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 featured 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 engineering 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 realworld problems. Engineering is the discipline that applies scientific knowledge and mathematical computation to design processes or products (i.e. technologies) to address the problems (Brophy et al. 2008).

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 education (Sanders 2009; Hoeg and Bencze 2017). One implication of such recognition would be the need to cultivate 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 engineering content or processes (Nadelson et al. 2013). There is consequently a clear need for professional development. Teacher professional development (TPD) is well recognized as the corner stone of all kinds of education reform (Desimone 2009; Fore et al. 2015; Guskey 2002). However, recent publications lament the lack of research in STEMTPD (Al Salami et al. 2017; Cavlazoglu and Stuessy 2017). 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 technological pedagogical and content knowledge (TPACK) framework as a lens to construct a descriptive theory

highlighting noteworthy findings.

Pedagogical content knowledge (PCK) (Shulman 1986)

has been proposed as the quintessential teachers profes

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sional knowledge. PCK is constituted through teachers 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). 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 professionspecific technologies. For example, biologist needs to master bioinformatics and engineers need to be trained in computerassisted 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; Hoeg and Bencze 2017). Parker et al. (2015b) 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, pedagogy and content that current STEMTPD is targeting at. This effort may foster connections between the fields which is necessary to advance STEMTPD and could contribute to a composite framework to analyse the quality of STEMTPD.

Data/Article Sourcing and Analysis

To understand the state of research on STEMTPD, 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, Technology, Engineering and Mathematics) AND teacher professional development) yielded only three intervention studies (Cavlazoglu and Stuessy 2017; Fore et al. 2015; Al Salami et al. 2017) in September 2017. This echoes Cavlazoglu and Stuessys (2017) 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. Twentythree 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 nonEnglish and those that research foci are students learning or those that uses STEM as a categorical label for teachers (e.g. science and mathematics teachers) but did not study STEMTPD. In all, 20 articles were retained for further analysis.

The articles were coded using Chai et al.s (2013) procedures of systematic review for TPACK, identifying the specific description about technologies employed, pedagogical/theoretical foundation for the professional development, and the content foci. Concurrently, the author also employed open coding and memoing (Strauss and Corbin 1998) to capture other important points. For example, issues or problems such as low achievement in STEM, students misconceptions and the need for 21st century were identified through open codes. The labels in Fig. 1 also reflect some of the codes used. After the coding, the codes were categorized and organized using axial coding to construct a descriptive theoryinpractice that reflects the state of research for STEMTPD. 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 STEMTPD?

2. What are the rationales for the conduct of STEMTPD?

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 STEMTPD and compare the findings with this study.

Findings

The TheoryinPractice of STEMTPD

Axial coding (Strauss and Corbin 1998) was performed to synthesize the emerging practice of current STEMTPD. Figure 1 provides an overview of STEMTPD which emerged through axial coding. The figure depicts

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

Properties: Pedagogical/theoretical Duration

Content foci TPD processes Community Technologies

Forms: universityschool partnership/ university courses/ STEM communities/ outreach programs

STEMTPD

Dimension:

Not reportedmultiple Hoursyear

Topic specific subject specific

Acquisition development refinement Weak strong

Absence dominance

Fig. 1 STEMTPD theoryinpractice

interrelated sets of categories. It includes the rationales that prompt the STEMTPD efforts and the contextual conditions that the STEMTPD operates in. These backgrounds shape the forms of STEMTPD, 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 technologies and the TPD processes. Specific actions were taken to address the contextual conditions. These interacting categories lead to the outcomes of the STEMTPD. The findings that emerged are organized and presented based on Fig. 1. Relevant issues are discussed at the end of each section.

General Research Trends in STEMTPD Education

Before moving into the details, general research trends of STEMTPD should be accounted. First, research pertaining to STEMTPD 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 theoretical framework and research methodology being employed (e.g. Al Salami et al. 2017; Cavlazoglu and Stuessy 2017; Fore et al. 2015). Most studies were directed at junior to senior high school teachers except for three studies on elementary teachers (Nadelson et al. 2013; Parker et al.

2015a; Radloff and Guzey 2017). Nadelson et al. (2013) 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 STEMTPD especially for elementary teachers. Radlof and Guzey (2017) 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, 2012) and two other studies (Granucci et al.

2017; Whannel and Tobias 2015), 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 highquality study.

Rationale

The rationale articulated for the conduct of the STEMTPD seems to focus mostly on the need to be competitive in the technologydriven global economy. The intrinsic pedagogical 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 STEMrelated fields. Unfortunately,

students motivation, interest and/or achievement to study STEMrelated subjects are declining (see e.g. Al Salami et al. 2017; Cavlazoglu and Stuessy 2017; Kovarik et al. 2013). 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 K12 education (see Hoeg and Bencze 2017) to remedy the situation. The new standards surface gaps in teachers knowledge and skills which lead to the need for STEMTPD.

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 STEMTPD. Jho et al. (2016) 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 crossdisciplinary 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; Radloff and Guzey 2017). The supports and recognition for doing STEM may also need attention (Aslam et al. 2018; Kisiel 2014). Teachers are also commonly concerned about students readiness. The current facilitating condition is that STEM is recognized as important with some policy articulated and funding provided. The availability of Information and Communication Technologies (ICT) has also facilitated communications and collaboration for communitybased learning (Jho et al. 2016). Depending on the contextual barriers and affordances that the researchers believed they are faced with, various forms of STEMTPD were implemented.

STEMTPD (Core Phenomenon)

Given the dynamic advancement of engineering and the diverse conditions, STEMTPD takes many forms and pedagogical approaches to address the different needs. STEMTPD 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 K12 curriculum. Teachers are unlikely to be taught in interdisciplinary context or taught engineering design (Nadelson et al. 2013; Singer et al. 2016). With engineering challenges emerging as the foci for many STEM education initiatives, the lack of engineering knowledge and engineering design processes becomes the content foci in many STEMTPD. 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; Cavlazoglu and Stuessy 2017; Fore et al. 2015; Granucci et al. 2017; Singer et al. 2016; Whannell and Tobias 2015). 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 predeveloped curriculum materials and simulations to support the teachers (Al Salami et al. 2017; Cavlazoglu and Stuessy 2017; Faber et al. 2014; Granucci et al. 2017; Hardre et al. 2014; Kovarik et al. 2013; Singer et al. 2016). For example, Faber et al. (2014) 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 K12 setting (Clark et al. 2015). 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.