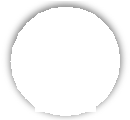
Asia-Pacific Edu Res <https://doi.org/10.1007/s40299-018-0400-7>

REGULAR ARTICLE



Teacher Professional Development for Science, Technology, Engineering and Mathematics (STEM) Education: A Review from the Perspectives of Technological Pedagogical Content (TPACK)

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Abstract This review identifies 20 studies pertaining to teacher professional development for STEM education. Using a mixture of content analysis with reference to the TPACK framework, and open and axial coding, a descriptive model was constructed. The model describes the connection of the various categories of variables associated with teacher professional development for STEM. How content, pedagogy, and technology are fea- tured in current STEM research are treated as properties of the core phenomenon of teacher professional development for STEM. Design considerations for future research are presented. The study recommends that design thinking, epistemic fluency and technological pedagogical engi- neering knowledge could be the anchors of future research.

Keywords Teacher professional development · STEM ·

Technological pedagogical content knowledge

# Introduction

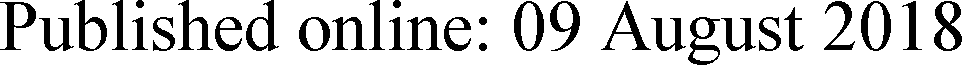
Science, Technology, Engineering and Mathematics (STEM) are closely interrelated content areas. One way to understand the complex interrelationships is in the context of solving real-world problems. Engineering is the disci- pline that applies scientific knowledge and mathematical computation to design processes or products (i.e. tech- nologies) to address the problems (Brophy et al. [2008](#_bookmark16)).

Technologies in turn are used to facilitate scientific and mathematical knowledge advancement and engineering design. Having sufficient STEM knowledge, and the ability to integrate these knowledge resources to design solutions for emerging problems, is the core competency sorted by most society. The collective competency of a society to create STEM knowledge determines its status in the world. Thus, there is surging interest in integrative STEM edu- cation (Sanders [2009](#_bookmark17); Hoeg and Bencze [2017](#_bookmark16)). One implication of such recognition would be the need to cul- tivate teachers who are knowledgeable in STEM subjects and engineering design. Teacher education, however, usually focuses on one or two subject matter except for primary education, and curriculum studies are subject specific. In addition, teachers are not familiar with engi- neering content or processes (Nadelson et al. [2013](#_bookmark10)). There is consequently a clear need for professional development. Teacher professional development (TPD) is well rec- ognized as the corner stone of all kinds of education reform (Desimone [2009](#_bookmark16); Fore et al. [2015](#_bookmark1); Guskey [2002](#_bookmark16)). How- ever, recent publications lament the lack of research in STEM-TPD (Al Salami et al. [2017](#_bookmark11); Cavlazoglu and Stuessy [2017](#_bookmark15)). Given its importance, the lack of research in TPD to date is puzzling. Nonetheless, this review attempts to consolidate what have been researched using the tech- nological pedagogical and content knowledge (TPACK) framework as a lens to construct a descriptive theory

highlighting noteworthy findings.

Pedagogical content knowledge (PCK) (Shulman [1986](#_bookmark18))

has been proposed as the quintessential teacher’s profes-

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sional knowledge. PCK is constituted through teacher’s ability to integrate pedagogical knowledge and content knowledge such that the content knowledge becomes accessible to students. More recently, the framework has been expanded to include technology, namely TPACK, and

it is regarded as the new model of teachers’ expertise for the 21st century classroom (Mishra and Koehler [2006](#_bookmark16)). If technologies need to be integrated in today classroom, its importance in STEM education is even more acute. Almost all contemporary STEM professionals need to master some form of profession-specific technologies. For example, biologist needs to master bioinformatics and engineers need to be trained in computer-assisted design. In the TPACK framework, these technologies can be regarded as technological content knowledge (TCK). Integral to both TPACK and STEM education is technology. It is now commonly accepted that teachers need to develop TPACK to integrate technology and it seems likely that STEM education would require teachers to activate and expand their TPACK for STEM lesson design. In addition, TPACK and STEM are both targeted at developing students’ 21st century capacities (Mishra and Koehler [2006](#_bookmark16); Hoeg and Bencze [2017](#_bookmark16)). Parker et al. ([2015b](#_bookmark19)) have associated teachers’ TPACK with STEM and argued that these two fields of study need integration. Thus, this study employs the TPACK framework to examine the technology, peda- gogy and content that current STEM-TPD is targeting at. This effort may foster connections between the fields which is necessary to advance STEM-TPD and could contribute to a composite framework to analyse the quality of STEM-TPD.

# Data/Article Sourcing and Analysis

To understand the state of research on STEM-TPD, the researcher first searched for empirical studies in the Web of Science, limiting the search to journals included in the social science citation index only. Using broad search terms ((‘‘STEM education’’ AND/OR ‘‘Science, Technol- ogy, Engineering and Mathematics’’) AND ‘‘teacher pro- fessional development’’) yielded only three intervention studies (Cavlazoglu and Stuessy [2017](#_bookmark15); Fore et al. [2015](#_bookmark1); Al Salami et al. [2017](#_bookmark11)) in September 2017. This echoes Cavlazoglu and Stuessy’s ([2017](#_bookmark15)) lament. The search was repeated and broaden using the same terms in Web of Science with the inclusion of all indexes such as science citation index, expanded science citation index at the end of March 2018. Twenty-three articles surfaced. Similar search was performed on Scopus database with 21 returns. After removing repeated entries, the article abstracts were read and when in doubt, the whole article was read. Excluded are articles that are non-English and those that research foci are student’s learning or those that uses STEM as a categorical label for teachers (e.g. science and mathematics teachers) but did not study STEM-TPD. In all, 20 articles were retained for further analysis.

The articles were coded using Chai et al.’s ([2013](#_bookmark16)) pro- cedures of systematic review for TPACK, identifying the specific description about technologies employed, peda- gogical/theoretical foundation for the professional devel- opment, and the content foci. Concurrently, the author also employed open coding and memoing (Strauss and Corbin [1998](#_bookmark20)) to capture other important points. For example, issues or problems such as ‘‘low achievement in STEM’’, ‘‘students’ misconceptions’’ and the ‘‘need for 21st cen- tury’’ were identified through open codes. The labels in Fig. [1](#_bookmark0) also reflect some of the codes used. After the coding, the codes were categorized and organized using axial coding to construct a descriptive theory-in-practice that reflects the state of research for STEM-TPD. As the codes were generally based on published articles, the following report can be assessed for its accuracy. Several guiding questions were formulated to guide the review:

1. What are the notable trends of research in STEM- TPD?
2. What are the rationales for the conduct of STEM- TPD?
3. What are the pedagogical/theoretical foundations of teacher professional development for STEM?
4. What are the content foci?
5. What are the roles of technology?
6. What are the contextual constraints, concerns and barriers that shape the intervention and research?

# Limitations

This review is limited by the databases it employed, which are Web of Science and Scopus. These databases are important databases commonly used for university ranking. They are more likely to surface rigorous research for international readers. Nonetheless, the researcher is aware that there are other rigorous studies conducted in places such as China and Korea, which could be reported in their respective native languages. There are also good studies in journals not included in the two databases. Future research can therefore expand the search of literature pertaining to STEM-TPD and compare the findings with this study.

# Findings

The Theory-in-Practice of STEM-TPD

Axial coding (Strauss and Corbin [1998](#_bookmark20)) was performed to synthesize the emerging practice of current STEM-TPD. Figure [1](#_bookmark0) provides an overview of STEM-TPD which emerged through axial coding. The figure depicts

**Causal conditions: Rhetorical rationale reported by the studies**

**Technology driven world; Economic competitiveness; job market need; students’ performance in mathematics and science**

**Intervening contextual conditions**

**Demands of New Standards Time: to learn, design and teach**

**Expertise: Lack of engineering/ science knowledge**

**Access: Technologies and facilities Resources: teaching materials**

**Support: from experts, leaders, community Student readiness**

**Properties: Pedagogical/theoretical Duration**

**Content foci TPD processes Community Technologies**

**Forms: university-school partnership/ university courses/ STEM communities/ outreach programs**

**Core Phenomenon**

**STEM-TPD**

**Dimension:**

**Not reported--- multiple Hours---year**

**Topic specific subject specific**

**Acquisition–development—refinement Weak strong**

**Absence dominance**

**Perceptions: efficacy, willingness; conceptions** **Processes: teacher noticing;**

**Performances: rated classroom observations Products: lesson design, digital resources**

**Action taken: inclusion of engineering professionals, community, creating outreach programs with materials; visit to STEM organization; resource sharing**

**Action needed: policy, recognition, funding**

**Outcomes**

**Interactions**

Fig. 1 STEM-TPD theory-in-practice

interrelated sets of categories. It includes the rationales that prompt the STEM-TPD efforts and the contextual condi- tions that the STEM-TPD operates in. These backgrounds shape the forms of STEM-TPD, which constitute the core phenomenon with its properties and dimensions. The properties of the core phenomenon are the content foci, pedagogical approaches, the role of community and tech- nologies and the TPD processes. Specific actions were taken to address the contextual conditions. These inter- acting categories lead to the outcomes of the STEM-TPD. The findings that emerged are organized and presented based on Fig. [1](#_bookmark0). Relevant issues are discussed at the end of each section.

General Research Trends in STEM-TPD Education

Before moving into the details, general research trends of STEM-TPD should be accounted. First, research pertaining to STEM-TPD are mostly based in the United State (*N* = 17). Other sites of research are Australia, Korea and United Kingdom with one article, respectively. There is a slow upward trend in this area of research from 2011 (*N* = 1) to 2017 (*N* = 5) with more sophisticated theoreti- cal framework and research methodology being employed (e.g. Al Salami et al. [2017](#_bookmark11); Cavlazoglu and Stuessy [2017](#_bookmark15); Fore et al. [2015](#_bookmark1)). Most studies were directed at junior to senior high school teachers except for three studies on elementary teachers (Nadelson et al. [2013](#_bookmark10); Parker et al.

[2015a](#_bookmark19); Radloff and Guzey [2017](#_bookmark19)). Nadelson et al. ([2013](#_bookmark10)) argue that it is important to start STEM education at the elementary schools from the perspective of addressing misconceptions and young learners’ interest in creating. This implies that there is insufficient research of STEM- TPD especially for elementary teachers. Radlof and Guzey ([2017](#_bookmark19)) is the only study that focuses on preservice teacher, which is another area for concern.

The highest number of research approach employed is mixed method (*N* = 10), followed by qualitative (*N* = 6), quantitative (*N* = 2) and two reports did not explicitly report their method. Except for the two reports (MacLeish et al. [2011](#_bookmark12), [2012](#_bookmark13)) and two other studies (Granucci et al.

[2017](#_bookmark5); Whannel and Tobias [2015](#_bookmark19)), the rest of the studies are small sample (*N* B 30) studies. In addition, none of the studies can qualify as experimental study. The general trend reflects the general lack of high-quality study.

Rationale

The rationale articulated for the conduct of the STEM-TPD seems to focus mostly on the need to be competitive in the technology-driven global economy. The intrinsic peda- gogical value of STEM education in developing human capacities to serve others was not reported at all. The general rhetoric is that current socioeconomic landscape compels all economic entities to have substantial number of people to work in STEM-related fields. Unfortunately,

students’ motivation, interest and/or achievement to study STEM-related subjects are declining (see e.g. Al Salami et al. [2017](#_bookmark11); Cavlazoglu and Stuessy [2017](#_bookmark15); Kovarik et al. [2013](#_bookmark8)). This forms the broad background and the casual conditions for most studies.

Accordingly, new standards such as the Next Generation Science Standards (NGSS) have been drafted for K-12 education (see Hoeg and Bencze [2017](#_bookmark16)) to remedy the sit- uation. The new standards surface gaps in teachers’ knowledge and skills which lead to the need for STEM- TPD. However, in the design of STEM-TPD workshops or activities, the teacher educators need to consider the context.

Contextual Barriers of STEM Education

Overall, STEM-TPD is challenging to design as the teacher educators have to address numerous contextual barriers that constitute the intervening contextual conditions. These contextual conditions shape the forms and content of the STEM-TPD. Jho et al. ([2016](#_bookmark7)) reported some difficult conditions that teachers faced in Korea, which seems generalizable elsewhere though with different degrees and effects. Teachers may lack subject matter knowledge and face difficulty in communication in cross-disciplinary context. Teachers also lack time and expertise to design and implement STEM curriculum. Resources such as teaching materials or access to advanced technologies may be lacking (Granucci et al. [2017](#_bookmark5); Radloff and Guzey [2017](#_bookmark19)). The supports and recognition for doing STEM may also need attention (Aslam et al. [2018](#_bookmark14); Kisiel [2014](#_bookmark9)). Teachers are also commonly concerned about students’ readiness. The current facilitating condition is that STEM is recog- nized as important with some policy articulated and fund- ing provided. The availability of Information and Communication Technologies (ICT) has also facilitated communications and collaboration for community-based learning (Jho et al. [2016](#_bookmark7)). Depending on the contextual barriers and affordances that the researchers believed they are faced with, various forms of STEM-TPD were implemented.

STEM-TPD (Core Phenomenon)

Given the dynamic advancement of engineering and the diverse conditions, STEM-TPD takes many forms and pedagogical approaches to address the different needs. STEM-TPD can be described with a set of common properties with some variations in its dimensions. Building content knowledge, especially engineering knowledge seems to be the main concern.

Content Foci

The content foci reported are widespread and their links to current school curricular are not clear. Engineering emerged as the key content focus and science is the most common school subject in which STEM is integrated. Engineering is obviously not a core subject in K-12 cur- riculum. Teachers are unlikely to be taught in interdisci- plinary context or taught engineering design (Nadelson et al. [2013](#_bookmark10); Singer et al. [2016](#_bookmark19)). With engineering chal- lenges emerging as the foci for many STEM education initiatives, the lack of engineering knowledge and engi- neering design processes becomes the content foci in many STEM-TPD. The engineering topics covered in the reviewed studies include biomedical, earthquake, nanoscience, material science, engineering in healthcare and agricultural engineering, respectively (e.g. Al Salami et al. [2017](#_bookmark11); Cavlazoglu and Stuessy [2017](#_bookmark15); Fore et al. [2015](#_bookmark1); Granucci et al. [2017](#_bookmark5); Singer et al. [2016](#_bookmark19); Whannell and Tobias [2015](#_bookmark19)). The lack of knowledge and expertise in engineering is usually addressed by employing engineering faculty or practicing engineers to teach and coach the teachers, organization of field trips to laboratories or industries and the use of pre-developed curriculum mate- rials and simulations to support the teachers (Al Salami et al. [2017](#_bookmark11); Cavlazoglu and Stuessy [2017](#_bookmark15); Faber et al. [2014](#_bookmark2); Granucci et al. [2017](#_bookmark5); Hardre et al. [2014](#_bookmark6); Kovarik et al. [2013](#_bookmark8); Singer et al. [2016](#_bookmark19)). For example, Faber et al. ([2014](#_bookmark2)) adopted the internship model for teachers to work in biomedical and engineering fibres and films centres as scientists supported by the faculty. Science is apparently the anchoring subjects for STEM education in K-12 setting (Clark et al. [2015](#_bookmark3)). However, the engineering topics listed above, though important, seem to be remotely connected to school curricular and the sustainability of these studies conducted through university–school partnerships is questionable.

Except for Fore et al. ([2015](#_bookmark1)) which mentioned the cal- culation of nanometre surface area, how mathematics was addressed seems rather obscure. English ([2017](#_bookmark16)) has high- lighted the issue of equitable representation of subject matter. When mathematics is not adequately represented, mathematics teachers may not be motivated to participate in STEM education. They are likely to be protective over their curriculum time. Obviously, such underrepresentation needs attention for future studies. In addition, K-12 schools usually teach mathematics as a logical deductive process rather than a problem-solving process with reference to the real world. Perhaps schools should incorporate some or more engineering/applied mathematics anchor by engi- neering challenges rather than teaching pure mathematics. Engineering, mathematics and science research can be separated into many subfields. Given the diversity and

dynamic nature of these knowledge resources, some strategic pedagogical decision seems necessary for educa- tion authorities to consider. Curriculum time is always limited. Changes in curriculum seem necessary so that engineering topics that contain important cross-disciplinary concepts, vital to local economy, and perhaps within stu- dents’ reach could be included. One emerging area is computational thinking (English [2017](#_bookmark16)), which was not addressed in the reviewed articles. While computational thinking has the potential to enhance mathematics and science learning, English ([2017](#_bookmark16)) has also highlighted many issues pertaining to its integration to STEM that needs further research.

*Pedagogical Approaches*

The pedagogical approaches and its theoretical foundations for current STEM-TPD can be characterized as under- girded by norms of current TPD, which are largely con- structivist and adult-learning oriented. A complete developmental process would comprise three stages: knowledge acquisition, lesson development and enactment, reflective refinement. These stages seem to target at three stages of teachers’ developmental trajectory: knowledge acquisition, appropriation and creation. Active, construc- tive, experiential and collaborative learning in community of practice are commonly emphasized. The adherence to the three-stage model corresponds to the forms and the duration of the STEM-TPD. There seems to be four increasing complex forms of STEM-TPD, namely work- shop only, workshops with lesson design, workshop with lesson design, implementation and refinement, and pro- fessional learning communities. The common element for the reviewed STEM-TPD studies is workshop.

Studies that report workshop-only approach is usually without much theoretical explication and they are likely to be part of an outreach program (MacLeish et al. [2011](#_bookmark12), [2012](#_bookmark13); Whannell and Tobias [2015](#_bookmark19)). The workshop- only approach is conducted within several hours using developed materials for teachers to use in class. The pur- pose is limited to helping teacher to acquire some latest knowledge and to create awareness among students. The content covered is usually beyond school syllabi such as Biomedical science in outer space (MacLeish et al. [2011](#_bookmark12), [2012](#_bookmark13)).

Naturalistic research pertaining to outreach program were conducted by Aslam et al. ([2018](#_bookmark14)) and Kisiel ([2014](#_bookmark9)). Their findings indicate that teachers see field trips for outreach programs as involving complex preparation to ensure students learning and safety. Teachers also need to develop capacity to work within school and with the staff from the outreach centres. However, such capacities were developed on the job without formal TPD. While the

outreach program has a place in STEM education since school has limited access, resources or obligation to research and produce advanced engineering knowledge, outreach programs seem to be peripheral to STEM education.

More substantial TPD usually involves substantial acquisition of mainly engineering knowledge, followed by the transfer of knowledge through the design of curriculum materials (Nadelson et al. [2013](#_bookmark10); Cavlazoglu and Stuessy [2017](#_bookmark15); Faber et al. [2014](#_bookmark2); Fore et al. [2015](#_bookmark1); Granucci et al. [2017](#_bookmark5)). For example, Nadelson et al.’s ([2013](#_bookmark10)) three-day summer institute involves exposing teachers to the content, using the teaching materials and developing lesson ideas. A common theme concerning STEM-TPD in this group of studies is deep learning. Cavlazoglu and Stuessy’s ([2017](#_bookmark15)) 6-day workshop employed concept mapping to improve teachers’ structural knowledge of essential concepts for earthquake science and they view forming well-struc- tured knowledge as a good indicator for deep learning. Faber et al. ([2014](#_bookmark2)) 6-week science research immersion program highlighted that teachers need to develop the necessary agency to assume responsibilities for deep learning. Fore et al. ([2015](#_bookmark1)) discussed Guskey ([2002](#_bookmark16)) and Desimone ([2009](#_bookmark16)) TPD theories. Their findings highlighted the role of teacher’s subjectivity in filtering information and consequently formulating tactical responses in terms of whether and how the TPD would be translated into class- room teaching. Their case study of the week-long TPD clearly reflects that the teachers’ beliefs about their stu- dents’ readiness and school socio-political environment determine the teachers’ subsequent action. While the teachers reported that they learnt, some are not inclined to implement the lessons developed. How to define, measure and promote deep learning could be a theme that needs further research.

The most comprehensive STEM-TPD models encom- pass translating the knowledge acquire in workshop through lesson development followed by enactment and sometimes with reflective refinement. They are at least a week long and may be supported through mentor- ing/coaching. Al Salami et al.’s ([2017](#_bookmark11)) week-long intensive workshop was followed by 12- to 15-week implementation of the designed curriculum with support from doctoral students. It was based on Guskey ([2002](#_bookmark16)) model of teachers’ change, which portrayed that deep changes, including beliefs changes, will occur if the teachers observed positive changes in students’ learning. Similarly, Parker et al.’s ([2015a](#_bookmark19)) two-week summer school was followed with implementation led by STEM master teachers and they adopted team-based teaching with peer observation. It was grounded in Desimone’s ([2009](#_bookmark16)) recommendations of TPD that emphasizes coherence, content focus, active learning, collective participation with substantial duration as

principles of design. The qualitative findings support the usefulness of Desimone’s suggestions. Clark et al. ([2015](#_bookmark3)) adopted four sessions of follow-up mini-workshop with university faculty as mentors for the enactment. They reported that the degree of implementation affects the effectiveness of the STEM curriculum in promoting stu- dents’ sense making. Hadre et al. ([2014](#_bookmark6)) comprehensive evaluation of their yearlong TPD that was initiated by 6-week on-campus workshop affirmed the importance of having engineering professors as mentors and access to the university research laboratories. However, their arrange- ment of one professor mentor to two STEM teachers is hardly scalable and sustainable as engineering professors are not easily available. In addition, while community was established for the teachers, teachers rarely comment on each other’s lesson. These studies attest that mentor’s ongoing support is important for deep changes, and some mentors may need professional development on mentor- ing/coaching (see Richmond et al. [2017](#_bookmark19)). These studies aim for deep changes through complete cycle of development with expert support. Future research may need to unpack with detailed description how teachers develop in such context, perhaps with specific focus on how the experts scaffold the teachers’ thinking, and if and how co-creation of viable new practice and knowledge occurs.

Ongoing continuous professional development with teacher’s communities of practice seems to be the sus- tainable and scalable form of STEM-TPD (Jho et al. [2016](#_bookmark7)). The Korean government has implemented a comprehensive plan in promoting STEAM (with the addition of Art in STEM). It is a three-stage (entry, basic and advanced) development trajectory that seems to correspond with knowledge acquisition, appropriation and finally creation. Under this broad background, two successful cases of ongoing teacher’s communities were studied through the lens of community of practice (CoP). The two cases attest to the importance of establishing joint enterprise among teachers through a common concern of promoting better public education; mutual engagement where openness and distributed power and expertise were exercised; and the creation of shared lesson guides, materials and experi- mental kits that have been tested and reflectively refined. Jho et al. advocate that STEM-TPD should shift its emphasis from individual competencies to collective competencies. Given the interdisciplinary nature of STEM, collective competencies are sensible dependent variables for future study. This would entail future research in developing means to measure collective competencies.

In summary, the core phenomenon described different approaches in STEM-TPD with different aims and theo- retical grounding. Teachers’ beliefs, which were only dealt with by Fore et al. ([2015](#_bookmark1)), may need more attention. In addition, teachers’ design and development of lessons was

treated as an essential stage of TPD but the teachers’ design processes, which interact with their beliefs, were not studied. Study in TPACK has now moved to focus on this aspect. Future research in STEM-TPD could mirror such focus (see e.g. Boschman et al. [2015](#_bookmark21)). Such study would allow researchers to understand how and why teachers use and transform the knowledge input into classroom teaching and learning.

Technologies

Three essential roles of computer-based technology emerged from the review. They are technology as subject matter-specific tool (i.e. TCK), technology as learning tool, and technology as general information and communication tool to sustain the CoP. Attention to TCK is associated with more sophisticated STEM-TPD.

In advanced studies of any contemporary discipline, computer-based technology constitutes part of the content to be mastered. The literature reviewed highlights to a certain extent such specialized technologies. Kovarik et al. ([2013](#_bookmark8)) describe their TPD as focusing on the use of bioinformatics where the bioinformatics databases served as the anchoring technology. They highlighted that bioin- formatics is central to modern biology but it is not featured in school biology. Cavlazoglu and Stuessy ([2017](#_bookmark15)) dis- cussed the role of earthquake simulation in helping teach- ers to understand earthquake-related science and engineering. Parker et al.’s ([2015b](#_bookmark19)) study of teachers’ use of technology in the context of STEM education reveals that teachers rated as intensive user incorporate the use of subject-specific technology. Incorporating TCK is an important mediator of learning by doing and authentic learning since the software embeds the knowledge struc- tures and knowing processes in dealing with data input and output interpretation. Acquiring TCK is essential for the sense-making processes about the subject matter. Future research on how teachers pedagogize TCK is an identified gap in TPACK literature (Chai et al. [2013](#_bookmark16)) and it should be attended to for STEM-TPD.

Video records were used as a learning tool for preservice teachers who otherwise lack access to STEM classroom. Coupled with the pedagogical strategy of teachers’ notic- ing, Radloff and Guzey ([2017](#_bookmark19)) helped preservice teachers to identify significant happenings in STEM classroom, make sense of the events and connect them to pedagogical knowledge. This shift the teachers’ focus from superficial elements such as subjects’ representation and broad inte- gration strategies towards the creation of contextualized real-world problems and the facilitation of student-centred activities. The study can be seen as an example of the teacher educators’ TPACK (see also Cavlazoglu and Stuessy [2017](#_bookmark15)). Another general use of technology is in the

support of community-based activities (Clark et al. [2015](#_bookmark3); Hardre et al. [2014](#_bookmark6); Jho et al. [2016](#_bookmark7)). These researchers consider the role of technology as instrumental to the STEM-TPD.

Outcomes of STEM-TPD

In general, most studies produced positive changes except Al Salami et al.’s ([2017](#_bookmark11)) and Parker et al.’s ([2015b](#_bookmark19)). Multiple forms of data can attest to the changes cause by the STEM-TPD. As the STEM-TPD becomes more com- plex and theory-driven, more varied forms of outcomes were measured. This review uses the categories of per- ceptions, processes, performance and products (4P) to organize the outcomes. In the perception changes cate- gories, teachers’ satisfaction with the STEM-TPD and associated material and resources constitute commonly measured outcomes in the workshop-only approach (e.g. Whannell and Tobias [2015](#_bookmark19)). Deeper perception changes are teachers’ attitude, confidence, engagement, self-effi- cacy and perceived relevance (Kovarik et al. [2013](#_bookmark8); Nadelson et al. [2013](#_bookmark10)). Inductive qualitative analysis of teachers’ reflective journal and their interview data usually reveals that teachers are more confident in developing open-ended science and/or engineering challenges after they have worked closely with scientist and engineers (Faber et al. [2014](#_bookmark2)).

Perceptions are essentially psychological outcomes. While positive changes in perception seem relatively easy to achieve (see Nadelson et al. [2013](#_bookmark10)), such changes are important as they constitute basic psychological conditions for teachers to embark on further mastery of STEM teaching.

Process, products and performance are also used dependent variables in research of STEM-TPD. Qualitative description of process and products without criterion-based scoring could reveals qualitative changes, while scored processes and products are regarded as performances in this study. Radloff and Guzey ([2017](#_bookmark19)) provided insights of changes among preservice teachers’ processes of noticing. Fore et al. ([2015](#_bookmark1)) described teachers’ reasoning process to illustrate how subjectivity is influencing teachers’ learning. Jho et al. ([2016](#_bookmark7)) described the processes in CoP through observation and interview to reveal the mechanism of establishing joint enterprise and mutual engagement. With the advent of learning analytics, future research may employ computer logs to reflect more objective process changes. As STEM-TPD usually involves multiple parties with increasing emphases on building community, social network analysis may also be important for future research. In the performance categories, Singer et al. ([2016](#_bookmark19)) adopted the Reformed Teacher Observation Protocol to rate the video records of the teachers’ pre-intervention

lesson and two subsequent post-intervention lessons. The changes reveal how the teachers’ performance improved over time in facilitating in-depth science discussion and connecting science and engineering practices in the classrooms.

Products of TPD can be in the forms of portfolio (classroom artefacts and instructional materials), concept maps, and proposal. Parker et al. ([2015b](#_bookmark19)) coded the teachers’ portfolio using categories derived from standards (e.g. NGSS) and distinguished teachers as intensive, med- ium or minimal users who differ in the type of use of technology and teaching strategies. Cavlazoglu and Stuessy ([2017](#_bookmark15)) scoring of the pre-and-post concept maps seems to be the only one that objectively measure teachers’ knowl- edge change. Finally, Hadre et al. ([2014](#_bookmark6)) scored the teachers’ research proposal (the product) to assess their achievement. There are, however, no reports on rubrics that can be used for scoring the teachers’ lesson plan which could be another means of ascertaining changes.

# Discussion and Conclusion

This review has constructed a descriptive theory-in-prac- tice based on the reported studies as represented in Fig. [1](#_bookmark0). It depicts the state of research for STEM-TPD. The fig- ure may provide an initial analytical framework for future STEM-TPD education research. Teacher educators can examine Fig. [1](#_bookmark0) to consider the aspects they need to address or theories that need to be employed when they design and study STEM-TPD. Table [1](#_bookmark4) summarizes important design considerations arising from the review. Arguably, future STEM-TPD design based on these considerations can be viewed as the teacher educators’ TPACK for STEM as it is a synthesis of all relevant forms of knowledge that has been discussed in TPACK research (see Boschman et al. [2015](#_bookmark21); Mishra and Koehler [2006](#_bookmark16)). The TPACK framework could offer a clearer account of the knowledge changes.

This review adopts the TPACK framework as the ana- lytical framework as it is proposed to be current quintessential form of teachers’ professional knowledge (Chai et al. [2013](#_bookmark16); Mishra and Koehler [2006](#_bookmark16)). Underlying the TPACK framework is the notion of teacher as designer who creates TPACK to facilitate students’ learning through design thinking. STEM education requires teachers to integrate technology, pedagogy and associated content knowledge through design. Current studies did not seem to focus on the teachers’ design processes to unpack how teachers think when they design. In addition, it seems obvious that interdisciplinary epistemic fluency (see Mor- rison and Collins [1995](#_bookmark16)) is also essential for STEM-TPD for teachers to integrate different ways of subject matter knowing into the STEM curriculum. However, current

Table 1 Summarized design guides for STEM-TPD Categorical factors Design considerations

Contextual Policy and curriculum standards

Time, expertise, resources, access and supports available

Content development Clear connections between the STEM subjects, equitable representation of each subject and their alignment with relevant standards

Pedagogical/TPD theories

Guskey’s ([2002](#_bookmark16)) teacher’s change model, Desimone’s ([2009](#_bookmark16)) design principles, teachers’ subjectivity and beliefs (Fore et al. [2015](#_bookmark1)), CoP theories (Jho et al. [2016](#_bookmark7)) and teachers’ TPACK development

General technology Communication platforms and other general technological tools to facilitate learning and communication

Topic-specific technology

Topic-specific technologies needed for tasks

Assessment Data (perception, process, products and performances) to be collected and assessed to ascertain learning

STEM-TPD is yet to design ways of promoting and mea- suring teachers’ STEM-TPACK, design thinking and epistemic fluency. The author proposes that this may be an important future direction for STEM-TPD.

Sustainable and scalable STEM curriculum is likely the product of a team of designer. Jho et al. ([2016](#_bookmark7)) highlighted the importance of facilitating teachers’ continuous growth of collective competency through teachers’ CoP. Well- established school-based STEM CoP would indicate that STEM education has gained ecological foothold in K-12 classrooms. The implication to practice would be to foster school-based STEM CoP. More research is needed to unpack how the CoP closes the gaps in teachers’ knowl- edge and expertise.

Lastly, current research for STEM-TPD is scarce and STEM-TPD lacks distinctive theoretical framework. It is also not clear if there is sufficient number of teacher edu- cators with the interdisciplinary expertise for STEM-TPD. The TPACK framework along with general theories of TPD, coupled with epistemic fluency, is proposed as a possible starting framework. Given that engineering design is emerging as the key focus, there may also be a need to examine teacher educators and teachers’ Technological Pedagogical Engineering Knowledge (TPAEK). Future research is needed in this direction.

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