding the coding of the thematic quotations in relation to the content and the nature of the discussion, as well as in relation to the design influences.
7.4 Contribution

The findings of this study contribute to the literature related to science education and STEM as follows:

7.4.1 Theoretical

The present study implemented Roehrig’s et al (2021) conceptual framework of integrated STEM comprised by 7 key STEM characteristics for the analysis of teachers’ developed STEM lesson plans. Hence, the findings informed the literature with empirical findings regarding the extent to which teachers implement each key characteristic as well as the overall applicability of this framework for school practice. In specific, the extent to which this framework relates to the school practice and the educational context was investigated through the design of STEM teaching that in-service teachers carried out. In this light, we contributed to the framework by revealing main patterns of teachers’ practices in each key STEM characteristic. In particular, the affordances and barriers as well as ways that teachers implement each key STEM characteristic were identified. These findings speak to the importance that teachers give in each key characteristic, the applicability of each one of these aspects for school teaching and the methods that teachers use to highlight each one of these aspects. Furthermore, by implementing a disciplinary lens of analysis, we also provided in-depth insights concerning teachers’ practices in each key characteristic in relation to teachers’ S-T-E-M disciplinary background. To our knowledge, such an approach towards this framework is missing, hence these insights can inform further iterations of STEM conceptual frameworks towards this direction.

In order to analyse the interdisciplinary themes that teachers identified in the developed modules, we adopted the boundary objects framework (Akkerman & Bakker, 2011). In specific, teachers were called upon to identify concepts/phenomena/applications that could not be taught under a unidisciplinary approach, and reflect on them verbally during the LC meetings. Hence, we provided topic-specific examples of boundary objects that were derived from the collaboration of teachers with STEM academics in four independent LC groups. These examples can act as indicative examples for the use of boundary objects in contemporary STEM topics, such as NST in the present study. In addition, we explored the nature of boundary objects by using categories defined from a group of STEM academics during the IDENTITIES project (www.identitiesproject.eu). The findings contribute towards the extent to which boundary objects are used by S-T-E-M teachers in each one of these categories developed by researchers. In this light, findings of the study inform the literature related to boundary objects in relation to teachers’ identification and use of boundary objects in the context of NST. Moreover, as in the previous case, differentiations in applying boundary objects in relation to disciplinary backgrounds are also examined, which is also missing from the literature. Hence, further studies can make use of these
boundary objects categories and the applicability patterns found in this study in order to further develop the concept of boundary objects and its nature.

The analysis of teachers’ reported challenges on STEM education was analysed by an adaptation of Bronfenbrenner’s bioecological model for STEM education, based on its use by Hackman et al. (2021). In specific, we additionally regarded teachers’ interactions with other S-T-E-M disciplinary knowledge and peer teachers at the mesosystem, and analysed our data under this approach. Also, we implemented contingencies due to the covid era in the exosystem. Therefore, we contributed on an adjusted systemic model for STEM education, which was developed based on a collaborative S-T-E-M teacher context and under extreme/unexpected educational restrictions. This updated version of Bronfenbrenner’s model for STEM education can be further elaborated and used in studies in similar research contexts.

Finally, regarding the technology integration study, our theoretical contribution was twofold. First, we provided empirical groundings regarding theoretical aspects of the Nature of Technology (NoT) (Waight & Abd-El-Khalick, 2012), by analysing teachers’ reflections on technology. In specific, we found that pre-service teachers had limited and often instrumental notions of technology, while we stressed how different culture and values affect the implementation of technology in school laboratories. Although there is an extended number of studies that discuss NoT from a theoretical and philosophical point of view, the present study provides insights based on empirical data from a case study focused on teachers’ views and practices on technology. Therefore, it contributes to NoT frameworks through a ‘bottom-up’ approach, specifically from a teachers’ point of view. Second, we informed the TPACK literature by providing empirical results on the TPACK development process that pre-service teachers practice. Our case study findings support that teachers followed a PCK to TPACK process (Koehler et al., 2014), revealing similarities with technology integration studies with in-service teachers (Niess et al., 2010). To our knowledge such a TPACK development process study for pre-service teachers is missing in the literature. Therefore, these results add insights about pre-service teachers development of TPACK and hence, extends and supports the analysis already carried out for in-service teachers.

7.4.2 Methods & Methodological

The Model of Educational Reconstruction for Teacher Education revisited

Regarding the design and implementation of the research, we implemented the model of Educational Reconstruction for Teacher Education (ERTE). The ERTE model is a model for framing science teacher education research and development (Duit et al., 2012; Van Dijk & Kattmann, 2007). In order to meet the needs of our study, we elaborated on the model in order to be used for technology integration studies (Chapter 5,6). Therefore, we propose an enrichment in the domain of empirical studies in the model, by also including studies related to TPACK, apart from PCK studies that are included in the existing model. TPACK relates to the knowledge needed for
effectively teach science content with the use of technology (Mishra & Koehler, 2006). Therefore, by considering TPACK, the teacher knowledge base would be more aligned to technology-enhanced science teacher education. Furthermore, we consider it of great value to inform the empirical studies domain regarding to how teachers integrate technology, i.e. the potentialities and obstacles that teachers address and the use of the technological tools that teachers perform.

Elementarisation is a fundamental process in the Model of Educational Reconstruction (MER) (Duit et al., 2012), as well as in the ERTE model. According to this process, the science content is been analysed to its core ideas and been reconstructed to science content for instruction, by also taking under consideration students’ ideas and attitudes, and teaching and learning processes. Regarding technology integration studies, adoption of technological tools often tend to follow a ‘faith-based approach’ (Waight & Abd-El-Khalick, 2012), neglecting the ‘baggages’ that these technologies carry, i.e. the cultures and values of the ones who developed them as well as the ones who use them (Waight & Abd-El-Khalick, 2018). Hence, we agree with Waight and Abd-El-Khalick (2018) that technologies should also been examined to the extent to they fit in the classroom ecologies and the aims of the specific educational environment. In that light, we proposed that technologies should also been inspected and educationally reconstructed in order to be used for science teaching, a process which needs further research. Results from such an approach can orient researchers towards the examination and revision of the technological tools regarding their educational appropriateness. Consequently, future technology-enhanced teaching can work on pertinent models which examine all factors of the ecosystem.

Similarly, we adopted the ERTE model for STEM teacher education (Chapter 2,3,4). In this case we made the following adjustments: First, in relation to the knowledge base, we took under consideration STEM integration studies, in a similar sense that we implemented technology integration studies in the technology integration study. Therefore, empirical studies on how teachers conceptualise and practice STEM integration inform and get informed from the other two domains of the model: the design of STEM learning environments and guidelines for STEM teacher education.

Collaboration has long been stressed as a facilitating role in science education (Thompson et al., 2019), as also supported in our study (Chapter 6). However, in the context of STEM we claim that collaboration plays an important and integral role. The reasoning behind that claim is that teachers enter in STEM by having their own disciplinary knowledge, methods and epistemologies, as well as their deficiencies. Therefore, collaboration with peers and academics gains a critical role in the context of STEM. Hence, we regard that collaborative learning studies should be included in teachers’ knowledge base.

Finally, in relation to the subject matter, content and skills from the four disciplines should be analysed to the core ideas and educationally reconstructed to content for STEM instruction, in a similar way as with the reconstruction of the science subject matter. However, the educational reconstruction should also take into consideration aspects of interdisciplinarity that should be
made explicit in the educationally reconstructed content for instruction. Although the present study provides some the act of reconstructing content for STEM content for instruction as well as indicative content-specific examples, this process needs further research.

Consequently, the present study proposes informed models for integration studies, i.e. technology integration studies and STEM integration studies. Also, the two empirical studies of this thesis provide some empirical implementations of the adapted ERTE model. Therefore, PD designers of STEM PD programmes as well as technology-integrated PD programmes can use the adjusted ERTE models as proposed in our study for the special needs of designing and implementing STEM and technology-enhanced science instruction, respectively. Further research on applying the ERTE models for STEM and technology integration studies can contribute more towards this direction.

**Design visualisations as a tool**

In order to visualise and analyse the STEM design process (Chapter 2), we initiated in creating design visualisations. Design visualisations are schematical representations comprised by a) the LC group members as nodes, b) the STEM ideas ideas/themes discussed and c) linking arrows with linking words representing design actions (e.g. introduce, support, extend an idea, etc.). The design visualisations were created with the use of CMapTools software. Design visualisations serve the goals of both representing the STEM design process that took place in chronological order during each LC meeting, as well as in noting frequencies regarding the nodes’ activity and the ideas/themes’ activity. To our knowledge, such a technique for visualising and analysing STEM design and the generation and evolution of design ideas is missing from the STEM-related literature. We suggest the use of design visualisations for analysing the creation and evolution of STEM design ideas and themes, as well as for creating a representative network of ideas and themes.

**STEM lesson plan template**

In this study, we implemented a modified version of the IDENTITIES (www.identitiesproject.eu) template for designing interdisciplinary teaching modules, which was used among researchers and teacher educators for designing STEM courses for tertiary education. In specific, we modified the template to be used for in-service secondary teachers by removing elements that relate to teacher education designers and adjusting the template to the design and analysis of STEM teaching modules for secondary education. Therefore, the template consists of: a) general information (context, didactical time needed, students’ characteristics, etc.), b) lesson plan description as well as description of methods and tools, c) disciplinary analysis, i.e. knowledge and skills from each S-T-E-M discipline, and d) interdisciplinary analysis. This category includes themes in which interconnections among disciplines is made explicit, concepts/phenomena/applications that could not be taught under a unidisciplinary approach, strategies to highlight
interdisciplinarity and multidimensional analysis of the module (e.g. societal, educational, political dimensions). Furthermore, we tested the template with in-service teachers and we analysed teachers' responses in the template. Hence, we consider it a valuable and practical tool both for structuring STEM teaching material, and grasping teachers’ views concerning STEM integration practices. This tool can be used as well as further modified by fellow PD designers for the needs of specific STEM PD programmes.

7.4.3 Epistemological

STEM and STEM disciplines

Teachers’ reflections at the end of the PD programme (Chapter 4) provided insights about the ways teachers conceptualise integrated STEM Education. Particularly, we used Ring’s et al. (2017) science teacher-generated STEM models as a reference point in order to spur the epistemological discussion on what is STEM and how teachers conceptualise the application of STEM. In addition, findings complement the STEM models that appear in the literature with teachers’ justifications and arguments about their desirable and undesirable STEM models.

On the one hand, our findings provide empirical groundings on teachers’ preferred STEM models from a different geosociopolitical context than the one documented in the literature. On the other hand, we inform the literature with epistemological reflections on STEM of teachers from all S-T-E-M disciplinary backgrounds. This is one of the main contributions of this study in my point of view, since, according to my knowledge, a study including teachers from all S-T-E-M backgrounds is missing from the literature. Hence, by including disciplinary agents from all S-T-E-M disciplines we can gain deeper and more reliable insights through comparisons with agents from the other disciplines. Regarding teachers’ views in specific, we found some tendencies on teachers’ perceptions of what is STEM which seemed to be affected by disciplinary backgrounds, as also stated by teachers themselves in some cases. Moreover, this study advocates for the existence of divergencies among disciplines regarding teacher STEM practices as well. In specific, we found that these divergencies to a considerable extent follow the stereotypical classification of ‘natural’ sciences (science, mathematics) and ‘design’ sciences (technology, engineering).

Additionally, particular peculiarities in each S-T-E-M discipline also appeared through the analysis of teachers’ STEM lesson plans and STEM design practices. For example, we found that teachers identify science in STEM mostly in terms of content knowledge, while technology and engineering mostly in term of skills. The marginal role of mathematics in STEM was also confirmed in the present study as well, while considerations of science teachers as the ones who would contribute in the formulation of the initial idea/problem became apparent. Insights derived from the analysis at the epistemological level can inform the literature on S-T-E-M epistemologies as well as can guide more personalised STEM PD programmes depending on the special affordances, needs and integration model preferences of its participants.
7.4.4 STEM teaching material examples

This study describes exemplar STEM teaching material, i.e. STEM modules and artefacts in the context of NanoScience-NanoTechnology (NST), designed by four independent S-T-E-M teacher groups in collaboration with STEM academics. In specific, we presented the finalised STEM modules and artefacts, as well as the main topics discussed during the STEM design process by the LC groups. These STEM themes developed can be further used or elaborated by teachers as well as STEM PD designers.

Furthermore, the study provides examples of how the cutting-edge topic of NST is been implemented for STEM teaching by secondary in-service teachers. Hence, teachers’ preferences as well as reflections on NST content/phenomena/applications contribute to insights regarding which NST themes could be selected for STEM instruction at the secondary school level. Furthermore, the study provides examples of how a partnership of teachers and researchers educationally reconstruct NST-relayed teaching material for STEM teaching.

Moreover, we provided empirical results regarding the implementation of technological tools for laboratory teaching. More specifically, we provide results on the extent to which teachers make use of datalogging systems, as well as innovative features of the tools such as predicting the evolution of a graph or portability of the devices. These results can enrich the literature on teacher education in technology-rich environments, as well as they can inform educational technology designers on how teachers make use of the technological tools and their innovative features. These outputs can inform subsequent phases of designing educational technology tools for primary school science instruction.

7.5 Implications

7.5.1 Implications for theory

The findings of the study have implications regarding theoretical aspects in STEM and in science education in general. First, our study adopted and elaborated on informed conceptualisations in STEM, framed within integrative STEM approaches that focus on highlighting the explicit interconnections among the disciplines. We adopted theoretical assumptions that make use of the theoretical construct of ‘disciplines’ as an organised body of knowledge, methods and epistemologies that has historically been developed in order to facilitate teaching. Therefore, we consider that disciplines can be productively taken into consideration under an interdisciplinary teaching approach (Klein, 2017). Contrastingly, we disregarded trivial notions of STEM in terms of a-disciplinary, instrumental or transdisciplinary approaches that neglect the affordances of using the human-made construct of disciplines. In this light, we deemed that the disciplinary background and expertise that each teacher brings along when
entering STEM is a fruitful asset that can provide additional value to the development of informed STEM teaching. Therefore, findings of this project provide insights about how informed integrative STEM approaches were been implemented in the context of a PD programme for in-service teachers, as well as in the context of an undergraduate pre-service course. Consequently, this project provides theoretical groundings as well as empirical results of interdisciplinary approaches that could act as guidelines for further development of STEM integration frameworks.

Second, under the aforementioned interdisciplinary approach, we also elaborated on a technology integration approach for science teaching that takes into serious consideration notions of technology, its nature and use, as well as the culture and values that technology entails. In contrast to instrumental views of technology as a mere tool that will facilitate the teaching process, we tried to investigate teachers’ views and practices in meaningfully integrating technology for science teaching. Findings can inform theorists and philosophers of the Nature of Technology in the context of science education, and datalogging systems in specific.

Third, in order to highlight the interconnections among disciplines, which is the main goal of interdisciplinary approaches discussed above, we encouraged explicit discussion and reflections about STEM integration, through the identification and discussion on topic-specific themes/examples. In this light, we implemented the boundary objects framework (Akkerman & Bakker, 2011) for the interdisciplinary analysis of the designed STEM teaching, based on the outputs of the IDENTITIES project group of STEM academics (www.identitiesproject.eu). In specific, we provided specific content examples of boundary objects in the context of NST, and we informed the literature regarding the nature of boundary objects that teachers identify and use for the design of STEM teaching. Findings of this project can contribute to explicitly highlighting interdisciplinarity in teaching modules with the use of boundary objects framework, while the boundary objects categories and examples used in the present study can act as guidelines for future work on the boundary objects framework in the context of STEM education. However, in this study we did not explore the learning mechanisms that boundary objects enact (Akkerman & Bakker, 2011). Additional work towards this direction as well as in other content topics is needed in order to further inform the boundaries object framework.

Fourth, we explored S-T-E-M teachers’ epistemological views on the nature of STEM by analysing their post-interview reflections and justifications at the end of the PD programme. Hence, theorists on the nature of STEM can benefit from teachers’ point of view on STEM in order to ‘bridge the gap’ between theory and practice concerning the Nature of STEM. Future work on STEM frameworks can therefore make use of teachers’ insights about the plausibility and applicability of STEM models in the literature.

Fifth, this project implemented Roehrig’s et al. (2021) conceptual framework of integrated STEM, comprised by 7 key characteristics of STEM, for the analysis of the in-service teachers’ developed STEM lesson plans. Inferences regarding the extent to which teachers implemented each key characteristic, as well as the ways that teachers implemented each characteristic can
inform the conceptual framework about its applicability and plausibility from teachers. In specific, major implications to the framework based on our findings suggest that: a) divergencies exist to the extent to which teachers implement the real-world relevance, as well as the engineering design. b) The vast majority of teachers did not plan activities highlighting STEM careers and STEM identity development aspects. Therefore, without specific focus on teachers’ training in STEM identity aspects, it shouldn’t be expected that teachers would implement these dimensions. c) Most teachers did not plan specific activities in which they would explicitly discuss about integration of the disciplines with the students; integration would be implicitly experienced through the activities. Subsequent work is still needed towards teachers’ realisations and practices in each key characteristic in order to inform and enrich the framework with empirical groundings.

Finally, we adopted an adaptation of Bronfenbrenner’s bioecological framework for STEM education in order to analyse the challenges that teachers addressed, according to their post-interview reflections. In specific, we initiated in exploring cross-disciplinary interactions in the mesosystem layer of the framework, as well as contingencies such as the recent covid restrictions at the exosystem layer. These adjustments can inform future work on the framework in the context of STEM education.

7.5.2 Implications for research

The empirical studies carried out as part of this PhD thesis respond to the gap in the literature concerning the epistemological barriers that exist at the disciplinary level when doing interdisciplinary work (Millar, 2020). In specific, Millar (2020) called upon to take into account the unique epistemologies of the constituent disciplines in STEM and drew attention to any potential differences among ‘pure/natural’ and ‘applied/design’ sciences. The present study responds exactly to these issues, since we included participants from all S-T-E-M backgrounds, an initiative that, to our knowledge, does not exist in STEM literature. In this light, we implemented a disciplinary lens of analysis in order to explore teachers’ views and practices both during the STEM design and development phase as well as during the design lesson plans phase. Divergencies found at the disciplinary level in terms of the nature of themes discussed in the LC meetings, the sequence and type of the teaching activities designed, the interdisciplinary elements identified, as well as in teachers’ preferences on STEM models. These divergencies in most cases fell into the stereotypical classification natural-design sciences. However, we identified a few examples of teachers that exerted extended boundary crossing as well. I consider that these findings gain further robustness since a) the LC groups were purposefully designed to include teachers from all disciplines, therefore, these peculiarities appear in a collaborative space of epistemological ‘multivoiceness’, b) these findings are cross-compared from four LC groups who worked in parallel as independent case studies in order to develop interpretations with increased trustworthiness. The findings of the study spur the discussion in the literature concerning the role of disciplinary
backgrounds and epistemologies in teachers’ views and practices in STEM, and calls upon for further research on teachers’ views and practices in STEM at the disciplinary level. Similar studies examining STEM views and practices of all S-T-E-M agents would help increasing the trustworthiness of this study, as well as to further provide insights towards this direction.

Second, our study advocates for the importance of scrutinising teachers’ practices during the design and development phase. A frequent research practice is to analyse the end products, e.g. the developed teaching material in its final form, as well as teachers’ initial views. In contrast, this study revealed that there also is important information during the STEM design process, both in terms of analysing the content and the nature of the topics discussed, and the activity of the individual nodes. In specific, we showed that the ‘survival’ or rejection of ideas and themes across the sequence of LC meetings can shed light on teachers’ design thinking and design practices. Similarly with the above, in Chapter 6 we showed that analysing the content and the nature of the LC discussions can shed light on the realisations of technology in science classrooms and insights about teachers’ views on technology. However, in the present project we did not analyse more in-depth the decision-making process and the argumentation that led the LC groups in taking design decisions in particular points or debates. Further research could give interesting insights towards this direction.

Third, both empirical studies in this project support the facilitating role of collaboration in teacher education. On the one hand, we showed in Chapter 6 that the LC group embraced a collaborative stance by increasing peers’ participation, increasing negotiative discussion and increasing design influences from peers. On the other hand, in Chapter 2 we demonstrated how collaboration among diverse S-T-E-M disciplinary agents contributed in discussing ideas/themes and in designing and developing STEM modules and artefacts that encompasses all S-T-E-M disciplines. Furthermore, in Chapter 4 we went further by revealing the particular collaboration preferences among S-T-E-M teachers, which retrieved in-depth information about their needs and epistemological ‘vicinities’. More specifically, this study revealed that the main collaboration pattern was the complementarity of knowledge and skills, since most teachers stated that they were seeking to collaborate with peers that had expertise in domains they had lack of. Notably, the most common pattern for non-technology experts was to collaborate with the technology expert. Moreover, collaboration with STEM academics and experts was deemed important in both empirical studies, in terms of contribution in design ideas as well as in providing support and resources. These findings contribute to the literature of collaborative learning, particularly for STEM integration studies.

Fourth, this study provided insights about the constituent disciplines in the context of STEM. Notably, some vagueness was noted in conceptualising what is engineering in the context of secondary education, even among engineering teachers. We interpreted this result in relation to the affinity with technology (Murphy et al., 2015), the lack of understanding of engineering at the K-12 level, but also because of a terminology issue in the Greek language. Further research is
needed in other educational contexts and other countries and cultural contexts in order to contribute towards this claim.

Regarding the role of mathematics, this study contributed to the well-documented marginal role of mathematics in STEM (English, 2016). However, qualitative analysis revealed the existence of more deep reasons related to the fact that many mathematics teachers tended not to self-identify themselves as important agents in STEM, even in cases in which these LC members did contribute adequately. More research is needed in terms of the development of STEM identity for mathematics teachers in STEM.

Fifth, our findings from teachers’ post-interview reflections enrich the existing literature regarding science teachers’ conceptualisations on STEM (Ring et al., 2017), and their hierarchy (Dare et al., 2019). In specific, we extended the knowledge base concerning the existing STEM integration models in two ways: a) by including STEM model reflections from teachers from all S-T-E-M backgrounds, i.e. engaging teachers with a non-science background, b) by providing S-T-E-M teachers’ justifications and arguments for their model preferences.

Sixth, we informed the literature regarding the TPACK development model that pre-service teachers implement when they integrate technology for science teaching. In specific, we found that pre-service teachers’ views and prior PCK representations affect the TPACK development process, in a similar way as occurs with in-service teachers (Niess et al., 2010). Therefore, a PCK-to-TPACK approach prevailed in our case study. Future work on TPACK development can confirm or provide further insights in this research topic.

Seventh, the findings of our study highlighted the existence of some divergencies at the disciplinary level, mainly within the stereotypical classification of natural and design sciences, as mentioned earlier. However, Nathan et al. (2013) criticise this classification in the context of integrated STEM, while Li et al. (2019) consider it important to highlight the design features in ‘traditional’ school disciplines such as science and mathematics. Therefore, our study on the one hand it reveals a problematic situation and on the other hand advocates for the need of research in order to foster ways and methods to highlight the non-stereotypical attributes of the disciplines.

Finally, regardless of the divergencies found at the disciplinary level, we found in our study that STEM design centrality was not discipline-dependent. Teachers with substantial contribution in designing STEM teaching material appeared from all S-T-E-M backgrounds. This implies that all teachers can gain a satisfying level of STEM competency, a claim which needs further research.

### 7.5.3 Implications for practice

Implications for practice that could be derived from this project relate to the development of teacher PD programmes for STEM integration, as well as for technology integration studies. In specific, we advocate for personalised teacher training according to teachers’ disciplinary
knowledge, skills and expertise, as well as collaborative settings including diverse disciplinary agents and academics. Moreover, our study provides examples of STEM modules and artefacts as exemplar STEM teaching material.

In specific, taking under consideration the outputs of this project, we suggest the following implications for practice and recommendations in the context of teacher education:

- Teachers should be encouraged to make the interconnections among disciplines explicit to students. In this light, we recommend that teacher educators support teachers in planning activities that explicitly address interdisciplinary thinking, i.e. discussing and reflecting about interdisciplinarity in the activities students experienced or they are about to experience. Under no guidance towards this direction, it shouldn’t be expected that most teachers will plan this type of sessions.

- Similarly with the above, orienting teachers in explicitly reflecting and analysing the interdisciplinarity in their designed STEM lesson plans may foster fruitful discussions that can enhance interdisciplinary thinking. Using reflection questions related to the identification of boundary objects, such as the ones in the IDENTITIES template can appear as a productive means for designing STEM teaching. Paired with the interdisciplinary analysis, we also suggest a preliminary disciplinary analysis in order to assist teachers to identify disciplinary elements in each S-T-E-M discipline.

- Teachers should be encouraged to engage in STEM design practices, in which they should be given the opportunity to collaboratively develop their PCK in innovative, thought-provoking and open-ended working environments.

- PD programmes should consider both the similarities and the unique peculiarities and traits of the constituent disciplines. Therefore, we advocate for more personalised teacher training in the context of STEM, since teachers do not start with the same backgrounds. In specific, most natural sciences teachers seem to lack engineering design experiences, as well as technological knowledge and skills, while design sciences teachers often overlook the connections with content and the real-world contextualisation of the problem. Informed and adjustable PD programmes could assist teachers in developing the needed ‘disciplinary adequacy’ and the bird-eye view needed to teach STEM.

- Opportunities for collaboration should be carefully taken into account in STEM working groups. We recommend the creation of interdisciplinary groups comprised by STEM academics, experts, and teachers from diverse S-T-E-M disciplinary backgrounds. Hence, group members can benefit from the complementarity of knowledge and skills from their peers. Furthermore, working on the same topic and sharing resources can enhance the collaboration effect since members can feel increased task relevance.

- Support to non-technical experts through the collaboration with a technology expert is a crucial issue in LC groups, both at the primary and the secondary level.
• We recommend that the design of the PD programmes and teacher training courses includes a considerable number of LC meetings and iterations of designing teaching material. Therefore, the collaboration effect could increase in latter iterations, while the members may benefit from peers’ familiarity with the topic and the tools used.

• We also recommend engaging teachers with contemporary and interdisciplinary topics that relate to real-world phenomena and applications, such as the topic of NST. This way teachers are given the chance to challenge their existing PCK and we pave the way for the adoption of educational innovations, such as STEM.

• Integration of technology for science teaching should not follow an instrumental use, e.g. using technology as a mere tool. We should take into account informed conceptualisations of technology, their affordances and limitations, as well as the aims, culture and values they bring along in order to be effectively and meaningfully integrated.

• Finally, it should be expected that teachers hold diverse perceptions about STEM and STEM integration models. PD programmes should allow teachers have a degree of ownership of each educational innovation that fits both their style and interests. Nevertheless, teachers should be supported in making explicit interconnections between the disciplines and utilise integrative approaches in their practices.

7.6 Transferability of the findings

The two empirical studies, although they were carried out in a geographically restricted part of a south European country and the participants were to a high extent homogenous in relation to race and culture, we consider that the findings of the studies can be extrapolated to other contexts and cultures, due to the reasons mentioned as follows.

First, as regards to STEM education, we consider the first empirical study (Chapters 2,3,4) relevant to many other contexts worldwide, since STEM Education has drawn extended attention from researchers in education, educational stakeholders, teachers, students, etc. from all over the world. Therefore, this study contributes to a mainstream topic in education and hence can inform a big number of teacher PD programmes. Similarly, integrating technological tools such as dataloggers in science laboratory education is a main and continuous goal for science educators worldwide. Therefore, given the importance of integrating technology in schools, the findings of the second empirical study (Chapters 5,6) become relevant to other research and practice communities as well.

Second, the disciplinary lens that the analysis of the first empirical study applied, included science/technology/engineering/mathematics disciplinary backgrounds. Hence, the findings of the study become transferable to other contexts since these disciplines are considered ‘traditional’ and well-established in every country.
Third, regarding the content topic that this PD programme implemented, which is NST, we can see that NST is generally regarded as a very popular topic worldwide, since students learn about NST concepts/phenomena/applications through non-formal educational environments (e.g. news, internet sources, video games, etc.) in many parts of the world. Also, the massive attention and growth that NST has gained in industry and commerce has resulted in the development of low-cost NST materials; therefore it is possible to engage students and teachers with the interdisciplinary topic of NST and/or also use low-cost NST materials (e.g. superhydrophobic surfaces or sprays) for experimentation in many other locations and contexts as well.

Fourth, the second empirical study aimed in implementing the developed technology-enhanced experiments for teaching in the university science teaching laboratory during the implementation of educational school visits at the university; therefore it was implemented in a non-formal context. Considering the growing interest that the science education community has shown towards non-formal education, the findings of this study may contribute towards teacher training and the development of such non-formal learning environments. Similarly, developing STEM artefacts as the ones that teachers developed in the first empirical study becomes also relevant to non-formal educational contexts.

Fifth, both studies relate to teacher education, hence, both the design of the PD programmes as well as the findings of the empirical studies can be relevant for teacher educators and PD designers in other contexts. In specific, the findings can inform the design of more personalised PD programmes, adjusted to the specific affordances, needs, experiences, disciplinary backgrounds and attitudes of the teachers.

7.7 Suggestions for future research

The findings of the study trigger the need for further research in various fields. Indicatively, some arising issues that gain research interest in our point of view are further described below.

- The first empirical study revealed differences in STEM views and practices in relation to teachers’ disciplinary background and revealed collaboration trends mainly based on complementarity. However, questions that arise from this could be *what is the appropriate design of a collaboration group composed of teachers with diverse disciplinary backgrounds? Are there disciplines where teachers should have the support of a second colleague with the same background?*

- Similarly, the first study examined teachers’ design centrality and findings support that a considerable decline appeared among teachers. Therefore, *what is the appropriate design of a collaboration group in relation to the extent of the inclusion of central/active members? What is the activity of groups which include no central/active members? Does that cause other inactive or averagely active members to take more initiatives?*
Both studies examined the design of teaching material by teacher groups. However, questions remain unanswered such as what are the (internal/external) processes that determine the collaborative decision-making in relation to STEM design?

The findings of the study support that vagueness was noted regarding views on what is Engineering among teachers, at least in the Greek context. Do teachers in other countries/places which use a term for Engineering which is different from the Greek one (Μηχανική) also address lack of understanding of what is Engineering in K-12 education?

Regarding the disciplines, teachers mostly regarded S-T-E-M disciplines through views which could well be characterised stereotypical, such as the natural-design sciences taxonomy. How could these stereotypical views been to some extent overcome? How could we highlight the non-stereotypical attributes of the disciplines (such as the design process in Mathematics or the theoretical aspects of Technology)?

Also, the study drew attention on the examination of the technological tools for their applicability and appropriateness for science teaching. Therefore, what are the features that technological tools should have in order to best support inquiry-based science instruction?

These are only a few research questions related to the findings of the study that we find it interesting to be further investigated.

7.8 A final note

To conclude, this project provides empirical evidence on teachers’ views and practices in STEM, through the examination of four independent LC groups. The analysis of teachers’ STEM design practices, the STEM lesson plans and the post-interview reflections reveal differences in relation to teachers’ disciplinary background. Collaboration seems to establish a facilitating context in STEM integration and technology integration studies. In specific, collaboration patterns among teachers highlight the cooperation with peers with complementary set of knowledge and skills, while collaboration with a technology expert was deemed critical both at the primary and the secondary level. However, teachers often hold limited understandings of technology and perform instrumental use of technology.

What I have personally learned and realised from this study is that cognition is a multifaceted, never-ending, challenging and always unfulfilled process. Therefore, teachers and researchers in STEM ought to be open to new models, strategies, and methodologies while practicing boundary-crossing that enables them to enter spaces that might challenge their views and practices.