Article

Sustaining Teacher Professional Learning in STEM: Lessons Learned from an 18-Year-Long Journey into TPACK-Guided Professional Development

Maria Meletiou-Mavrotheris [1,*] and Efi Paparistodemou [2]

1   Department of Education Sciences, European University Cyprus, Nicosia 2404, Cyprus
2   Cyprus Pedagogical Institute, Nicosia 2252, Cyprus; paparistodemou.e@cyearn.pi.ac.cy
*   Correspondence: m.mavrotheris@euc.ac.cy

Abstract: This article is a self-narrative of our 18-year research into the Technological Pedagogical Content Knowledge (TPACK)-guided professional development of teachers in ICT-enhanced mathematics learning. Using autoethnography as the methodology to elucidate our transformative personal evolution in implementing the TPACK model, we describe how we conceptualized and enacted the TPACK framework across three distinct phases of our research trajectory. In the first phase, our efforts focused on offering afternoon seminars and workshops on using educational software. Mathematics teachers attended the seminars and workshops voluntarily. In the second phase, we concentrated on designing programs guided by the principles of adult education, which emphasize the importance of learner autonomy and relevance, and socio-constructivist views of teacher professional growth, which stress the role of collaboration and reflection in learning. In the final phase, we adopted a systemic, school-based approach to investigating and expanding TPACK for mathematics and other STEM/STEAM teachers. At the end of each phase's description, we delve into the profound lessons learned and how these led to a paradigm shift, expanding our perspective on TPACK as practitioners and researchers. Finally, we present a set of recommendations for future research and practice aimed at facilitating the sustainability of STEM/STEAM teacher professional learning initiatives.

Keywords: mathematics education; STEM education; TPACK; professional development; autoethnography; sustainability; sustainable teacher professional development

1. Introduction

The ascent of novel and evolving technologies and industries, alongside the emergence of intricate global challenges, such as climate change and aging populations, has brought into sharp focus the imminent skills gap within the workforce and the need to modernize educational systems so as to develop human resources able to adapt to the demands of the rapidly changing labor market and to contribute to sustainable development [1–4]. The development of key competencies related to Science, Technology, Engineering, and Mathematics (STEM) disciplines plays a direct role in creating an educated population and well-skilled workforce capable of finding sustainable technical solutions to complex global issues [2,3,5,6] and is set high on the priority list of educational systems worldwide.

Although the increasing demand for a robust STEM workforce is acknowledged by academic, non-profit, and governmental entities, formidable challenges persist, imperiling society's capacity to attract, educate, and retain such a workforce in ways that are efficacious, sustainable, and conducive to a culture of innovation [7]. A burgeoning body of evidence derived from respected international studies of student achievement, such as the Program for International Student Assessment (PISA) and the Trends in International Mathematics and Science Study (TIMSS), consistently highlights deficiencies in mathematical and scientific proficiency among a significant portion of the global student population. Moreover,

well-documented evidence indicates a waning interest in key science and mathematics subjects, as well as in pursuing careers within the STEM fields [8]. This unfortunate situation poses a serious challenge since mathematical and scientific literacy serve as foundational areas of knowledge that drive technological advancement in knowledge-based economies.

Traditional instructional methods have been pinpointed as exacerbating students' low achievement and declining interest in STEM fields. These methods are often regarded as unappealing by the majority of students, as they are perceived as outdated and lacking relevance to their interests and lived experiences [8–10]. Often, concepts are presented in an excessively theoretical and abstract manner, with limited opportunities for students to actively engage in problem-solving and experimentation [8]. Accountability pressures push schools to increasingly emphasize low-level skills and decrease emphasis on valued qualities that are not assessed, such as higher-order thinking, collaboration, and resilience [11]. Thus, to overcome the phenomenon of the 'silently excluded' crisis in schooling, where many students complete secondary education without really learning much about mathematics and science [3], and to equip all learners with the higher-level skills and competencies required in modern society, an urgency exists for educational systems to reform their school curricula and methods of instruction in STEM subjects.

Technological advancements present a promising avenue for ameliorating the present situation by furnishing tools for enhancing STEM instruction. A vast array of powerful and easily accessible technological resources provides the potential for a substantial transformation and enrichment of STEM pedagogy [8,12,13] through the development of more student-centered, interactive, collaborative, inclusive, inquiry-based learning environments [14] that are aligned with the 21st century. An expanding body of research literature demonstrates that the strategic integration of technological tools can yield a beneficial effect on both student attitudes and learning of mathematical and scientific concepts and processes [15–17] while at the same time helping students to develop critical thinking, and the problem-solving and innovation skills required to cope with the demands of the complex digital era [13,17].

Acknowledging the educational potential of technology, the research of both authors of this article has always focused on the exploitation of the affordances of new and emerging technologies for enhancing the learning of statistics and other areas of mathematics (and, more recently, STEM/STEAM). Recognizing the pivotal role of teachers in facilitating change and fostering innovation, we have concentrated our research efforts on ICT-enhanced teacher professional development. For the past 18 years, our endeavors have been rooted in Technological Pedagogical Content Knowledge (TPACK), the robust and influential conceptual framework introduced by [18]. We have employed TPACK in various capacities: (i) As a framework to delineate the essential knowledge foundation requisite for teaching mathematics with technology; (ii) as a compass for designing and implementing professional development initiatives; (iii) as a lens for comprehending how knowledge about mathematical content, pedagogy, and technology intersect to inform decisions regarding curriculum and instruction; (iv) and as an evaluative model to gauge the efficacy of professional development initiatives on enhancing teacher knowledge of mathematics and its pedagogy [8,17].

In this article, we describe the transformative learning journey we have experienced in enacting the TPACK model over these past 18 years. We provide a synthesis of the main insights gained from the TPACK-guided programs we have designed and implemented in an effort to highlight not only the significant benefits but also the limitations and challenges of adopting TPACK as a framework for sustainable teacher professional development. Employing autoethnography as the methodology to think deeply about our experiences [19], we take a retrospective look at how we have conceptualized and enacted the TPACK framework at different phases of our research journey and at how this might have impacted the possibility of long-term sustainability of professional development initiatives. We discuss the factors that we have identified as potential influences on the sustained use of

new practices and conclude with recommendations and considerations for future research and practice in the field of STEM teacher education.

2. Literature Review

Educational systems in many countries have, in recent years, redeveloped their curricula in mathematics and other STEM disciplines to include new technologies. While the creation of new curricula, textbooks, or educational materials can facilitate technology-enhanced reform initiatives, it is essential to recognize that teachers constitute the linchpin in the process of effecting transformation and ensuring the sustainable implementation of change [20–22]. Their role is paramount to the successful integration of ICT in educational settings [4,13,22]. Nevertheless, the research literature underscores that the integration of ICT has brought new challenges for educators [23], introducing an additional layer of complexity to their already demanding responsibilities of lesson planning and implementation. Ample research evidence indicates that harnessing the growing prominence of digital technologies and their transformative capabilities in instructional settings places significantly higher demands on teachers than initially envisaged [8]. Furthermore, many educators remain inadequately prepared to effectively utilize ICT tools in their teaching practices [8,24,25]. Consequently, there often exists a disparity between curricular initiatives and reform efforts and the practical implementation thereof within classroom settings, leading to the persistence of traditional, teacher-centered approaches [17,26,27]. Research conducted across educational levels indicates that although most educators hold favorable attitudes toward incorporating modern technologies into instruction, viewing them as essential elements of the contemporary learning environment, many teachers often fail to fully appreciate the educational benefits and potential offered by these technologies [8,28–30]. The reported utilization levels of technological tools for educational purposes notably fall short compared to their widespread use in everyday life or in professional contexts beyond teaching [31]. Moreover, teachers' use of technology is often determined by the dominant interpretation of teaching, concealing the real affordances of technology. There tends to be a mismatch between tasks and available resources [32].

Undoubtedly, STEM teachers need to expand their technology toolbox to meet the needs of today's technologically savvy students. They need to bring inside the classroom the technology that students use in their daily lives to learn, communicate, and entertain themselves. Technology should serve to enhance the educational process and extend the possibilities of traditional learning tools. Educating 21st-century learners entails leveraging technology to facilitate and stimulate student innovation and creativity, as well as to design and implement personalized and collaborative learning experiences and assessments, exemplify interdisciplinary work and learning in the digital age, and advocate for equity, digital citizenship, and responsibility [33]. Providing high-quality pre-service and in-service teacher professional development is pivotal in fostering the requisite changes in teaching practices that will enable STEM education to fully harness the benefits of technology [13,14,17,22,23,28]. However, as the literature indicates, there are significant gaps in the training of both prospective and practicing teachers on the effective instructional integration of ICT [17,34], where notable disparities exist in the efficacy of teacher professional development programs [23,35].

In recent decades, providing professional development to support teachers in integrating new technologies into STEM teaching and learning has emerged as a significant area of research [36]. Various frameworks for teacher professional development in technology integration have been proposed in the literature. One such framework is Technological Pedagogical Content Knowledge (TPACK), proposed by [18] as a response to the lack of guiding theory in technology integration within education. The TPACK framework, which extends Shulman's concept of Pedagogical Content Knowledge [37], underscores the significance of cultivating an integrated and interconnected understanding of three core forms of knowledge: technology, pedagogy, and content. Central to this framework is the premise that effective technology integration in pedagogy, particularly within specific

subject domains, necessitates a nuanced comprehension of the dynamic interplay among all three knowledge components. Thus, ICT training should not be conducted in isolation; rather, it should be accompanied by a focus on the interrelations between technology, pedagogy, and content [8,17]. The aim is to guide teachers beyond technocentric approaches that solely emphasize technology and instead foster their critical reflection on the educational uses of technology [8,17,38].

In recent years, TPACK has emerged as a focal point in research on technology education and teacher professional development across various disciplines [8,39–42]. In the area of STEM education, numerous studies targeting both prospective and in-service teachers have been anchored in the TPACK framework [28,43–51]. These studies demonstrate the efficacy of TPACK as a research framework for promoting and evaluating teachers' professional development in the use of ICT in STEM education. As indicated by the literature, the cultivation of TPACK among teachers facilitates the integration of technology into their STEM teaching practices, consequently leading to potential improvements in student motivation and learning outcomes [52].

Although teacher professional development on ICT-enhanced pedagogy and research about it using TPACK or other frameworks is a growing field internationally, there is still little knowledge on how to escalate teachers' capabilities in a systematic and sustainable manner. Research on sustainable impact within educational disciplines is generally lacking [22,53,54]. The sustainability of a teacher professional development program refers to the durability of the initiative beyond its initial timeframe [23]. Ensuring that a program's impact can be discerned at a sufficiently distant point in time following the conclusion of the program [55] is core to establishing the coherence and improvement of learning outcomes [23]. As highlighted by [54], the anticipated outcomes of professional development initiatives should not solely focus on the short-term effects occurring during or immediately after the program but also on the long-term effects that manifest post-program completion. While short-term effects are essential to build stakeholders' trust [56], establishing long-term capacity for improvement is also vital since it will ensure the continuation of achieved benefits and effects by empowering individuals and/or institutions to react autonomously to the changing conditions and to foster innovation and change [54].

3. Methodology

The methodology of autoethnography that we have utilized to explicate our transformative personal journey into the enactment of the TPACK model of teacher professional development is a qualitative narrative approach to research and writing that links the personal to the cultural, rendering personal experience as a source of knowledge. Through making oneself the subject of study and critical inquiry, autoethnography strives to comprehend the past and present conditions, experiences, and modes of existence within a given context [57]. It seeks to systematically analyze and describe writing (graphy) personal (auto) experiences or investigations in order to understand the culture (ethno) in which they take place [58]. When applied to practice-based research, autoethnography allows the researcher's emotions, battles, and failures to be incorporated into the research narrative [59].

The following research question provided direction for our investigation reported in the paper: What were the pivotal moments where our perspective/beliefs shifted in relation to our understanding of teacher professional learning and of how to implement the TPACK framework? We constructed our research around epiphanies—remembered moments that have significantly influenced our trajectory of teacher education perspectives and practices. This forced us to attend to and analyze the experiences and events occurring during the implementation phase of our research, or that emanated from past experiences that led to a shifting of our perspective on optimal ways of developing teachers' TPACK [59,60]. We framed our analysis around three different phases: (i) Phase 1: building teachers' TPACK through afternoon seminars and workshops; (ii) Phase 2: enacting TPACK-guided profes-

sional development based on the principles of adult education and socio-constructivism; (ii) Phase 3: adopting a systemic approach to assess and enhance teachers' TPACK.

Recognizing that teachers' continuous professional growth is central to the attainment of high-quality ICT-enhanced teaching and learning [21,36], our analysis paid particular attention to the issues of sustainability of teacher professional development. Although none of the TPACK-guided professional development programs included in our analysis was explicitly designed (based on theoretical considerations) to support sustainable impact, our retrospective analysis examined not only the factors that were critical to the success of the initial implementation efforts but also what came after the program was over. We reflected on how specific aspects of the TPACK-guided model of professional development enacted at each phase might have influenced its long-term impact. We held several meetings, discussing and critically reflecting on the pivotal moments of our long journey as practitioners-researchers embracing the TPACK approach. In those meetings, additionally to our memories, we also used articles we had published to help us recall the details of our research journey, and the lessons learned at each phase of our transformative learning journey.

While subjectivity and researcher bias are both unavoidable in autoethnographic research [60], we have tried to avert ethnocentrism and to make our situatedness as researchers transparent through a full explication of our epistemological stance [61]. We have situated our developing knowledge, thinking, and educational judgments at each phase of our journey within the overall social and cultural context of teacher education research and practices. Rather than being overly self-absorbed, we have maintained a high level of reflexivity, looking at our research experiences through a self-critical lens and framing them with relevant research literature and a more structured methodology [62]. This has hopefully helped to improve the authenticity and credibility of our self-narrative [63].

4. Our Research Journey into TPACK-Guided Professional Development of Mathematics Teachers

4.1. Phase 1: Building Teachers' TPACK through One-Shot Seminars and Workshops

Our research journey commenced in 2006, a time when technology was not a central component of mathematics instruction in most countries, including Cyprus. The results of a survey study conducted at the time indicated that the vast majority of both elementary and secondary Cypriot teachers seldom utilized computers in their mathematics classrooms [64,65]. When computers were used, their usage typically revolved around basic tasks such as routine calculations, skill practice, and answer verification. Students rarely, if ever, employed technology for solving complex problems, exploring mathematical principles and concepts, processing and analyzing data, producing graphical representations, or constructing models through simulations [64,65].

A major hindrance to incorporating technology into mathematics instruction stemmed from the limited availability of professional development opportunities for teachers. In Cyprus during that period, professional development programs provided to teachers predominantly concentrated on the acquisition of technical skills. Despite the participation of a large number of educators in these programs, they primarily enhanced educators' computer literacy skills rather than equipping them with the necessary tools to effectively incorporate technology into mathematics teaching and learning [65]. Several other underlying factors contributed to the limited utilization of technology in mathematics education. One notable factor was the absence of technology integration within the curriculum [65]. While advocating for the utilization of calculators and computers, teacher guides lacked specific directives on how to incorporate these tools into the instructional process or recommendations regarding suitable software options [65]. In the survey study of elementary and secondary school teachers conducted by [64], the majority of respondents cited various factors that significantly impeded the use of computers in mathematics instruction. These factors included inadequate support from specialists in integrating technology into the curriculum, an overcrowded curriculum, limited availability of computers, lack of suitable

software, and limited familiarity with the appropriate software [65]. While these challenges were not unique to the Cypriot educational context and were indicative of the situation in numerous educational settings globally during the early 2000s, the fact remained that technology had yet to be effectively integrated into mathematics classrooms at any level of K–12 education in Cyprus.

At this initial phase of enacting the TPACK framework, we focused our efforts on offering afternoon seminars and workshops on the educational use of dynamic mathematics and statistics software (Cabri Geometry, Geometer's Sketchpad, Fathom, Tinkerplots) that were attended by individual teachers on a voluntary basis. We designed each of these seminars and workshops based on the TPACK model, aiming at enriching the participants' technological, pedagogical, and content knowledge of mathematics or statistics by immersing them in similar learning environments, technologies, and curricula to those they would encounter in their own classrooms. Through collaborative computer-based activities and experimentation, such as extensive use of simulations and visualizations and peer feedback and reflection, we aimed to assist the teachers in gaining a deeper understanding of how dynamic mathematics or statistics software could be integrated into the mathematics curriculum. Apart from the computer-based activities, the seminars and workshops facilitated discussions centered on students' learning and strategies to actively engage them in mathematics/statistics learning. We delved into a wide array of topics relevant to mathematics teachers, encompassing curriculum considerations such as the role of statistics in national and international mathematics curricula [65]. Additionally, we explored research in mathematics and statistics education, including the development of mathematical and statistical reasoning in children and common student misunderstandings. Teachers actively contributed examples from their own experiences and proposed ways to enhance their students' learning through the use of dynamic mathematics or statistics software [65].

Lessons Learned in Phase 1

Findings from Phase 1 were very encouraging. In [65], for example, we present insights from a study involving teachers participating in professional development seminars on statistics teaching using the dynamic statistics software Tinkerplots®. Through a case-study approach, we collected and analyzed various forms of data, including video recordings of group activities and discussions, participant observation, mini-interviews, and samples of teacher work, to assess the teachers' confidence and proficiency in teaching statistics using technology. Analysis of these data indicated that the exposure to Tinkerplots® during the seminars led to significant changes in the teachers' comprehension of statistics and its pedagogy. The dynamic statistics software's presence increased the participating teachers' enthusiasm for statistical investigation and afforded them novel opportunities to explore data. The data analysis tools provided by the software also enabled teachers to prioritize their conceptual understanding and statistical problem-solving over the mere reliance on computational procedures and formulas. A cohort of highly motivated educators emerged, enthusiastic about the potential of the software to facilitate in-depth data analyses. Convinced that the use of Tinkerplots® could enhance students' comprehension of statistical concepts, these teachers expressed eagerness to integrate the software into their own classrooms.

Despite the success of our initiatives in improving educators' TPACK of ICT-enhanced mathematics/statistics pedagogy, in retrospect, we recognized several limitations of fragmented, one-shot training workshops, leading to a very limited long-term impact on teaching practices: (i) An underlying assumption of a transition of knowledge from "experts" (teacher educators) to "novices" (teachers); (ii) an individualistic approach to teacher professional development; (iii) limited opportunities for collegial interactions and exchanges; (iv) failure to consider the contextual factors influencing professional development; and (v) a lack of follow-up classroom experimentation. Similarly to other researchers [21,66,67], we also concluded that teachers' need for collaboration, experimentation, and reflection

cannot be adequately addressed by short-term workshops that solely showcase innovative technological tools and instructional materials in isolation from teaching contexts. Recognizing the necessity for professional development that supports teachers to apply their newly acquired knowledge and skills in their own classrooms and to engage in collective discussions regarding the implementation challenges with supportive colleagues, we transitioned to Phase 2 of our research journey.

4.2. Phase 2: Enacting TPACK-Guided Professional Development Based on the Principles of Adult Education and Socio-Constructivism

The experiences and insights we acquired as teacher educators and researchers in Phase 1 helped us to recognize the need for the mathematics education field to move away from models of professional development focused on the transmission of knowledge from experts towards models promoting the building of communities of practice and on workplace learning [68]. The shortcomings of the workshop-based professional development model led us to the design of professional development programs, guided by the principles of adult education and by socio-constructivist views of teacher professional growth.

EarlyStatistics, a three-year EU-funded initiative (Ref. No: 226573-CP-1-2005-1-CY-COMENIUS-C21), was conceived in response to the imperative of enhancing the quality of statistics instruction in European schools. This project was meticulously designed to acknowledge the continuous professional development and learning of teachers as pivotal factors in promoting instructional innovation and fostering success for their students [69]. Leveraging the capabilities offered by open and distance learning technologies, the project aimed to provide high-quality statistics education experiences to teachers around Europe. [70]. A consortium comprising five higher education institutions from four countries (Cyprus, Greece, Spain, and Norway) collaborated to develop and pilot test an intercultural online professional development course in statistics education tailored for European elementary and middle school mathematics teachers. The course objectives were to augment teachers' (i) knowledge of statistics, (ii) understanding of technology-enhanced statistics teaching and learning, and (iii) practical knowledge [70]. Guided again by the TPACK model, the professional development approach in this project departed from the previous efforts, adopting 'learning' and 'community' models instead of 'instructional' models [71–73]. The participants actively engaged in constructing their own knowledge through collaborative and participatory activities, such as projects, experiments, and computer explorations, using real and simulated data. Additionally, they participated in group work, discussions, and a cross-cultural exchange of experiences and ideas. These activities facilitated the enhancement of participants' TPACK in statistics. As active practitioners, they subsequently applied their newfound knowledge and skills in real classroom settings [70].

The course followed a hybrid format, commencing with local teachers in each country who convened for a one-week intensive seminar. During this seminar, they were introduced to the course objectives and pedagogical framework, became familiar with the e-learning environment, and engaged in interactions with fellow teachers in their country. This in-person gathering helped mitigate issues of trust and social presence in the online environment [70]. The remainder of the course was conducted at-distance, using the project information base for teaching, support, and coordination purposes. Aside from delivering course content, the online platform granted access to a range of links and supplementary resources [70]. Moderated online discussions facilitated the exchange of ideas and instructional strategies among teachers, creating an environment conducive to addressing the intricacies of teaching statistics and applying educational theory to practice [74]. Synchronous communication was facilitated through technologies such as video-conferencing and audio/video streaming. Furthermore, one-way informational postings such as articles and videos served as supplementary resources to support interaction [70].

A follow-up classroom experimentation was conducted to assess the applicability and effectiveness of the course. The participating teachers designed and implemented teaching episodes that integrated the tools and resources provided in the course. Various

assessment methods were employed to gather evidence of changes in teachers' TPACK of statistics, their attitudes toward the subject, and their teaching practices resulting from participation in the professional development course [70]. These assessments included pre- and post-questionnaires, video recordings of classroom sessions, interviews with teachers and students, samples of student work, and statistical data automatically generated by the online information base. The analysis of the collected data guided the refinement of the course pedagogical framework, instructional materials, and curriculum, along with enhancements to the tools and resources available in the course platform [70].

Lessons Learned in Phase 2

The EarlyStatistics project facilitated the cultivation of intercultural awareness and the exchange of experiences and ideas among European educators. It provided a conducive environment wherein participants could collectively generate knowledge relevant to their professional lives. Through collaborative activities and discussions, educators not only engaged in the learning process but also reciprocally enriched each other's understanding of statistics while sharing effective pedagogical strategies. These interactions fostered the establishment of robust relationships and the formation of a supportive community dedicated to advancing best practices and innovation in statistical instruction. EarlyStatistics successfully achieved its objectives by enhancing educators' TPACK of statistics. It achieved this by offering interactive, technology-rich instructional resources and services that augmented the teaching and learning dynamics. Additionally, the program afforded participants the opportunity to collaborate with peers, laying the groundwork for the development of a community of practice. Furthermore, analysis of the multiple forms of data obtained from the teaching interventions in the participants' classrooms indicated notable improvements in both student learning outcomes and attitudes toward statistics [70,75].

Despite the overall success of EarlyStatistics, several shortcomings surfaced during the initial implementation of the course. The main challenge encountered by the consortium pertained to the establishment of a lively online community of teaching practitioners [70,75]. The participants' busy schedules and the diverse array of their cultural and professional backgrounds posed significant hurdles to the creation of a cohesive online community of practice. The EarlyStatistics team encountered analogous obstacles to those documented in [76], witnessing a notably lower level of learner-to-learner interaction than originally anticipated (for further elaboration, refer to [75]). An in-depth investigation of the collaborative endeavors and knowledge-sharing initiatives among teachers participating in the first delivery of EarlyStatistics enabled the identification of various factors that potentially hindered our efforts in online community cultivation. Leveraging these insights, we proceeded to revise the course by incorporating the design considerations and strategies tailored to foster the establishment of a vibrant online community conducive to professional growth among teachers. These revisions resulted in markedly improved outcomes in online community development in the subsequent iterations of the course (as detailed in [77]).

In summary, our implementation of EarlyStatistics yielded predominantly positive experiences and successful project outcomes, which culminated in the program receiving the 2009 Best Cooperative Project Award in Statistical Literacy, a distinction conferred biennially by the International Association of Statistics Education (IASE). However, despite the program's overall success, insights from the Phase 2 studies highlighted a limitation of the individual-oriented focus of the TPACK model guiding EarlyStatistics. Specifically, the model overlooked the social, organizational, and cultural factors influencing professional development, with many individual teachers potentially lacking institutional support to transfer what they learned through the program to their classroom practices. This realization prompted us to transition to Phase 3 of our research journey, where our focus has been on the promotion of local, school-based communities of practice.

4.3. Phase 3: Adopting a Systemic Approach to the Development of Teachers' TPACK

In our recent studies in mathematics education (e.g., [28,78]) and STEM/STEAM education (e.g., [79–81]), we have embraced a systemic approach to the exploration and augmentation of teachers' TPACK. Central to our approach is a heightened focus on the socially mediated contexts in which educators cultivate their TPACK skills (as highlighted in [28]). Phillips' re-contextualized TPACK has served as a guiding framework for the development of professional development initiatives in these studies [82]. This model acknowledges the socio-cultural factors influencing pedagogical technology practices and identity transformations while emphasizing the pivotal role of the context (such as the school or educational institution) in which the TPACK framework is applied [77].

Consistent with the revised TPACK model proposed by [82], our investigations during Phase 3 have expanded upon the foundational TPACK model by incorporating the elements of communities of practice [83] and school-based teacher development [84]. We have embraced a systemic, collaborative approach to professional development anchored within the school environment. This model emphasizes the comprehensive preparation and continuous involvement of all key stakeholders, including teachers, students, school management teams, and parents [28,78–81].

A good example of a study conducted during Phase 3 is the case study described in [28], which investigated the design and implementation of a two-year professional development program in a primary school in Cyprus, which was aimed at the seamless integration of tablet technologies into the mathematics curriculum for students aged 6–12. Employing a systemic approach to the introduction of tablets within the school environment, the program endeavored to equip teachers (n = 33) with the necessary knowledge, skills, and support mechanisms for the effective integration of mobile technologies into the mathematics curriculum design and instructional practices. Drawing upon the distinctive characteristics and requirements of the stakeholders and guided by the revised TPACK model [82], a series of school-based teacher professional development activities took place. These activities were designed to establish a robust support framework for tablet integration into the mathematics curriculum, fostering a constructivist social environment where teachers drove their professional growth amidst an environment rich in challenges, interactions, and collaborative endeavors. To strengthen the connection between the school and home environments and ensure secure and efficient tablet use, both on the school premises and at home, parents were also actively involved in the adoption process, receiving training and assistance, both prior to the introduction of mobile devices into the school and throughout the implementation phase. The [28] article describes the initial state of the utilization of portable devices within the school ecosystem, outlines the tablet integration process, and explores the self-reported reflections of a core team comprising six teachers (n = 6) on their professional development experiences within the program.

Lessons Learned in Phase 3

Through our utilization of Phillips' revised TPACK model across multiple studies [28,78–81], we have discerned that a community-oriented, school-wide approach to teacher enhancement yields superior outcomes compared to the more 'traditional' formats of professional development that the majority of teachers participate in, which tend to focus on individual and/or isolated forms of professional learning. In accord with the research literature [66], we have found that a systemic, school-based model of teacher professional learning tends to be more effective in providing a support system that motivates teachers to actively participate in and sustain their engagement in professional development activities, irrespective of their prior experience or expertise in the instructional use of technological tools. The integration of the socio-cultural context into teachers' professional development, coupled with the direct link to teaching practice, enhances the active engagement of teaching staff and other stakeholders and promotes a culture of dialog and mutual support.

In the [28] study, for example, the adoption of the revised TPACK framework significantly aided the smooth incorporation of mobile devices into the school setting and

supported teachers' professional learning. Insights from interviews with the core team of teachers highlighted the pivotal role of Phillips' revised TPACK framework [82] in the school's efforts to effectively integrate mobile devices. School-based professional learning activities were instrumental in nurturing a flexible, professional learning environment that encouraged cooperation among teachers with varied levels of expertise in educational technology and facilitated the exchange of knowledge, experiences, and best practices. Echoing findings in the existing research literature [85–89], the study underscored the importance of teachers' engagement in professional learning activities, such as lesson design and field experience (e.g., classroom teaching/co-teaching, classroom observation, and action research), for enhancing their teaching skills with ICT and deepening their understanding of TPACK in ways applicable to their own instructional practices. Aligned with prior scholarship [55,90,91], the study also affirmed the critical significance of school leadership in incentivizing teachers to proficiently apply their acquired TPACK competencies into their teaching practices. Teachers credited the strong support from the school management team as crucial to the professional development program's success. They also valued the specialized guidance provided by academic experts and mentors throughout the process, emphasizing the valuable role that an 'expert teacher' (a 'knowledgeable other') can play in school-based professional development [87]. Moreover, the participants noted that implementing a systemic approach to innovation, which entailed providing information and training support to parents as well, promoted parental engagement, thereby enhancing teachers' efforts to integrate tablets into mathematics instruction.

At the same time, in line with the findings of other researchers [82,90,92,93], we have also found that teachers exhibit varied responses to the same professional development opportunities. While the systemic professional development model we have employed in Phase 3 appears to be generally effective, not all involved teachers within a school automatically engage with the program or with each other. In the [28] study, despite unanimous positive attitudes towards mobile-enhanced mathematics instruction, actual levels of teacher participation and commitment varied. While some educators fully embraced the process, others participated peripherally during the first year of the program and were hesitant to enact significant changes in their teaching practices. Nevertheless, the school's persistent efforts to involve more staff members, which extended into the second year of program implementation, eventually succeeded. By the program's conclusion, tablets had been integrated into every mathematics classroom within the school and were also utilized in other subjects such as language learning and science.

The first author's collaboration with the school continued after the conclusion of the professional development program on mobile mathematics learning described in [28], albeit in a context outside mathematics education. Specifically, the school participated in the EU-funded project Living Book (Ref. No: 2016-1-CY01-KA201-017315), coordinated by the first author, and its ongoing follow-up project Readtwinning (Ref. #: 2019-1-IT02-KA201-063241). The systemic approach to teacher professional development was also adopted in Living Book, again with high success. The school's participation in Living Book was so successful, and the instructional exploitation of innovative technologies such as Augmented Reality so exemplary (for more details, see [80]), that the school was selected to receive the European Innovative Teaching Award in Primary Education in recognition of their outstanding teaching and learning practices.

In 2020, however, significant changes occurred within the school environment. Most of the teachers in the core team that had led the projects described in [28,80] relocated to different schools due to a regulation prohibiting public school teachers in Cyprus from remaining at the same school unit for more than six years. There was also a change in the school management team. The onset of the COVID-19 pandemic further exacerbated the situation, casting a shadow over the school's culture of innovation. Teachers' lack of prior training in online instruction and the substantial time they had to devote to become familiarized with the e-learning tools/applications employed during emergency remote teaching discouraged most of them from experimenting with innovative technologies such

as games, simulations, and virtual laboratories. Throughout the lockdown period, most teachers in the school reverted to utilizing e-learning resources and practices in a manner resembling traditional, teacher-centered instructional approaches observed in face-to-face classrooms, such as limiting technology use to PowerPoint presentations.

5. Discussion and Implications

This paper has explored our transformative learning journey into enacting the TPACK framework in our professional development initiatives, targeting mathematics teachers initially and STEM/STEAM teachers more recently. Through self-narrative, we have depicted our evolving self-awareness as researcher-practitioners who have utilized the TPACK model for the past 18 years. This insight has been gained through critical reflection, encompassing not only our successes but also the struggles and challenges we have encountered.

The conduct of retrospective autoethnographic research has deepened our comprehension of how our positionality has influenced our enactment of the TPACK model in our teacher professional development initiatives. It has enabled us to reflect on, reinterpret, and reconceptualize some of our personal and professional experiences and to relate them to the relevant research literature in mathematics education (and STEM/STEAM education in recent years). We do not seek to proclaim our emerging knowledge as scientific truth or a discovery beyond us. Instead, we regard it as a creative construction stemming from our experiences as practitioners and researchers in the field of teacher education on ICT-enhanced mathematics learning. Nevertheless, we do believe that our self-narrative offers useful insights for other researchers and/or practitioners in the STEM fields interested in adopting the TPACK framework.

Insights from the retrospective analysis align with the findings in the research literature, indicating that the utilization of a conceptually grounded theoretical framework like TPACK can significantly enhance teachers' professional learning [52]. Mishra and Koehler's TPACK framework [18] proves invaluable in the development of professional development programs for several reasons. Firstly, it serves as a useful framework for identifying the knowledge base required to teach a specific subject with technology. Secondly, it guides the understanding of the intersection of content, pedagogy, and technology knowledge domains, informing decisions related to curriculum and instructional practices. Lastly, it functions as a model to facilitate the evaluation of the impact of professional development initiatives on teachers' TPACK [3]. In STEM education, the TPACK framework can be instrumental in enhancing teachers' competencies to effectively integrate technological tools into instruction, thereby fostering students' mathematical and scientific reasoning as well as problem-solving skills. Additionally, Phillips' re-contextualized TPACK model [82], underscoring the significance of contextual factors, offers a robust framework for studying, developing, and evaluating teacher proficiency in applying newly acquired TPACK constructs within authentic school settings.

Our commitment to providing teachers with high-quality professional growth opportunities in ICT-enhanced learning remains ongoing, with our understanding of successful professional development continually evolving. While both the generic and Phillips' re-contextualized TPACK frameworks have proven useful, barriers to sustaining successful small-scale programs, as described in our retrospective autoethnographic research, have prompted us to acknowledge the need for the field to adopt further revised TPACK models of professional development that are tailored to promote school-based sustainability of educational innovation [55]. The COVID-19 pandemic and subsequent widespread school closures have heightened our awareness of the need for continuous professional development that will empower teachers to navigate uncertainty, adapt to evolving educational landscapes and technological advancements, respond to crises or emergencies, and effectively manage and drive change [21]. Of course, as stressed by [94], the need for teacher readiness to adapt to change does not imply that educators bear the sole responsibility for their professional development [21]. On the contrary, sustainable professional growth must be a shared responsibility of all key education stakeholders. This includes local

and national authorities, who must work synergistically to provide ongoing support for teachers' development of competencies and professional skills.

An essential step in designing and implementing sustainable professional development programs is to meticulously address and facilitate the factors conducive to long-term impact while mitigating the hindering factors [54]. Additionally, at the initial stage of professional development planning, it is imperative to incorporate opportunities for follow-up support into the program [54].

Much remains to be understood regarding the sustainability of teacher professional development initiatives, as research designs rarely allow for assessing whether short-term changes endure over time [66]. Only a small minority of studies on teacher professional development are longitudinal or include any follow-up after a program's completion to examine the long-term effects and changes in teaching practice [23]. As highlighted by the findings of the present study, future research should place greater emphasis on sustainability issues. It is imperative to investigate not only the initial implementation efforts of professional development initiatives but also the long-term impact of new, ICT-enhanced practices and interventions, along with the factors that facilitate or hinder their sustained use.

Research on the sustainability of professional development faces significant challenges, extending to the underlying theoretical concepts [54]. Sustainability, as evidenced in the literature and our experience, is dynamic and should be studied accordingly [95]. When assessing the long-term impact of professional development, one should anticipate adaptations, partial continuation, or integration with new environmental conditions rather than mere endurance [55,95]. It is essential to recognize that even successful initial implementation efforts may diminish over time due to various factors such as shifts in priorities, changes in resource availability, or contextual influences like teacher turnover and competing demands. Thus, an analysis of sustainable impact should not only focus on the effects planned at the program design stage but also explore the unintended consequences that may emerge over time [54]. Examining the long-term impact of professional development at organizational and systemic levels and utilizing models that adopt an ecological or complex-systems perspective to assess sustainability is crucial [66,95,96]. Despite the methodological challenges, it is imperative for STEM education researchers to explore ways to measure this impact, as systemic-level change is vital for fostering widespread improvements in STEM teaching and learning [96].

There are other important implications of our study for both STEM education practice and research. As illustrated through our self-narrative, self-reflection can serve as a valuable tool for the professional growth and development of teacher educators. Continuously engaging in reflective practices throughout all stages of their professional work and negotiating these experiences through the lens of theory [17,97] can offer STEM educators opportunities for an in-depth consideration and readdressing of issues of content and pedagogy with the use of technology [98]. Taking the time to reflect on one's own research can also be a meaningful learning process for STEM education researchers, enabling them to revisit their positions on research and practice, critically and transparently justify their chosen approach, and recognize how it may evolve over time.

Findings that emerge from autobiographical research can contribute to the wider STEM education community by providing insights into teacher educators' epistemologies and how these might impact their teacher education practices. While extensive research exists on various facets of teachers' professional development, very little is currently known about teacher educators [98]. Our experience from adopting the autobiographical approach to research has convinced us about the usefulness of autobiography as a research methodology that can help shed light on mathematics/STEM educators' knowledge and practices. We hope that the critical reflection we have presented in this article might invite other scholars to also engage in autobiographical research, exploring their learning journeys into STEM education research.

References

1. Amalu, E.H.; Short, M.; Chong, P.L.; Hughes, D.J.; Adebayo, D.S.; Tchuenbou-Magaia, F.; Lähde, P.; Kukka, M.; Polyzou, O.; Oikonomou, T.I.; et al. Critical skills needs and challenges for STEM/STEAM graduates increased employability and entrepreneurship in the solar energy sector. *Renew. Sustain. Energy Rev.* **2023**, *187*, 113776. [CrossRef]
2. Alkhawaldeh, A. School-based Teacher Training in Jordan: Towards On-school Sustainable Professional Development. *J. Teach. Educ. Sustain.* **2017**, *19*, 51–68. [CrossRef]
3. Hynes, B.; Costin, Y.; Richardson, I. Educating for STEM: Developing entrepreneurial thinking in STEM (Entre-STEM). In *Enhancing Entrepreneurial Mindsets Through STEM Education. Integrated Science*; Kaya-Capocci, S., Peters-Burton, E., Eds.; Springer: Cham, Switzerland, 2023; Volume 15, pp. 165–194. [CrossRef]
4. Nketsia, W.; Opoku, M.; Saloviita, T.; Tracey, D. Teacher Educators' and Teacher Trainees' Perspective on Teacher Training for Sustainable Development. *J. Teach. Educ. Sustain.* **2020**, *22*, 49–65. [CrossRef]
5. Wu, X.; Zhang, Y. Effects of individual attributes, family background, and school context on students' global competence: Insights from the OECD PISA 2018. *Int. J. Educ. Dev.* **2024**, *106*, 102996. [CrossRef]
6. Stringer, L.R.; Lee, K.M.; Sturm, S.; Giacaman, N. A systematic review of primary school teachers' experiences with digital technologies curricula. *Educ. Inf. Technol.* **2022**, *27*, 12585–12607. [CrossRef] [PubMed]
7. Segarra, V.A.; Natalizio, B.; Falkenberg, C.V.; Pulford, S.; Holmes, R.M. STEAM: Using the arts to train well-rounded and creative scientists. *J. Microbiol. Biol. Educ.* **2018**, *19*, 1128. [CrossRef]
8. Meletiou-Mavrotheris, M.; Mavrou, K.; Stylianou, G.; Mavromoustakos, S.; Christou, G. Teaching mathematics with tablet PCs: A professional development program targeting primary school teachers. In *Tablets in K-12 Education: Integrated Experiences and Implications*; An, H., Alon, S., Fuentes, D., Eds.; IGI Global: Hershey, PA, USA, 2015; pp. 322–344. [CrossRef]
9. Hiğde, E.; Aktamış, H. The effects of STEM activities on students' STEM career interests, motivation, science process skills, science achievement and views. *Think. Ski. Creat.* **2022**, *43*, 101000. [CrossRef]
10. Mystakidis, S.; Christopoulos, A.; Pellas, N. A systematic mapping review of augmented reality applications to support STEM learning in higher education. *Educ. Inf. Technol.* **2022**, *27*, 1883–1927. [CrossRef]
11. Thompson, G.; Harbaugh, A. A preliminary analysis of teacher perceptions of the effects of NAPLAN on pedagogy and curriculum. *Aust. Educ. Res.* **2013**, *40*, 299–314. [CrossRef]
12. Chng, E.; Tan, A.L.; Tan, S.C. Examining the Use of Emerging Technologies in Schools: A Review of Artificial Intelligence and Immersive Technologies in STEM Education. *J. STEM Educ. Res.* **2023**, *6*, 385–407. [CrossRef]
13. Durdu, L.; Dag, F. Pre-Service Teachers' TPACK Development and Conceptions through a TPACK-Based Course. *Aust. J. Teach. Educ.* **2017**, *42*, 150–171. [CrossRef]
14. Leavy, A.; Dick, L.; Meletiou-Mavrotheris, M.; Paparistodemou, E.; Stylianou, E. The prevalence and use of emerging technologies in STEAM education: A systematic review of the literature. *J. Comput. Assist. Learn.* **2023**, *39*, 1061–1082. [CrossRef]
15. Banas, J.; Polly, D. Instructional design and technology trends in teacher education: An AECT teacher education division special issue of TechTrends. *TechTrends* **2016**, *60*, 2–3. [CrossRef]
16. Wellington, A.; Easton, G.; Davis, J.P.; Yeh, A. Beat and rhythm: Teaching science via integrated STEAM and digital technologies. *Teach. Sci.* **2020**, *66*, 20–25.
17. Meletiou-Mavrotheris, M.; Prodromou, T. Pre-Service Teacher Training on Game-Enhanced Mathematics Teaching and Learning. *Technol. Knowl. Learn. TKNL* **2016**, *21*, 379–399. [CrossRef]
18. Mishra, P.; Koehler, M.J. Technological pedagogical content knowledge: A framework for teacher knowledge. *Teach. Coll. Rec.* **2006**, *108*, 1017–1054. [CrossRef]
19. Luguetti, C.; Oliver, K.L. A transformative learning journey of a teacher educator in enacting an activist approach in Physical Education Teacher Education. *Curric. J.* **2021**, *32*, 118–135. [CrossRef]
20. Krainer, K. Scaling up professional development: Chances and challenges. In *Educating the Educators: International Approaches to Scaling-Up Professional Development in Mathematics and Science Education, Proceedings of the Conference Hosted Jointly by Project Mascil (Mathematics and Science for Life) and the German Centre for Mathematics Education (DZLM), Essen, Germany, 15–16 December 2014*; Maaß, K., Barzel, B., Törner, G., Wernisch, D., Schäfer, E., Reitz-Koncebovski, K., Eds.; WTM-Verlag fur Wissenschaftliche Texte und Medien: Münster, Germany, 2015; pp. 96–110.

21. Mardapi, D.; Herawan, T. Community-based teacher training: Transformation of sustainable teacher empowerment strategy in Indonesia. *J. Teach. Educ. Sustain.* **2019**, *21*, 4866. [CrossRef]

22. Maaß, K.; Wernisch, D.; Reitz-Koncebovski, E.; Schäfer, E. Conference: Educating the educators. In *Educating the Educators: International Approaches to Scaling-Up Professional Development in Mathematics and Science Education, Proceedings of the Conference Hosted Jointly by Project Mascil (Mathematics and Science for Life) and the German Centre for Mathematics Education (DZLM), Essen, Germany, 15–16 December 2014*; Maaß, K., Barzel, B., Törner, G., Wernisch, D., Schäfer, E., Reitz-Koncebovski, K., Eds.; WTM-Verlag fur Wissenschaftliche Texte und Medien: Münster, Germany, 2015; pp. 5–10.

23. Hennessy, S.; D'Angelo, S.; McIntyre, N.; Koomar, S.; Kreimeia, A.; Cao, L.; Brugha, M.; Zubairi, A. Technology use for teacher professional development in low-and middle-income countries: A systematic review. *Comput. Educ. Open* **2022**, *3*, 100080. [CrossRef]

24. Ertmer, P.A.; Ottenbreit-Leftwich, A.T.; Sadik, O.; Sendurur, E.; Sendurur, P. Teacher beliefs and technology integration practices: A critical relationship. *Comput. Educ.* **2012**, *59*, 423–435. [CrossRef]

25. Hill, J.E.; Uribe-Florez, L. Understanding secondary school teachers' TPACK and technology implementation in mathematics classrooms. *Int. J. Technol. Educ.* **2020**, *3*, 1–13. [CrossRef]

26. Hiebert, J. *Conceptual and Procedural Knowledge: The Case of Mathematics*; Routledge: New York, NY, USA, 2012.

27. Lavicza, Z.; Weinhandl, R.; Prodromou, T.; Anđić, B.; Lieban, D.; Hohenwarter, M.; Fenyvesi, K.; Brownell, C.; Diego-Mantecón, J.M. Developing and Evaluating Educational Innovations for STEAM Education in Rapidly Changing Digital Technology Environments. *Sustainability* **2022**, *14*, 7237. [CrossRef]

28. Meletiou-Mavrotheris, M.; Paparistodemou, E.; Christou, C.M. Integrating Mobile Devices in the Mathematics Curriculum: A Case Study of a Primary School in Cyprus. *Int. J. Mob. Blended Learn.* **2019**, *11*, 19–37. [CrossRef]

29. Alalwan, N.; Cheng, L.; Al-Samarraie, H.; Yousef, R.; Alzahrani, A.; Sarsam, S. Challenges and prospects of virtual reality and augmented reality utilization among primary school teachers: A developing country perspective. *Stud. Educ. Eval.* **2020**, *66*, 100876. [CrossRef]

30. Wijnen, F.; Walma van der Molen, J.; Voogt, J. Primary school teachers' attitudes toward technology use and stimulating higher-order thinking in students: A review of the literature. *J. Res. Technol. Educ.* **2023**, *55*, 545–567. [CrossRef]

31. Meletiou-Mavrotheris, M.; Mavrou, K.; Rebelo, P.V. The Role of Learning and Communication Technologies in Online Courses' Design and Delivery: A Cross-National Study of Faculty Perceptions and Practices. *Front. Educ.* **2021**, *6*, 558676. [CrossRef]

32. Sanders, M.; George, A. Viewing the changing world of educational technology from a different perspective: Present realities, past lessons, and future possibilities. *Educ. Inf. Technol.* **2017**, *22*, 1–19. [CrossRef]

33. Stroud, A.; Baines, L. Inquiry, Investigative Processes, Art, and writing in STEAM. In *STEAM Education, Theory and Practice*; Swe Khine, M., Areepattamannil, S., Eds.; Springer Nature: Cham, Switzerland, 2019; pp. 9–26. [CrossRef]

34. Haydn, T.A.; Barton, R. Common needs and different agendas: How trainees make progress in their ability to use ICT in subject teaching. Some lessons from the UK. *Comput. Educ.* **2007**, *49*, 1018–1036. [CrossRef]

35. Cheng, H.J.; Zhan, H. Examining pre-service teachers' instructional strategies for technological pedagogical content knowledge via video-conferencing. *J. Educ. Technol. Dev. Exch.* **2012**, *5*, 57–76. [CrossRef]

36. Huang, B.; Jong, M.S.Y.; Tu, Y.F.; Hwang, G.J.; Chai, C.S.; Jiang, M.Y.C. Trends and exemplary practices of STEM teacher professional development programs in K-12 contexts: A systematic review of empirical studies. *Comput. Educ.* **2022**, *89*, 104577. [CrossRef]

37. Shulman, L.S. Those who understand: Knowledge growth in teaching. *Educ. Res.* **1986**, *15*, 4–14. [CrossRef]

38. Harris, J.; Mishra, P.; Koehler, M. Teachers' technological pedagogical content knowledge and learning activity types: Curriculum-based technology integration reframed. *J. Res. Technol. Educ.* **2009**, *41*, 393–416. [CrossRef]

39. Koh, J.H.L. TPACK design scaffolds for supporting teacher pedagogical change. *Educ. Technol. Res. Dev.* **2019**, *67*, 577–595. [CrossRef]

40. Lee, C.J.; Kim, C. An implementation study of a TPACK-based instructional design model in a technology integration course. *Educ. Technol. Res. Dev.* **2014**, *62*, 437–460. [CrossRef]

41. Wang, W.; Schmidt-Crawford, D.; Jin, Y. Preservice Teachers' TPACK Development: A Review of Literature. *J. Digit. Learn. Teach. Educ.* **2018**, *34*, 234–258. [CrossRef]

42. Zhang, W.; Tang, J. Teachers' TPACK Development: A Review of Literature. *Open J. Soc. Sci.* **2021**, *9*, 367–380. [CrossRef]

43. Chai, C.S.; Koh, J.H.L.; Tsai, C.C. Facilitating preservice teachers' development of technological, pedagogical, and content knowledge (TPACK). *J. Educ. Technol. Soc.* **2010**, *13*, 63–73.

44. Chai, C.S.; Rahmawati, Y.; Jong, M.S.Y. Indonesian science, mathematics, and engineering preservice teachers' experiences in STEM-TPACK design-based learning. *Sustainability* **2020**, *12*, 9050. [CrossRef]

45. Drijvers, P.; Tacoma, S.; Besamusca, A.; Doorman, M.; Boon, P. Digital resources inviting changes in mid-adopting teachers' practices and orchestrations. *ZDM-Int. J. Math. Educ.* **2013**, *45*, 987–1001. [CrossRef]

46. Kajonmanee, T.; Chaipidech, P.; Srisawasdi, N.; Chaipah, K. A Personalised mobile learning system for promoting STEM discipline teachers' TPACK development. *Int. J. Mob. Learn. Organ.* **2020**, *14*, 215–235. [CrossRef]

47. Karampelas, K. Examining the relationship between TPACK and STEAM through a bibliometric study. *Eur. J. Sci. Math. Educ.* **2023**, *11*, 488–498. [CrossRef]

48. Yildiz Durak, H.; Atman Uslu, N.; Canbazoğlu Bilici, S.; Güler, B. Examining the predictors of TPACK for integrated STEM: Science teaching self-efficacy, computational thinking, and design thinking. *Educ. Inf. Technol.* **2023**, *28*, 7927–7954. [CrossRef]

49. Parker, C.E.; Stylinski, C.D.; Bonney, C.R.; Schillaci, R.; McAulliffe, C. Examining the quality of technology implementation in STEM classrooms: Demonstration of an evaluative framework. *J. Res. Technol. Educ.* **2015**, *47*, 105–121. [CrossRef]

50. Pondee, P.; Panjaburee, P.; Srisawasdi, N. Preservice science teachers' emerging pedagogy of mobile game integration: A tale of two cohorts improvement study. *Res. Pract. Technol. Enhanc. Learn.* **2021**, *16*, 16. [CrossRef]

51. Srisawasdi, N. Fostering pre-service STEM teachers' technological pedagogical content knowledge: A lesson learned from case-based learning approach. *J. Korean Assoc. Sci. Educ.* **2012**, *32*, 1356–1366. [CrossRef]

52. Chai, C.S. Teacher professional development for science, technology, engineering and mathematics (STEM) education: A Review from the perspectives of technological pedagogical content (TPACK). *Asia-Pac. Educ. Res.* **2019**, *28*, 5–13. [CrossRef]

53. Meesuk, P.; Wongrusa, A.; Wangkaewhiran, T. Sustainable teacher professional development through professional learning community: PLC. *J. Teach. Educ. Sustain.* **2021**, *23*, 30–44. [CrossRef]

54. Zehetmeier, S.; Krainer, K. Ways of promoting the sustainability of mathematics teachers' professional development. *ZDM Math. Educ.* **2011**, *43*, 875–887. [CrossRef]

55. Tirosh, D.; Tsamir, P.; Levenson, E. Fundamental issues concerning the sustainment and scaling up of professional development programs. *ZDM Math. Educ.* **2015**, *47*, 153–159. [CrossRef]

56. Fullan, M. The future of educational change: System thinkers in action. *J. Educ. Chang.* **2006**, *7*, 113–122. [CrossRef]

57. Bell, D.; Canham, H.; Dutta, U.; Fernandez, J.S. Retrospective Autoethnographies: A Call for Decolonial Imaginings for the New University. *Qual. Inq.* **2020**, *26*, 849–859. [CrossRef]

58. Dyson, M. My Story in a Profession of Stories: Auto Ethnography—An Empowering Methodology for Educators. *Aust. J. Teach. Educ.* **2007**, *32*, 36–48. [CrossRef]

59. Charleson, D. *Filmmaking as Research: Screening Memories*; Palsgrave: London, UK, 2019. [CrossRef]

60. Ellis, C.; Adams, T.E.; Bochner, A.P. Autoethnography: An overview. *Hist. Soc. Res./Hist. Sozialforschung* **2011**, *12*, 345–357. [CrossRef]

61. Aboloson, K.; Willet, C. Putting ourselves forward: Location in aboriginal research. In *Research as Resistance: Critical, Indigenous, and Anti-Oppressive Approaches*; Brown, L., Strega, S., Eds.; Canadian Scholar's Press: Toronto, ON, Canada, 2005; pp. 97–126.

62. Anderson, L. Analytic Autoethnography. *J. Contemp. Ethnogr.* **2006**, *35*, 373–395. [CrossRef]

63. Bull, J.R. Research with Aboriginal peoples: Authentic relationships as a precursor to ethical research. *J. Empir. Res. Hum. Res. Ethics* **2010**, *5*, 13–22. [CrossRef]

64. Mavrotheris, E.; Meletiou-Mavrotheris, M.; Maouri, C. Towards a more constructive use of technology in mathematics and science. In Proceedings of the 1st International Conference on Information & Communication Technologies, ICTTA, Damascus, Syria, 23 April 2004; pp. 115–116.

65. Meletiou-Mavrotheris, M.; Paparistodemou, E.; Stylianou, D. Enhancing Statistics Instruction in Elementary Schools: Integrating Technology in Professional Development. *Mont. Math. Enthus.* **2009**, *6*, 57–78. [CrossRef]

66. Goos, M.; Bennison, A.; Proffitt-White, R. Sustaining and scaling up research-informed professional development for mathematics teachers. *Math. Teach. Educ. Dev.* **2018**, *20*, 133–150.

67. Song, M.J. Teacher professional development in integrating digital fabrication technologies into teaching and learning. *Educ. Media Int.* **2021**, *58*, 317–334. [CrossRef]

68. Trust, T.; Horrocks, B. 'I never feel alone in my classroom': Teacher professional growth within a blended community of practice. *Prof. Dev. Educ.* **2017**, *43*, 645–665. [CrossRef]

69. Weinberg, A.E.; Balgopal, M.M.; Sample McMeeking, L.B. Professional Growth and Identity Development of STEM Teacher Educators in a Community of Practice. *Int. J. Sci. Math. Educ.* **2021**, *19* (Suppl. S1), 99–120. [CrossRef]

70. Chadjipadelis, T.; Meletiou-Mavrotheris, M.; Paparistodemou, E. Statistics teacher of the new era: Another specialized mathematician or a totally different person? In *Data and Context in Statistics Education: Towards an Evidence-Based Society, Proceedings of the Eighth International Conference on Teaching Statistics (ICOTS8)*; Reading, C., Ed.; International Statistical Institute: Voorburg, The Netherlands, 2010; pp. 1–6.

71. Kelley, T.R.; Knowles, J.G.; Holland, J.D.; Han, J. Increasing high school teachers' self-efficacy for integrated STEM instruction through a collaborative community of practice. *Int. J. STEM Ed.* **2020**, *7*, 14. [CrossRef]

72. Pepin, B.; Gueudet, G.; Trouche, L. Investigating textbooks as crucial interfaces between culture, policy and teacher curricular practice: Two contrasted case studies in France and Norway. *ZDM* **2013**, *45*, 685–698. [CrossRef]

73. Visnovska, J.; Cobb, P. Learning about whole-class scaffolding from a teacher professional development study. *ZDM* **2015**, *47*, 1133–1145. [CrossRef]

74. Kayler, M.; Weller, K. Pedagogy, self-assessment, and online discussion groups. *J. Educ. Technol. Soc.* **2007**, *10*, 136–147.

75. Meletiou-Mavrotheris, M.; Paparistodemou, E.; Mavrotheris, E.; AzcArate, P.; Serradó, A.; Cardenoso, J.M. Teachers' professional development in statistics: The early statistics European project. In *Joint ICMI/IASE Study: Teaching Statistics in School Mathematics—Challenges for Teaching and Teacher Education, Proceedings ICMI Study*; Batanero, C., Burrill, G., Reading, C., Rossman, A., Eds.; IASE: Monterrey, Mexico, 2008; pp. 1–6.

76. Gould, R.; Peck, R. Inspiring secondary statistics. *MSOR Connect.* **2005**, *5*, 1–3. [CrossRef]

77. Meletiou-Mavrotheris, M.; Serradó, A. Distance education of statistics teachers. In *Teaching Statistics in School Mathematics-Challenges for Teaching and Teacher Education*; New ICMI Study Series; Batanero, C., Burrill, G., Reading, C., Eds.; Springer: Dordrecht, The Netherlands, 2011; Volume 14, pp. 383–394. [CrossRef]
78. Kyriakides, A.; Meletiou-Mavrotheris, M. When robot A.L.E.X. trains teachers how to teach mathematics. In *Using Mobile Technologies in the Learning of Mathematics*; Calder, N., Larkin, K., Sinclair, N., Eds.; Springer: Cham, Switzerland, 2018; pp. 69–90. [CrossRef]
79. Lasica, I.-E.; Meletiou-Mavrotheris, M.; Katzis, K. Augmented Reality in Lower Secondary Education: A Teacher Professional Development Program in Cyprus and Greece. *Educ. Sci.* **2020**, *10*, 121. [CrossRef]
80. Meletiou-Mavrotheris, M.; Carrilho, A.R.; Charalambous, C.; Mavrou, K.; Christou, C. Teacher Training for 'Augmented Reading': The Living Book Approach and Initial Results. *Educ. Sci.* **2020**, *10*, 144. [CrossRef]
81. Vekiri, I.; Meletiou-Mavrotheris, M.; Brouzou, A.; Brouzos, I.; Christoforou, A.; Stylianou, E. Adopting a role-model, game-based pedagogical approach to gender equality in STEAM: The FemSTEAM mysteries digital game. In *Handbook of Research on Integrating ICTs in STEAM Education*; Xefteris, S., Ed.; IGI Global: Hershey, PA, USA, 2022; pp. 41–60. [CrossRef]
82. Phillips, M. Re-contextualising TPACK: Exploring teachers' (non)use of digital technologies. *Technol. Pedagog. Educ.* **2016**, *25*, 555–571. [CrossRef]
83. Wenger, E. *Communities of Practice: Leaning, Meaning, and Identity*; Cambridge University Press: Cambridge, UK, 1998.
84. McLaughlin, M.W.; Talbert, J.E. *Building School-Based Teacher Learning Communities: Professional Strategies to Improve Student Achievement*; Teachers College Press: New York, NY, USA, 2006.
85. Aykan, A.; Yıldırım, B. The Integration of a Lesson Study Model into Distance STEM Education during the COVID-19 Pandemic: Teachers' Views and Practice. *Technol. Know. Learn.* **2022**, *27*, 609–637. [CrossRef]
86. Lau, M.; Multani, S. Engineering STEM teacher learning: Using a museum-based field experience to foster STEM teachers' Pedagogical content knowledge for engineering. In *Pedagogical Content Knowledge in STEM. Advances in STEM Education*; Uzzo, S., Graves, S., Shay, E., Harford, M., Thompson, R., Eds.; Springer: Cham, Switzerland, 2023; pp. 165–194. [CrossRef]
87. Jones, K.; Pepin, B. Research on mathematics teachers as partners I in task design. *J. Math. Teach. Educ.* **2016**, *19*, 105–121. [CrossRef]
88. Scott, A.; Clarkson, P.; McDonough, A. Professional learning and action research: Early career teachers reflect on their practice. *Math. Educ. Res. J.* **2012**, *24*, 129–151. [CrossRef]
89. Visnovska, J.; Cobb, P. Classroom video in teacher professional development program: Community documentational genesis perspective. *ZDM* **2013**, *45*, 1017–1029. [CrossRef]
90. Buffone, R. Teaching Teachers to Write: A Distributive Leadership Approach to Professional Development. Ph.D. Thesis, University of Pittsburgh, Pittsburgh, PA, USA, 2017, *unpublished*.
91. Dexter, S.; Richardson, J.W. What does technology integration research tell us about the leadership of technology? *J. Res. Technol. Educ.* **2020**, *52*, 17–36. [CrossRef]
92. Goldsmith, L.T.; Doerr, H.M.; Lewis, C.C. Mathematics teachers' learning: A conceptual framework and synthesis of research. *J. Math. Teach. Educ.* **2014**, *17*, 5–36. [CrossRef]
93. Sancar, R.; Atal, D.; Deryakulu, D. A new framework for teachers' professional development. *Teach. Teach. Educ.* **2021**, *101*, 103305. [CrossRef]
94. Mercer-Mapstone, L.; Fatnowna, T.; Ross, P.; Bricknell, L.; Mude, W.; Wheat, J.; Barone, R.P.; Martinez, D.E.; West, D.; Gregory, S.J.; et al. *Recommendations for Equitable Student Support during Disruptions to the Higher Education Sector: Lessons from COVID-19*; National Centre for Student Equity in Higher Education, Curtin University: Bentley, Australia, 2022.
95. Wiltsey Stirman, S.; Kimberly, J.; Cook, N.; Calloway, A.; Castro, F.; Charns, M. The sustainability of new programs and innovations: A review of the empirical literature and recommendations for future research. *Implement. Sci* **2012**, *7*, 17. [CrossRef]
96. Beswick, K.; Anderson, J.; Hurst, C. The education and development of practising teachers. In *Research in Mathematics Education in Australasia 2012–2015*; Makar, K., Dole, S., Visnovska, J., Goos, M., Bennison, A., Fry, K., Eds.; Springer Science+Business Media: Singapore, 2016; pp. 329–352. [CrossRef]
97. Schön, D.A. *Educating the Reflective Practitioner*; Jossey-Bass: Oxford, UK, 1987.
98. Psycharis, G.; Kalogeria, E. Studying the process of becoming a teacher educator in technology-enhanced mathematics. *J. Math. Teach. Educ.* **2017**, *21*, 631–660. [CrossRef]