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DEVELOPMENTAL PATHS OF TEACHER PROFESSIONAL KNOWLEDGE IN MODELING-BASED TEACHING: ANALYSIS FROM A LONGITUDINAL SOCIO-HISTORICAL PERSPECTIVE

Caminhos de desenvolvimento de conhecimentos profissionais docentes sobre ensino baseado em modelos e modelagem: Análise a partir de uma perspectiva longitudinal sócio-histórica

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Abstract

This study seeks to understand the development of teacher professional knowledge about models and modeling of a Chemistry Education associate professor, experienced and specialized in modeling-based teaching from a longitudinal socio-historical perspective. To do so, we analyzed her statements about her life history in terms of school and academic education, as well as professional practices for the last 18 years. Data were constructed from the transcription of those statements and interpreted according to theoretical-methodological procedures based on both a microgenetic analysis, promoting the decontextualization of contexts, and a macrogenetic analysis, from the recontextualization of contexts. This made it possible to trace her experiences from the student context at the secondary school to the experiences as university professor about to teach a course on models and modeling to a class of future teachers. The data analysis showed that, in her teaching history, various educational situations and contexts involving modeling-based teaching influenced her teacher professional knowledge about models and modeling, as well as how some turning points influenced and took part of the development of such knowledge. This study favors an understanding of the constitution of the subject (the associate professor) as it allows entering into her life contexts in which developmental paths of her teacher professional knowledge were identified and characterized. Furthermore, it contributes to the understanding of how science teachers can develop such knowledge from a longitudinal socio-historical perspective, which may have implications for teachers education.

Keywords: Teachers' professional knowledge; Professional development; Modeling-based teaching; Longitudinal study; Socio-historical perspective.

Resumo

A partir de uma perspectiva longitudinal sócio-histórica, este estudo busca compreender o desenvolvimento dos conhecimentos profissionais docentes sobre modelos e modelagem de uma professora universitária de Química, experiente e especialista em ensino baseado em modelagem. Para tanto, analisamos suas declarações sobre sua história de vida em termos de educação básica e acadêmica e suas práticas profissionais dos últimos 18 anos. Os dados foram construídos a partir da transcrição de tais declarações e interpretados de acordo com procedimentos teórico-metodológicos baseados tanto em uma análise microgênica, promovendo a descontextualização de contextos, quanto em uma análise macrogênica, a partir da recontextualização de contextos. Isto possibilitou remontarmos suas experiências desde o contexto estudantil no ensino médio até as experiências como formadora de professores de Química, prestes a ministrar um curso sobre modelos e modelagem para uma turma de futuros professores. A análise dos dados mostrou que, na história docente da professora, variadas situações e contextos de ensino e aprendizagem envolvendo o ensino baseado em modelagem influenciaram seus conhecimentos profissionais docentes

sobre modelos e modelagem. Foram evidenciados também como alguns pontos de transição influenciaram e participaram do desenvolvimento de tais conhecimentos. Este estudo favorece uma compreensão da constituição do sujeito (professora), pois permite adentrar em seus contextos de vida nos quais caminhos de desenvolvimento de seus conhecimentos profissionais foram identificados e caracterizados. Além disso, ele contribui para a compreensão sobre como professores de Ciências podem desenvolver tais conhecimentos em uma perspectiva longitudinal sócio-histórica, o que pode ter implicações para o campo de Formação de Professores.

Palavras-chave: Conhecimentos profissionais docentes; Desenvolvimento profissional; Ensino de Ciências baseado em modelagem; Estudo longitudinal; Perspectiva sócio-histórica.

INTRODUCTION AND RATIONALLY OF THE STUDY

Remembering the past is one of the ways to understand meanings of an academic and professional life. Schacter (2001) states that memory has such an influence on our daily lives that we often take it for granted until some distortion of it demands our attention. Therefore, it is necessary to pay attention to such memories and to search for means to treat their paths.

From socio-historical studies whose purpose is to understand the genesis and development of social behaviors of subjects, Wertsch (1998) assumes memory as an important element of our socio-historicity. On this premise, investigating educational practices from a socio-historical perspective can shed light on a variety of aspects inherent to teacher professional knowledge (TPK) such as: beliefs and values, which may change over time and contribute to better understand it. In this sense, the purposes of this study are to identify and characterize aspects of TPK on models and modeling (TPKMM) and factors that influence them from the analysis of a chemical education associate professor's statements, as well as, from a socio-historical developmental perspective, aiming at analyzing how such knowledge change over time. She is experienced in terms of professional teaching experiences in multiple spaces and contexts (Roth, & Jornet, 2014), and a specialist in terms of her education, professional teaching activities and research in Modelling-Based Teaching (MBT).

In order for MBT to be used in teaching and learning processes by science teachers, they need to mobilize several TPKMM that can be reflected in their abilities to elaborate and conduct activities and teaching sequences *on* models and modeling (Gilbert, & Justi, 2016). When searching the Science Education literature for studies on MBT, we came across a wide range of research focused on student learning. But when we turned our gaze to research on the characterization and development of TPKMM, we found few studies and those to which we had access present situations in which teachers faced challenges in the first teaching experiences in MBT (Henze et al., 2007). In addition, some authors (for instance, Justi, & Gilbert, 2002; Henze et al., 2007; van Driel, & Verloop, 2002) have characterized and tried to understand science teachers' TPKMM and how they conduct MBT, but focusing mainly on content knowledge (CK) and pedagogical content knowledge (PCK).

The few studies on CK on models and modeling to which we had access show that science teachers generally have limited views on the nature and functions of models (Justi, & Gilbert, 2002; Crawford, & Cullin, 2004). In terms of manifestation of this type of TPK, Kind and Osborne (2017) discuss that science teachers tend to rely on a more traditional approach – oriented towards the consideration of representational values of models – with explanatory and predictive perspectives of models being in the background (or even non-existing). Other researchers identify that such CK tend to be reflected in MBT in order to promote practices based on the use of ready-made models to represent a phenomenon or process (Gilbert, & Justi, 2016; Nielsen, & Nielsen, 2021). PCK on models and modeling were highlighted as the most challenging domain of TPK on models and modeling to be characterized (Gilbert, & Justi, 2016), with some researchers seeking to understand or generally characterize the manifestation of these PCK in MBT (as in Justi, & Gilbert, 2002; Henze et al., 2007).

The TPK that teachers manifest *about* and *in* MBT greatly influence the success of this educational perspective in terms of the involvement of students in epistemic practices and their subsequent learning. However, we found any study in which the academic and professional paths of an experienced and specialist professor on MBT (someone in charge of future teachers' education) have been analyzed from the perspective we adopted here, i.e., a longitudinal socio-historical perspective.

In a recent literature review on science teachers' TPK, Chan and Hume (2019) identified only two longitudinal studies in which data were collected for more than two years. In one of them, Henze et al. (2008)

analyzed the development of the PCK about a specific topic (models of the solar system and the universe). Nine science teachers were interviewed during the initial three years of teaching a new science syllabus. Two distinct types of PCK emerged from the data analysis: one focused on the content of the models and the other focused on the content, the production process and the nature of the models. In the second study, Findlay e Bryce (2012) interviewed physics teachers to study their PCK about electricity from their pre-service year for four-and-a-half years. Their main conclusion was that the teachers' PCK developed and reflected the way they taught (from a content-based teaching to a focus on contexts in which the content might be applied).

From their literature review, Chan and Hume (2019) emphasize the importance of conducting longitudinal studies of PCK development involving longer periods of time. They also assert that specialists in PCK recognize the importance and potential of such studies to support: broad understandings of aspects concerning the development of science teachers PCK (Chan, & Hume, 2019); proposition of meaningful implications for future decisions involving science education educational policies (Sickel et al., 2015); and clarification on the ways teachers move as they develop such TPK, expanding their repertoires through experience in contextualized situations (Park, 2019). Thus, longitudinal studies may generate valuable understandings about how to plan and conduct programs and experiences of professional development to support the continued growth of teachers' PCK at different stages of their career. Being focused on the experiences lived by our subject for a long period of time (more than 20 years) and told by her rather than on what she thinks about MBT, this study may contribute to advance the discussions in the area.

MAIN IDEAS FROM OUR THEORETICAL BACKGROUNDS

Socio-Historical Perspective and Science Education

Social, historical and cultural contexts have been increasingly taken into account by the Science Education research community to investigate beyond what goes on in the minds of individuals (as in Allchin, & Zemplén, 2020, and Kelly, & Crawford, 1996). A widely adopted perspective is that of Vygotsky (1978; 1997), whose theory presents variations of terms such as *"sociocultural" theory"*, *"cultural-historical"* and *"socio-historical theory*". In this study, we use the latter term, as it is quite suitable to direct research that seeks to understand and explaining aspects such as learning experiences in science and socially, culturally and historically mediated processes.

Seeking to understand these aspects, mainly in terms of origins and transformations of phenomena, Vygotsky (1997) proposes the use of two methods: *macrogenetic*, from investigations of aspects of social, cultural and historical contexts, and *microgenetic*, from detailed investigations into specificities of actions, interactions and scenarios in short events. In this sense, knowing a given subject's history can result in an awareness of their past and present because, as time goes by, new experiences are lived and can influence their daily practices (Rüsen, 1994).

Another great contribution of Vygotsky (1978) to socio-historical studies is the emphasis on the concept of *mediation*, which considers that human beings are agents that *act with* and *react to* mediational means, external resources to the mind (for instance, tools, instruments or signs) that allow subjects to master and control their own mental functions. Such concepts were deeply studied by other authors (for instance, Engeström, 1999; Leont'ev, 1978; Wertsch, 1998) resulting in better understandings about educational processes and practices (including the teaching one).

In the current study, we use the concept of mediation presented by Wertsch (1998) when proposing the theory of mediated action, which is based on the unit of analysis *agent-acting-with-mediational-means*, interacting with other subjects and acting on the world. From this perspective, mediated action is situated in social, historical, cultural, and institutional contexts interconnecting them, and can be modified according to changes that occur in these contexts. Thus, the transformation in mediated actions is a recurrent process in socio-historical contexts. Wertsch (1998) explains that this happens mainly when there is the introduction of new mediational means to the action or significant changes in behavior patterns from actions with previous means. Therefore, such transformation cannot be reduced only to considerations about improvements in skill levels or other attributes of the subject since what occurs is a type of imbalance in the systemic organization of the mediated action that triggers changes in other elements, such as the agent and the action. The author also emphasizes that mediated action is situated on one or more developmental paths, implying that *"agents, cultural tools, and the irreducible tension between them always have a particular past and are always in the process of undergoing further change"* (Wertsch, 1998, p. 34). So, *"from the perspective of the agents involved in mediated action, one form of perfection-development that is obviously at issue is mastering the set of cultural tools provided to them by a sociocultural setting"* (p. 37).

Thus, transformations in actions and developmental paths in a subject's life involve changes and/or socio-historical tensions characterized as *turning points*: situations in which changes in knowledge from different domains can be characterized (Mameli, & Molinare, 2013). As the current paper is focused on TPK, we take turning points as specific situations that produce changes in views (which can be theoretical or pedagogical), perspective (e.g., of teaching) or behavior (e.g., related to teaching posture) experienced by teachers in socio-historical contexts.

Teacher Professional Knowledge

Shulman was one of the first to draw attention to the fact that teachers are professionals and, as such, they have specific knowledge of this profession. On this premise, there is a foundation of TPK, a codifiable aggregate of knowledge, skills, technologies, ethics, dispositions and collective responsibility (Shulman, 1986; 1987). Based on Shulman's ideas, several models for TPK, mainly focusing on *Pedagogical Content Knowledge* (PCK), were proposed. One of the most recent is the *Refined Consensus Model* (RCM) (Figure 1), presented by Carlson and Daehler (2019) as one of the products of the 2nd PCK Summit, a meeting attended by researchers specialized in PCK who discussed the construct in the context of science education.

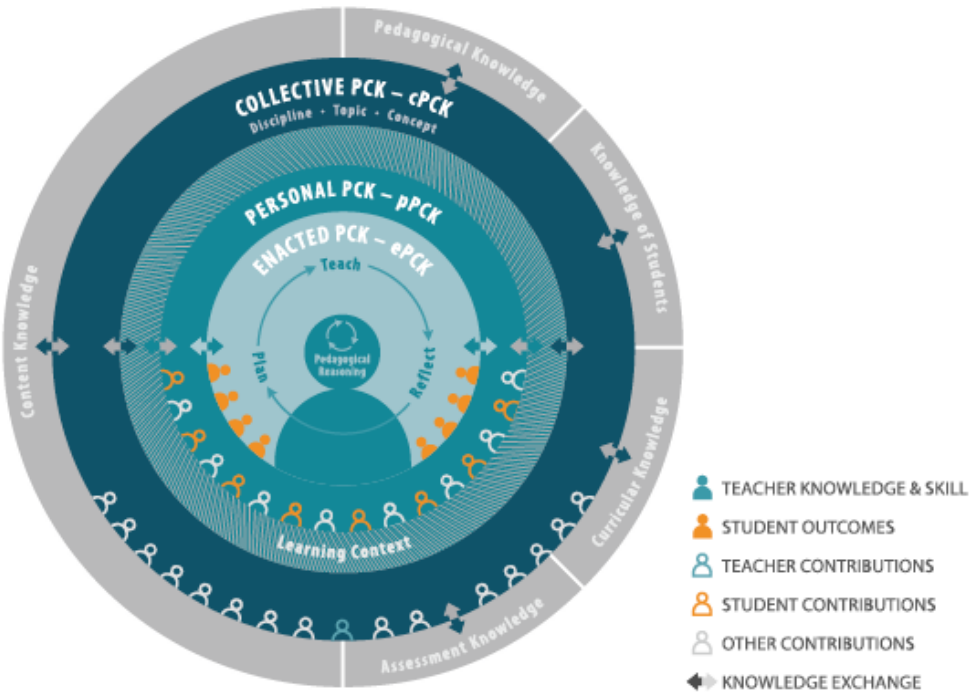

Figure 1 – The Refined Consensus Model (Carson, & Daehler, 2019, p. 83).

Figure 1 shows that the RCM is represented by concentric layers for the three distinct domains of PCK – *Enacted PCK* (ePCK)*, Personal PCK* (pPCK) and *Collective PCK* (cPCK) – and sought to consider the core of professional competence of science teachers and their relationships with the Professional Knowledge Bases and the Learning Contexts. To reinforce the interrelationships between the TPK, double arrows were included between the layers, indicating that the manifestation of different TPK occurs dynamically and in different directions, representing filters and amplifiers (such as teacher beliefs, teaching identity, motivations, guidelines, specific teaching contexts etc.). In addition, subject icons are represented in the model indicating (in general terms) how and where they can influence a teacher's TPK (Carlson, & Daehler, 2019).

In a simplified way, Carlson and Daehler (2019) define:

- *ePCK* as knowledge and skills used by a teacher in the act of teaching science in a particular way and in specific situations, involving a cycle of *pedagogical reasoning* (plan – teach – reflect) in a lesson;
- *pPCK* as the cumulative and dynamic set of pedagogical content knowledge and skills constructed from the experiences of a teacher (for instance, in formal education or teaching experiences) with students, teachers, researchers and scientists, or derived from reading papers, participating in courses, etc.

- *cPCK* as a type of PCK shared by more than one person (not private) and which can combine the own contributions of a teacher to shared knowledge by any group of educators and/or researchers.

- *Learning Context* as a space and time whose meaning can increase or limit knowledge and skills of each teacher and mediate their teaching activities. Therefore, they can be characterized as *amplifiers* or *filters*, being symbolized by a layer represented between pPCK and cPCK.

The outermost layer of the RCM represent aspects of the Professional Knowledge Bases:

- *Content Knowledge (CK)*, knowledge of academic content in a subject that includes, for example, broad understandings (such as those of nature of science), core disciplinary ideas and recognition of cross-cutting concepts;

- *Pedagogical Knowledge (PK)*, which includes general strategies for classroom management (for example, questioning techniques, instructional strategies to support differentiated planning and actions based on different student needs) seeking to involve students in these strategies;

- *Curricular Knowledge (CuK)*, which includes the objectives and structures of a curriculum, and how to organize specific activities and classes to promote learning;

- *Knowledge of Students (KS)*, which covers knowledge about students' cognitive development, their general characteristics and variations in their approaches to learning; and

- *Assessment Knowledge (AK)*, which includes knowledge of design and use of formative and summative assessments, as well as how to use the results of these assessments to plan or modify instructions.

In the current study, we use the RCM as a model for TPK because it makes elements that are central to our purposes explicit (such as the interdependent relationships between different knowledge, the influences of specific aspects on these TPK, and the view that TPK should be understood beyond something in the minds of teachers).

Models and Modeling in Science and Modeling-Based Teaching

Knuuttila (2005) defines models as epistemic artifacts intentionally constructed and materially incorporated with the status of thinking tools. Such a definition is more comprehensive than that of models as partial representations (mainly used in past decades). It implies that models can operate not only as tools and generators of inferences (as representations do), but also as objects that can be used to investigate, produce, assess, legitimize and communicate knowledge, from processes that involve creativity, reasoning, argumentation etc.

From the same perspective, Gilbert and Justi (2016) define modeling as a dynamic process of production, modification (perhaps followed by rejection) and use of models in sciences, being one of the central practices used by scientists in complex cyclical and non-linear processes of knowledge construction. So, they assume that modeling is a cyclic, non-linear and non-predetermined process, basically consisting of four stages: *creation* of a proto-model, *expression*, *test* and *evaluation* of a model. In the creation stage, understanding or defining the aim(s) of the model is central to guide obtaining initial information about the entity to be modeled and establishing relationships between them. In the expression stage, the model is materialized with a view to its communication. It can be expressed in various modes of representation (two-dimensional, three-dimensional, gestural, symbolic, verbal, etc.), and it is necessary to detail the meaning of the specific representation codes used. The testing stage is characterized by planning and conducting empirical and/or mental experiments appropriate to the entity being modeled based on available resources and/or conditions. If aspects of the model partially fail in one or more tests, it is necessary to reformulate it in order to circumvent such failures; otherwise, it is rejected and the process restarted. In the evaluation stage, the necessary identification of limitations, potentialities and scope of the model when used in different contexts occurs, seeking ways to validate it. Due to their nature, each of these stages involves sub-processes such as argumentation, use of thought experimentation, use of imagistic representations, and use of analogical reasoning (for more details, see Gilbert, & Justi, 2016).

Due to the importance of modeling in the production of scientific knowledge, it may play a key role in the development of students' knowledge and skills. By assuming the importance of involving students in scientific and epistemic practices, Gilbert and Justi (2016) propose MBT as a teaching approach in which students learn some scientific ideas by experiencing modelling. But, for being able to conduct MBT, teachers

must mobilize TPK on a range of aspects related to science education in general, and specifically on MBT, aiming at making the experience of the process in classrooms meaningful for students and encouraging their learning. As discussed in the previous section, adequate TPKMM are rare among science teachers.

RESEARCH QUESTIONS

Based on the results of the studies discussed in the initial section, as well as the views of PCK (Carlson, & Daehler, 2019), and modeling and MBT (Gilbert, & Justi, 2016) briefly expressed in the previous section, we justify the current study by assuming the importance of understanding both the manifestation of TPKMM in MBT contexts, and how such manifestation occurs from a socio-historical developmental perspective over time (Vygotsky, 1978). The emphasis on these didactic contexts has analytical potential and may contribute to discussions about the research questions (RQ) that guide this study:

- Which teacher professional knowledge on models and modeling were manifested in statements made by an associate professor involved in teachers' education about her life trajectory, from secondary education to university teaching profession?
- How did such knowledge manifest and change in the contexts and paths experienced and declared by her?

METODOLOGICAL ASPECTS

This paper is an excerpt from a broad case study that supported a comprehensive analysis of aspects of a Chemistry Education associate professor teaching history and her current teaching involving MBT focused on her TPKMM[1]. Briefly, we conducted a *microgenetic analysis*, a promising practice in studies of processes that occur in educational contexts (Wertsch, 1990), to construct data that include details of events and clippings of episodes, both focused on subjects, social relationships and specific situations (Stake, 1978).

Noting the existence of few studies on TPK of experienced and specialists science teachers in more contemporary teaching approaches, we planned and carried out a survey in the Brazilian educational context in search of someone with this profile in terms of MBT. The outcome was the identification and selection of Lizi (a fictitious name, as all other names we mention here). She has had a consolidated background in MBT and for a long time she has promoted MBT at different educational levels, as well as conducted research related to MBT. When Lizi accepted to participate in the study, she was about to start a course to discuss MBT with future teachers from their involvement in MBT activities. For this, she planned to use a teaching sequence consisting of several activities developed by herself or in collaboration with members of her research group (RG). All activities had already been applied by her in secondary and high education contexts. Seeking to get to know our research subject better, we characterized her profile and her school, academic and professional paths based on data collected in an interview.

Data Collection and Processing

To collect data on the school, academic and professional trajectories of Lizi that would relate to MBT, we produced a *semi-structured interview* script in a narrative interview format (Jovchelovitch, & Bauer, 2000). This type of interview is likely to generate powerful data since it allows the interviewer to build several narratives from distinct backgrounds, including scholar and academic paths, coexistence with work environments, and cultural insertions in time and space. So, the questions of the interview script were designed to favor the expression of contextual and motivational situations. The script was reformulated a few times so that, in the end, it consisted of 28 questions organized into general topics that referred to aspects of the trajectory of Lizi from her school and academic training to her performances as a professional and researcher (Table 1), in order to subsidize the general characterization of her profile. By addressing these topics, the interview favored the manifestation[2] of declared TPK (Mazibe et al., 2020), allowing the characterization and analysis of a range

[1] In the original case study, we established relations between the teaching practices in MBT contexts conducted by the professor in the past and the ones she conducted when the data were collected. The presentation of the whole case study is out of the scope of the current paper due to the focuses of its research questions.

[2] We consider the meanings attributed to the ways in which Lizi's TPKMM became expressed and, therefore, accessible, in her statements. Thus, we use the verbs: "to acquire", when the meaning is the acquisition of TPKMM by studies or when they manifested for the first time; "to mobilize", in situations in which such knowledge manifested from her personal TPKMM repertoire; "to complement" and "to integrate", when the meaning is to expand an already existing TPKMM; "to influence" and "to be influenced", when influences between TPKMM are evidenced; "to transform", when Lizi explained that there was a transformation of one type of TPKMM into another; and "to manifest" more generally, when the TPKMM were evidenced without focus on any of the "functions" identified for the other verbs.

of her TPKMM, as well as the characterization of her experiences in distinct contexts and the identification of factors that motivated them. The interview was conducted by the first author and video-recorded.

Table 1 – General themes and main subjects focused on the interview.

Theme	Specific subjects
Scholar and academic education and professional practices	Description of: scholar paths; profile of the schools where she studied; teaching promoted by her teachers during basic education, university, and post-graduation (master, doctorate and post-doctoral studies). General critical analysis of her whole educational path as student and researcher.
Career in teaching	Identification and/or characterization of: time working in the teaching profession; early career teaching; teachers who inspire(d) her and nature of their influences; personal aspects of teaching; teaching contexts; and main difficulties faced in these contexts.
Teaching experiences at the university where she works	Identification and/or characterization of: university teaching time and contexts; teaching experiences lived at that university; subjects she has been teaching; and possible changes in their teaching practice from the beginning of her career at the university to the present days.
Aspects of the teaching of and about modeling in her scholar and academic paths	Identification and/or characterization of: basic education classes in which topics related to models and modeling were addressed; possible relations between such classes and those she teaches on these topics; undergraduate classes/disciplines in which such topics were also addressed; how the topics were addressed in her teaching training; involvement with such topics in her postgraduate studies; general aspects of studies and research on/in MBT; and contributions from postgraduate experiences to her knowledge of MBT.
Aspects of the teaching of and about modeling in her professional life	Description and critical analysis of: her first time conducting activities of/about modeling in both basic and higher education; later experiences from similar contexts; possible differences between such experiences; current teaching on modeling; advantages and disadvantages of teaching from a MBT perspective.
Planning of lessons of and about modeling	Description and critical analysis of: how she planned classes in MBT contexts when she started using it as a teaching perspective; time spent on such plannings; adopted strategies; current lessons planning (including strategies used to plan them); main changes that occurred in her planning process over time; time currently spent on planning.

Data Analysis

Methodological perspective

The data content analysis was conducted from the perspective proposed by Bardin (1977), based on a detailed reading of all the transcribed material, on the identification of words or sets of words that make sense for the current study, and on the classification into categories or themes that have similarity in terms of syntactic or semantic criteria. For this, we carried out careful reading and re-readings of the transcribed material to organize the information according to the chronological order of the narrated facts. This was so because the contexts were not always superimposed on Lizi's statements, probably as a consequence of the typologies of the interview (semi-structured and from narratives). This organization was important for a holistic understanding of the data and the general context of the research, which contributed to the selection of the data for the next stage of the analysis: the exploration of the material. The data that showed manifestations of TPKMM in the trajectory narrated by Lizi were selected since they present analytical potential to meet some of our objectives.

Development of indicators that based data interpretation

To categorize the types of *TPK*, we created markers according to the criteria proposed by Bardin (1977) that emerged from evidence of Lizi's TPKMM manifested in her narratives. In addition, we looked for

evidence of how her TPKMM developed throughout the narratives, which allowed the characterization of contexts, times and spaces lived, as well as other factors that influenced such developmental processes.

From the elements of teachers' PCK presented in the RCM (Carlson, & Daehler, 2019), we defined the PCK on models and modeling (PCKMM) as the knowledge, underlying reasoning, and planning of teachers for teaching aimed at MBT in a specific way, with a specific purpose, for specific students and in specific contexts. Based on this, we present, in Table 2, the description of the components of the TPKMM and the contexts in which they were identified. Such elements of Table 2 resulted from successive reformulations in the pre-analysis, analysis and post-analysis stages by reading, revisiting and reformulating the analyses.

The next step was the definition of criteria used to identify and characterize Lizi's TPKMM in order to enhance the validity of the initial stage of data analysis. This contributed to the identification of information contained in the interview transcription that characterized each of the elements of the TPKMM described in Table 2. Therefore, we based on the theoretical background adopted by Liza to guide her current practice – the Gilbert and Justi's (2016) ideas on models and modeling – establishing some criteria at the micro level from discursive hints that indicated the manifestation of specific types of TPKMM. Additionally, as this paper is based on data collected in an interview that was carried out at a time relatively distant from the declared contexts, there is no sense in identifying ePCKMM, since Carlson and Daehler (2019) clearly associate ePCK to the act of teaching. So, all Lizi's statements related to her actions when teaching were categorized as pPCK.

We also identified and characterized filters and amplifiers that influenced the manifestation of TPKMM from: situations, actions, behaviors or contexts declared by Lizi that limited (filters) or enhanced (amplifiers) the manifestation of TPKMM in her practice; and beliefs, guidelines, motivations or aspects concerning teaching identity explained by her or clearly evidenced in the analyses. Thus, the description of the contexts and a holistic look at aspects beyond the oral discourse were determinant for such characterizations, that were produced by taking into account Lizi's perceptions about her performance and students behaviors that occurred in each declared MBT context. For this, we paid attention to the situations in which it was possible to highlight transformations in the mediated actions (Wertsch, 1998) of what she done when teaching or reflection on any factors that, in some way, limited or enhanced her practices in MBT.

Exploration of research data

After the pre-analysis process, we started the data exploration stage, which essentially consisted of coding and/or enumeration of data according to previously formulated criteria and in a systematic way, aiming at evidencing functional relationships between different variables, sustaining a deductive process and facilitating the construction of new hypotheses (Bardin, 1977). For this, we organize the data in a table, seeking to characterize elements related to Lizi's TPKMM or that influenced them (mainly filters, amplifiers and individuals involved in the process).

This organization made it possible to carry out an analysis of data in the microgenetic domain, which favored the identification of both levels of detail of the processes and data related to the origin of behaviors, ideas or construction of knowledge in specific spaces and times. Thus, we described what we call *critical didactic contexts* related to MBT: situations in which temporal structures and specific events are well defined and in which changes both in what we know and in the way we know can be characterized (Duschl, & Gitomer, 2011). At the end of this movement, we carried out an inverse path placing the data in the macrogenetic domain (Aljaafreh, & Lantolf, 1994), aiming at promoting the recontextualization of situations (Wertsch, 1990) from the regrouping of data into segments (Park, 2019). For instance, after the identification of excerpts from Lizi's speech contained in the data table related to her experiences in MBT as a Master's student, we analyzed each of them separately seeking details related to aspects of MBT that could integrate (even if only in that context) her TPKMM at the microgenetic level (decontextualization). After this mapping, we sought to integrate the data in the critical didactic context of the Master's course, in order to relate the information at the macrogenetic level (recontextualization).

Like Carlson et al. (2019), we understand that there are advantages of studying critical situations (in our case, critical didactic contexts) when analyzing TPK of science teachers, as they well illustrate situations in which the RCM guides teaching situations (from the perspective of a guiding tool) and analysis of teaching and learning situations (from the perspective of an analytical tool). Thus, when using our TPKMM categories for data analysis, we investigated the TPKMM in their contexts of manifestation and the main elements of influence in their manifestation.

Table 2 – Definition and identification context of TPKMM used in this paper.

TPKMM	Element	Definition in MBT	Identification contexts
pPCKMM	-	TPK and skills[3] of a teacher related to pedagogical aspects that reflect his/her experiences in MBT built from interactions with other teachers, researchers or students, readings, courses, professional experiences etc.	Statements of knowledge about the teaching of models and modelling constructed in some context of MBT or from theoretical studies on this topic.
cPCKMM	-	Set of TPKMM acquired by a teacher from mutual and collaborative contributions between teachers and/or researchers in specific contexts of teaching and learning.	Statements of aspects of mutual and collective collaboration with others in MBT contexts.
Professional Knowledge Bases on Models and Modeling	CKMM	Knowledge of academic content related to models and modeling that may support teaching and/or research in MBT contexts.	Statements involving definitions and characterizations of models or modeling and modeling stages theoretically associated with MBT.
	CuKMM	TPK about aims or structures of a MBT-based curriculum, which may relate to different levels of education, school grades, teaching sequences and activities.	Statements of knowledge about curricular aspects involved in the promotion of MBT.
	PKMM	General teaching strategies used in MBT, such as classroom management, encouraging student involvement, using questioning techniques and designing instructional strategies to assist students.	Statements about situations in which some general education strategy is considered appropriate to promote MBT.
Professional Knowledge Bases on Models and Modeling	KSMM	Knowledge about the development of students involved in activities about models and modeling.	Statements involving knowledge about individuals who participate in any course/lesson related to MBT; questions about aspects related to MBT and answers obtained for them; or situations related to MBT that students experienced (or should have experienced) at some previous time.
	AKMM	TPK on how to plan and use formative and summative assessments related to MBT and how to use the results of these assessments to plan or modify elements of MBT.	Statements on aspects of student assessment in MBT contexts.

We also used the Gilbert and Justi's (2016) ideas to guide our understanding of the processes declared by Lizi and her views on models and modeling, as well as to support some TPKMM (for example, the CKMM and the PKMM). In addition, the use of their theoretical ideas was particularly important to demarcate critical

[3] Although the analysis did not explicitly focus on skills, we kept this word in the characterization of pPCKMM because we consider that the mobilization of knowledge (one of the focuses of our analysis) requires specific skills.

didactic contexts for the manifestation of TPKMM, especially when aspects related to some stage of modeling were declared.

Next, we decoded Lizi's statements about her experiences in MBT and carry out a correlation analysis in which results from micro and macrogenetic analyses were organized, correlated and structured in the production of meanings, both situated and broad, with an emphasis on processes. By so doing, we were able to reassemble contexts and facts from Lizi's history in terms of teaching and/or learning processes involving MBT. For this, the two authors analyzed individually part of the data from the data table. Each analysis was reviewed by the other author and any discrepancies (in approximately 20% of the analyzed data) were discussed. Then, each author analyzed the entire dataset and, after reviewing the analysis produced by the other author, further discussions were held, resulting in consensus (less than 1% of disagreements solved in a simple way). This movement contributed to the validity of the final analysis and to the reliability of the results.

Among other results, this analytical process allowed the generation of figures that present the characterization of the manifestation of TPKMM in specific contexts of the path declared by Lizi – even recognizing that such figures favor a static and situated view of the manifestation of these TPK. Moreover, this process was built progressively from the educational social contexts and historical facts experienced by Lizi in learning and teaching situations from the MBT perspective.

RESULTS AND DISCUSSIONS

In order to support the readers' understanding of many of our statements, we open this section characterizing our research subject. Then, we present the results of our complex analytical process. In so doing, we present some figures of two types derived from the RCM (Carlson, & Daehler, 2019), aiming at favoring the reader's visualization of relevant elements discussed in the analysis. The first type characterizes the TPKMM identified in the specific critical didactic contexts declared by Lizi (decontextualization). In all of them, aspects that influenced the manifestation of such TPKMM in those contexts are considered. The second type characterizes the TPKMM manifested in these contexts, but in a socio-historical perspective that progressively constructs a developmental path of these TPKMM in Lizi's trajectory in MBT (recontextualization), of this long-term development. In addition, discussions on aspects that influenced the characterization of her TPKMM, such as *contexts*, *filters*, *amplifiers*, and *beliefs* related to her experiences in MBT, complement the analyses.

Characterization of the Research Subject

During secondary education, Lizi had a chemistry teacher, Armim, who inspires her as a teaching example because he had several qualities as a teacher: he managed to hold her attention in class, he was excited about chemistry, and he showed that he had "pleasure in explaining". After completing this stage of her education, Lizi entered the Chemistry course at a renowned university. In her freshman year at university, she participated in a Scientific Research Initiation (SRI) program in Inorganic Chemistry, and later in another SRI program in Science Education, supervised by Mary, a Chemistry Education full professor and researcher, experienced and specialized in MBT. This and other experiences in science education were crucial to support Lizi's decision to act as a teacher and to seek to establish links with other researchers in the area (from readings and participation in events). Mary had a key influence on this decision, in addition to influencing Lizi's teaching practice (as a model to be followed). In addition to Mary, other chemistry professors have marked her trajectory due to the teaching they conducted.

Even before completing her course (in 2003), Lizi taught private classes and chemistry classes at a secondary school, experiences that she considered important for "opening doors" for future professional experiences. After completing her education as a chemistry teacher, Lizi entered the Master's course in Science Education at the same university. In such context (2004-2006), some professors served her as a reference, mentioning Mary (who was also her supervisor) and Christian, both very inspiring in several aspects. In her Master's research, Lizi investigated students' learning in MBT situations in chemistry classes at a secondary school. Subsequently, she joined the Doctorate (2006-2009), continuing to be supervised by Mary and to investigate MBT contexts, but with a different analytical focus: their relations with manifestation and development of investigative skills.

At the beginning of her career as a graduated chemistry teacher (mid-2004), Lizi taught in a very traditional way, following textbooks and focusing on memorization of scientific contents. However, over the years, she began to try to involve her students in lessons by promoting more interactive situations with them and between them. In such experiences, one of her difficulties was meeting deadlines in school curricular

schedules, with which she generally did not agree. In 2005, still as a Master's student, Lizi began her career working as a temporary instructor at a university, an experience that lasted two years and had the participation of Christian, whom she would replace, and Mary. This collaborative work helped Lizi to overcome some challenges identified by her: mainly inexperience in university education and insecure to teach students very close to her age. To plan and conduct the subjects, Lizi highlighted the support of Mary, who shared and discussed teaching materials (such as lesson plans and other teaching materials) with her, something that made her feel more confident to take on that position and, in the future, the position of assistant professor at the university where she currently teaches. There, Lizi is responsible for subjects in the field of Chemistry Education for future teachers and also worked as a chemistry teacher at a secondary school. Lizi also led a postdoctoral project in which she investigated relationships between the MBT teaching perspective and aspects of nature of science (NOS).

When the data for this study were collected, Lizi had approximately 18 years of teaching career, six of which she had worked in secondary schools and 12 in higher education. In approximately 15 years studying and conducting research in MBT contexts, Lizi had already developed, applied and analyzed several activities in this perspective. Mainly for these reasons, we consider her both experienced and specialized in MBT.

TPKMM Manifested in Lizi's School, Academic and Professional Trajectories

We organized the results based on the premise pointed out by Kunter et al. (2013) that the development of science teachers' TPK is configured in a spectrum that should cover their entire school, academic and professional life. Thus, Lizi's TPKMM are configured in four domains: secondary education, university Chemistry course, postgraduate studies (Master's, Doctorate and Post-doctorate in Science Education) and professional practice. Some of these domains sometimes overlapped in the construction of the narrative, but we present the results following the temporal order of occurrence of the critical didactic contexts related to each of them.

Lizi's TPKMM characterized in the critical didactic context of secondary education

In secondary education, the only experiences in MBT that Lizi remembered having had were promoted by Armim, her chemistry teacher, who mentioned the history of models for the atom, but without highlighting any aspect of modeling. She described a strategy used by the teacher in that context – approaching the successive construction of models for the atom – as "memories" of her first contact with aspects related to MBT. This situation is highlighted in this study because it indicates a possible origin of the constitution of her TPKMM, specific to models for the atom, and aspects (even if superficial) of the processes of creation of those models. In these terms, there was a manifestation of both CKMM, because aspects about scientific models were learned by Lizi, and CuKMM, because she expressed the order of occurrence of historical facts as curricular components related to the content Atomic Models. PCKMM were also characterized in this context in terms of: cPCKMM, because she learned about the teaching of models with the collaboration of Armim, and pPCKMM, as we understand that all knowledge related to that context form the basis of Lizi's TPKMM.

In Figure 2, we present the characterization of the *TPK* acquired by Lizi as a secondary student. As in that context, she had opportunities to learn, from Armim, aspects of the nature of models that were remarkable for her, we emphasize his influence in this learning context (Figure 2) and of other teachers in subsequent (teaching and/or learning) contexts[4].

Some researchers (for example, Sorge et al., 2019; Tardif, & Lessard, 1999), understand that, even as students, future teachers learn from experiences in practices of their teachers that each one judges to be appropriate (or not), depending on the results they observe or experience. So, they can both incorporate into their TPK knowledge that they have built socially in the interactions in their educational contexts, and construct or ground beliefs, values etc. These factors must be considered in the development of TPK from the moment they contribute to teachers thinking and making choices in their teaching activities (Tardif, & Lessard, 1999). From this perspective, teachers' learning context is not limited to the professional practice. Therefore, we consider it important to make the TPK learning contexts of Lizi explicit in our study, adapting the figures from the RCM by adding an external layer that encompasses all TPK and which we call teachers' learning context.

[4] In the next figures, the subjects that influenced the manifestation of Lizi's TPKMM are located looking for this pattern and identified by different colors. When Lizi mentioned groups of subjects (for example, members of her RG or students), icons representing three identical subjects grouped together are used to represent them. In all figures, Lizi is represented by the icon located in the center of the model.

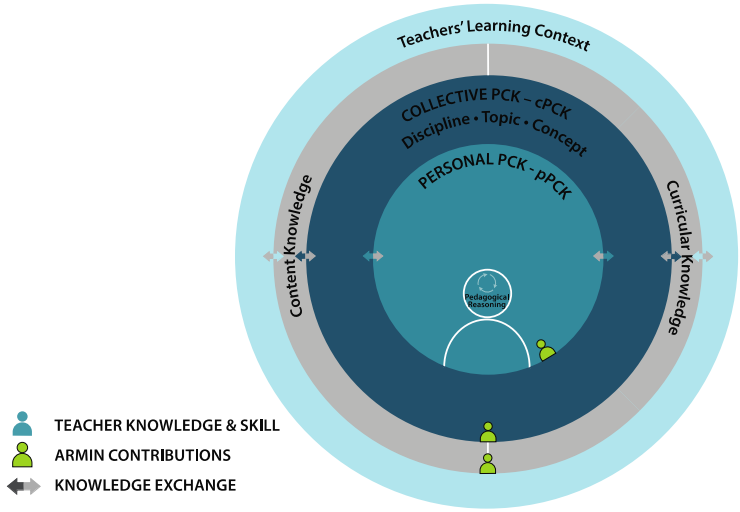

Figure 2 – Characterization of Lizi's TPKMM in the critical didactic context of secondary education (after Carson, & Daehler, 2019, p. 83).

Lizi's TPKMM characterized in the critical didactic context of her university chemistry course

During her university course, Lizi studied Chemistry and prepared to be a teacher. During the university course, she also experienced aspects of MBT involving models but not modeling. Considering her experiences in subjects taught by specific professors and participation in an SRI program in Chemistry Education, Lizi tried to remember someone who had promoted modeling activities and, without success, she was categorical in stating that "No situation at all! I had not even heard the word modeling yet."

In her university learning context, in addition to the expansion of her pPCKMM (mainly resulting from her participation in the SRI), there was an emphasis on the influences of Mary and other professors (such as those of Organic Chemistry) who used models in teaching and discussed a little about them, characterizing cPCKMM. The TPKMM declared by Lizi in such a context are represented in Figure 3. This is in line with what Sorge et al. (2019) state that contexts of teachers education especially favor the constitution of their TPK that are part of the Professional Knowledge Bases, as well as cPCK and pPCK since, generally, future teachers experience planning, acting activities (even if simulated) in teaching, and reflecting on such activities.

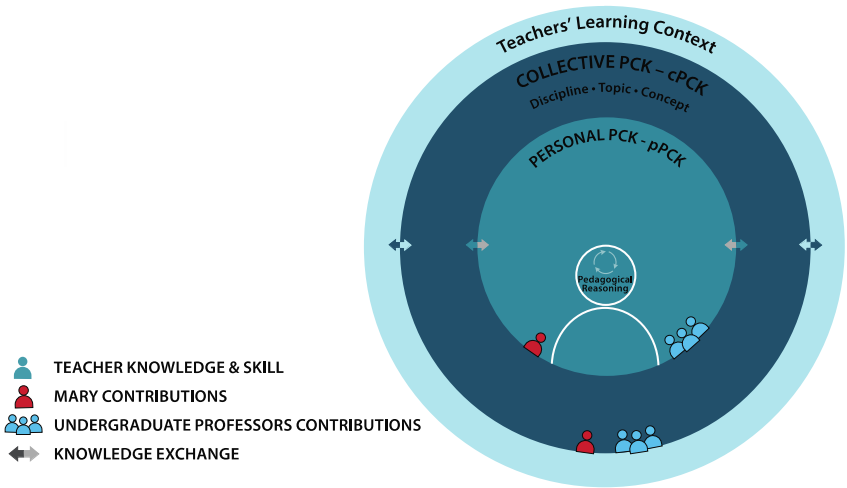

Figure 3 – Characterization of Lizi's TPKMM in the critical didactic context of the university course (after Carson, & Daehler, 2019, p. 83).

Lizi's TPKMM characterized in critical didactic contexts associated with her postgraduate studies

Lizi described three critical didactic contexts in her academic education (her studies to participate in the Master's admission process, her experiences in the Master's and the Doctorate) and an exclusive research context (her experiences as a postdoctoral fellow) in which TPKMM manifested.

To be approved in the Master's in Science Education admission process, she had to acquire and mobilize knowledge related to MBT to produce a mandatory pre-project and be prepared for an interview in which she was asked about her project. Lizi explained, in general terms, how she did so at the end of her university course:

> "I read about models and modeling to write my pre-project and had some discussions with Mary. But it was more significant when we debated after my approval, when there were more people [from RG] participating. I think I internalized the ideas more."

All over these studies, the influences of individual contact with literature and discussions with Mary are highlighted in the constitution of CKMM, cPCKMM and pPCKMM, marking the first turning point in her developmental path related to TPKMM. This is because she started to intentionally manifest TPKMM based on theoretical knowledge that helped her to understand MBT as a teaching perspective instead of experiencing only aspects related to models as a student.

In the context of the Master's course, Lizi expanded and mobilized more consistent TPKMM, the result of a variety of practices experienced in it, as emphasized next:

> "My research focused on both modeling and Chemistry content because my focus was the analysis of students' content learning from their participation in modeling activities. So I studied about how modeling takes place. In 2004, there was a subject that impressed me a lot, with professors Mary and Arthur, in which the class discussed theoretical aspects and empirical studies on models and modeling. That was when I really had to study modeling and participate in specific discussions about this topic."

Lizi's learning from such intense studies on MBT allowed the characterization of a situation of expansion of CKMM and pPCKMM. Her participation in a subject in which aspects of MBT were addressed was also another learning situation in which the construction of her cPCKMM was evident, since the class collaboratively studied and discussed many aspects of MBT. This also resulted in the creation of CKMM, once concepts and relationships about modeling were discussed, and pPCKMM, as a result of what Lizi learned in that context. In addition to these situations, her effective and unprecedented involvement (in her trajectory) with teaching practices for MBT when collecting data in her Master's research project seems to have been remarkable for her:

> "The first time I conducted modeling activities was when I collect data in two classes, being the first a pilot one. This was very important for me to evaluate the didactic sequence that I had produced, to evaluate my performance, and to think about how I would conduct the activities. At first, the biggest difficulty I had was not giving ready-made answers, but encouraging students to think, to think of problem situations that would be related to some previous knowledge or that would encourage them to resort to them. Even today, so many years later, I still think I conducted it well for a first time because I managed to ask good questions and I was able to let the students think."

In that context, the fact that Lizi experienced an action research on aspects of MBT in her Master's has brought her experiences at the action (ePCKMM) that, in the context of the interview, have characteristics pPCKMM (as justified before Table 2). The manifestation was also evident, hitherto unheard in her statements, of: KSMM, due to the descriptions of some of her teaching actions whose focus was on students, such as seeking to instigate them to elucidate their previous knowledge and realize that they were very questioning students; PKMM, from her explanations on aspects of applying general teaching strategies for promoting MBT in that context (for example, seeking to involve students in modeling activities without giving ready-made answers); and influences of students' learning contexts in the manifestation of these TPKMM, contexts that we also understand as Lizi's learning contexts.

Such results and reflections support our understanding that learning contexts can be of two types: *students learning contexts*, in which teachers mobilize knowledge of a more practical nature and that are strongly influenced by students and by what happens in the classroom with their participation; and *teacher learning context*, in which the teacher can mobilize (theoretical or practical) TPK of any type (for example, from Professional Knowledge Bases or from PCK). This second type is not one of the explicit elements of the RCM (Carlson, & Daehler, 2019).

When comparing the two applications of the teaching sequence, Lizi highlighted that:

> "The application of the sequence in the second class, whose data I analyzed, was much smoother because I had already thought about several situations... I think I even managed to do better with the surprises that came up."

This shows how the pPCKMM and PKMM that constituted her repertoire of TPKMM up to when she conducted the MBT in the pilot class were expanded and facilitated her teaching performance in the second class. This observation corroborates the Alonzo et al.'s (2019) statement that the pPCK of a science teacher provides the basis for promoting teaching in successive stages of pedagogical reasoning cycles, that is, resulting in the manifestation of ePCK in classrooms.

Lizi also described some challenges she faced in that context, the main ones being conducting teaching activities based on modeling for the first time, conducting classes in a more constructivist perspective, and managing classes. Despite these challenges, she was positively surprised by her performance and, in several opportunities, she highlighted the importance that her Master's experiences had for her in terms of increasing the significance of her understanding of MBT. Thus, the Master's course was a context for expanding her TPKMM both theoretical (because she studied about MBT) and practical (because she planned, taught, reflected and investigated her practice). Her statements made us more convinced that CKMM and pPCKMM were manifested in these experiences, from a perspective of constitution and expansion of these TPKMM. However, we emphasize that this was possible mainly because, in that context, she could put her knowledge into practice in action by mobilizing ePCKMM that have become part of her pPCKMM.

Due to the emphasis she gave to the importance of the experience of applying a teaching sequence for MBT for the first time in her trajectory in MBT, it was configured as an important turning point in the path of Lizi in MBT contexts. Until then, her TPKMM were built only from observation of professors practices, theoretical studies and discussions with others.

In her Doctorate, Lizi continued investigating MBT, contexts, but with new focuses:

> "My focus was on investigative skills related to scientific practices in the modeling process. So, I read much more, not only about modeling, but also about the potential of modeling for this type of learning, and about skills, in general. I also studied a lot about assessment because I had to analyze how these skills manifested in modeling contexts."

In this statements (and in the discussions that followed), Lizi manifested CKMM (derived from broad theoretical studies focusing on students skills in MBT) and AKMM (to assess students in that context). This resulted in the built of new pPCKMM, expanding her PCKMM since such knowledge influenced her ways of thinking about MBT and teaching from this perspective. Even putting herself at the center of these processes (for example, highlighting her individual readings), at other times she recognized the frequent sharing of knowledge related to MBT with Mary and members of her RG (in which she actively participated). Thus, her cPCKMM also manifested in the Doctorate, context in which Lizi presented an explicit situation of manifestation of AKMM, which had not yet been characterized in previous contexts.

Concomitant to the reflections on her experiences in the Doctorate, Lizi highlighted others that took place when she was a postdoctoral fellow:

> "When I collected the data in that project, I was really convinced of how impossible it is to talk about modeling without involving aspects of nature of science. I think they are together! I do not even need to worry about preparing specific lessons to teach nature of science because this can be discussed from the learning about modeling."

The nature of the main knowledge manifested in her statements concerning the postdoctoral context did not refer directly to MBT, but to other important topics in science teaching that relate to MBT (as NOS). By studying and analyzing such relationships, the construction of her CKMM and pPCKMM became evident.

Figure 4 represents the TPKMM manifested by Lizi in the context of all her postgraduate studies. Due to space limitations, we did not insert the figures corresponding to each postgraduate critical context separately; we rather merged them in Figure 4.

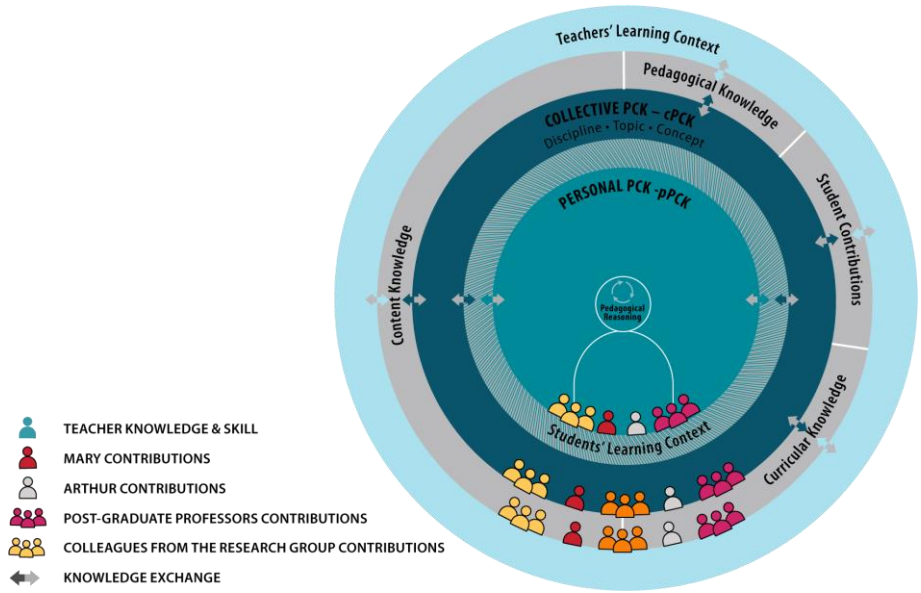

Figure 4 – Characterization of Lizi's TPKMM in the critical didactic context of postgraduate studies (after Carson, & Daehler, 2019, p. 83).

During Lizi's postgraduate studies, we identified influences of some *filters* and *amplifiers* in her TPKMM. During the Master's course, a *filter* was related to her difficulties in carrying out modeling activities for the first time. On the other hand, the following facts stood out as *amplifiers*: she studied and understood the important role of representations in MBT; she recognized that, even with the difficulties, she was able to conduct activities for MBT; she felt increasingly prepared to conduct such activities; and she understood that the experiences acquired in the first application of the activities enhanced the one in the second class.

Hints of bidirectional exchanges between distinct TPKMM were manifested in statements about her experiences in that context. Even pointing out that before collecting data for her Master's project she had not conducted activities for MBT, Lizi acknowledged that her previous knowledge helped in such task. They may also have contributed to the expansion of her pPCKMM, as they may have supported application of activities in later contexts.

Lizi's TPKMM characterized in the critical didactic context of professional teaching practices in MBT

Lizi detailed aspects of her planning of activities and actions for the promotion of MBT, but did not clearly identify in which contexts (secondary or university education) this occurred, which led us to understand them as general aspects of her teaching practices for MBT. The use of ready-made activity plans for MBT was one of her recurring practices:

> "All the modeling activities that I worked on were based on creation, application and research work carried out in the research group. I confess that I already had a pre-script, and I worked a lot on it to adapt the activities thinking 'what would I do differently' or if I would include some text. So, none of the activities I applied were created out of thin air."

Creating personal databases with educational resources (books, teaching sequences, activities etc.) and using them in lesson planning are common practices for science teachers. Making use of these practices, Lizi manifested PKMM by stating that she prepared her classes for MBT by accessing her own database. cPCKMM were also made explicit when she referred to the production of teaching plans with the collaboration of Mary and members of her RG – which we understand to reflect on her acquisition of pPCKMM.

Lizi also presented her view on the practice of planning in MBT:

> "I still find the planning of modeling activities very difficult. Even the one I thought was more direct, to this day I see how some things could be worked on better. But planning takes a lot of time. Comparing with the application, I think that planning modeling activities is still the hardest part. For example, the teaching sequence about polymers which I applied at the secondary school ... In the first application, we

> identified problems in some questions. There were moments when I stopped and told the students that we were going to discuss in the next class. But why? Because I had no way of dealing with their reasoning at that moment without giving the answer."

Here the mutual manifestation of PKMM and cPCKMM was evident based on references to situations of collaborative planning and application of the didactic sequence (with members of her RG) and pPCKMM with expressions about aspects of her learning in that context. In this scenario, bidirectional exchanges were also evidenced from these relationships between the *TPK*.

Lizi also highlighted aspects of her CKMM and pPCKMM when she described how a better understanding of aspects of modeling influenced her more conscious decisions making in MBT planning. For example:

> "It has been a short time since I was able to better understand the difference between testing and evaluating the scope of models. Today, from such an understanding, I think I can include more things in the planning and make the practice richer and more intentional. I can include questions about models and modeling, and propose tests! This is acquired with experience, right? The issue of working with students, for example, thinking about the path they can follow and, soon after, being able to ask questions that may test what they thought and, in some way, support their reasoning."

Lizi's PKMM and KSMM were evident in this excerpt when she stated that she conducted modeling practice more intentionally and that she thought of students when planning activities; indicated that she was looking for more viable questions to help students reason in MBT; and affirmed to consider their previous knowledge as something that could contribute to the conduction of distinct modeling stages.

In terms of teaching practice in the classroom, Lizi described her first experience in professional contexts:

> "I taught a workshop on models and modeling in 2008 at an event at a university. Then, I used a shorter didactic sequence because the workload was very small, I could not do much. I used a sequence of simple activities on a daily theme and I found it very useful as it was possible to relate well all the modeling stages in what was the first experience of those teachers and helped them to understand the MBT proposal. It was really good."

In this excerpt, Lizi manifested CuKMM and KSMM, as she had to choose the most appropriate teaching sequence for a specific audience (pre- and in-service teachers) and for the workshop context (mainly its objectives and duration time). This led her to consider that a shorter teaching sequence on an everyday topic was more suitable for that context than one that addressed some chemical content and was longer. As it served as a basis for further MBT experiences, we credit the TPKMM acquired in the context of that workshop as part of her pPCKMM. Lizi also made clear the *filter* related to the short time available for the workshop. On the other hand, opting for the teaching sequence of everyday context contributed to giving her enough time to address fundamental aspects of the MBT, which indicated a functional characteristic of an *amplifier*.

Lizi's comments on some teaching sequences aimed at MBT that she applied at different educational levels indicates she had: CuKMM related to how she organized herself to conduct the MBT; CKMM on how to conduct the modeling activities; and pPCKMM once she explained theoretical concepts on which she based her practice.

In Figure 5, we represent the TPKMM constructed or mobilized by Lizi from statements related to the promotion of MBT from the classroom teaching perspective.

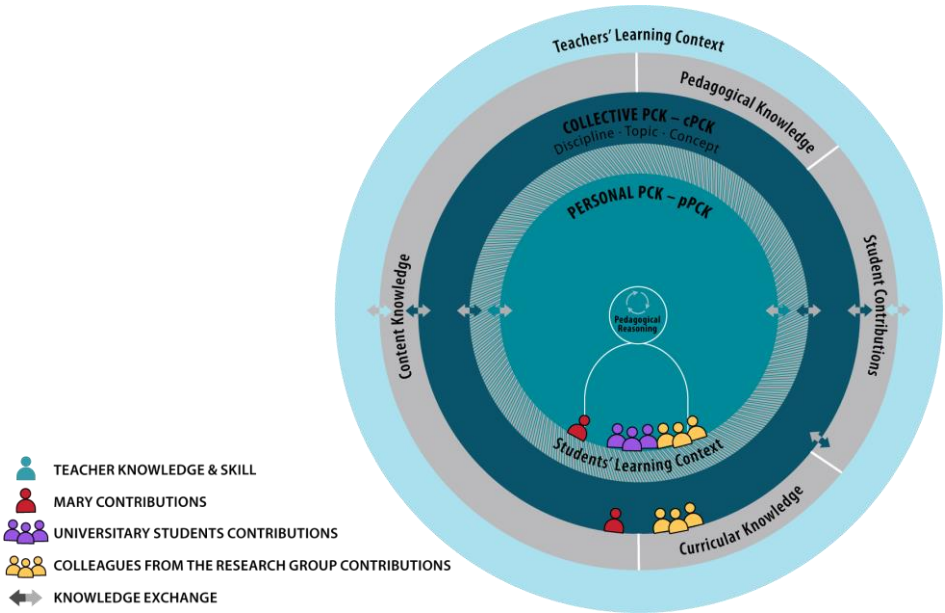

Figure 5 – Characterization of Lizi's TPKMM in the context of teaching practice to promote MBT (after Carson, & Daehler, 2019, p. 83).

In this context of teaching practices (mainly planning and acting in classrooms), some *filters* that influenced the manifestation of Lizi's TPKMM became evident, such as those associated with (i) the planning in MBT: the need to spending a lot of time on this practice, the difficulty in planning the activities (even more than applying them), and the need to replan activities or even classes when some interactions with students required it; and (ii) aspects of her teaching performance in terms of doubts and difficulties that still exist in relation to the characterization of the stages of testing and evaluating models. On the other hand, *amplifiers* also stood out (i) in the planning, from the mention that having activities for the MBT elaborated and validated by the RG facilitated their application; and (ii) on acting in the classroom, in terms of her clear view about how she currently understands the importance of modeling in MBT and conviction that, with the experience she acquired over the years, she is currently able to promote it more intentionally. Lizi also expressed the *belief* that it is necessary to choose well teaching sequences for MBT because they should be suitable for each educational context.

Lizi's TPKMM characterized in the critical didactic context from the perspective of the present

Although we did not ask explicitly (or so emphatically) about that present moment in the interview, some indications of her TPKMM were spontaneously mentioned in the dynamics of her narrative. For example, she identified and explained aspects that influenced her learning and understanding of MBT from the perspective of the present, that is, from that moment immediately prior to conducting a course on MBT for future teachers:

> "I understand that my experiences as a postgraduate student have greatly contributed to my learning about modeling-based education. If today I like and defend it, if I teach modeling and about modeling, I owe it mainly to research because today I am really convinced that this is a differentiated teaching perspective, which stimulates the reasoning and creativity of the students, their learning not only of chemical content knowledge, but of chemical knowledge in a way that makes sense to them. Today, I identify that there are other investigative skills that are manifested when students participate in modeling activities that I did not address in detail in my Doctorate study."

In this excerpt, Lizi manifested CKMM and pPCKMM, from definitions given to MBT that indicated a more comprehensive view of this teaching perspective than those presented in previous moments of the interview; as well as cPCKMM, when she mentioned the collaborations between her, Mary and members of her RG on aspects of MBT. In addition, when integrated, some expressions used by Lizi made explicit a broad definition for MBT (which mainly reflects her CKMM, cPCKMM and pPCKMM) summarized as: MBT is a teaching approach that integrates knowledge about NOS, favors the development of investigative skills

(among others) and stimulates students' reasoning, their creativity and the learning of chemical content knowledge.

Lizi compared her current experiences and views on MBT with those of her early career:

> "At the beginning, when teaching in secondary schools, I was very afraid of time. Today I think that when applying such activities I am not spending so much time, I am investing time because what is gained is so much more. And since I am now more aware of what is related to theoretical aspects of modeling, everything is clearer in my mind than when I have started."

She also reflected on how she perceives the field of studies on MBT today and how this has implications for her practice:

> "But the modelling area has been growing. Today, the view I have of modeling is very different from the view I had before, which was 'ok, to learn content', and then 'to develop investigative skills'. Then came the work of members of the research group and other researchers on analogies, nature of science and argumentative skills. So, today it is so broad that when I go to work with modeling, I can think 'wow, students are constructing analogies, observing an experiment, doing mappings, I am favoring argumentation'... So, I can see the process and ask questions about it – and it is much more than the view I had when I thought only about learning content."

This and other of Lizi's statements on how her view of MBT has developed over time, mainly characterize her CKMM and pPCKMM. She detailed how the development of her view on MBT was significant in terms of a broader understanding of the potential of this teaching perspective in Science Education, clearly demarcating situations in which such changes occurred. Pedagogical aspects were highlighted in her learning about MBT that influence her current practice: being able to intentionally ask questions to students; promote contexts of argumentation; use analogies and encourage their drawing by students, which indicates PKMM. KSMM were also showed when Lizi mentioned actions frequently taken by students involved in activities for MBT. Finally, she also made it clear how her participation in studies related to MBT led by members of her RG influenced her cPCKMM.

Two *filters* were highlighted in this context. One is her understanding that MBT is an ever-expanding field of study. This classification can be viewed as strange since the expansion of a field of study tends to be seen as something that results in the expansion of knowledge (aspect recognized by her at other times). However, the contextual hints in her discourse indicate that, at that time, she referred to such expansion as a problem in the sense of having to update herself frequently from literature, which required a considerable time that she did not always has available. The other filter is the fact that she has the feeling of spending a lot of time promoting MBT in previous contexts. This situation gained new characterization from her consideration that all the time used in the promotion of MBT is an investment, that is, an apparent *filter* (time) gained prominence from an *amplifier* when her view indicated a reflection on the process as a whole. Other *amplifiers* were evidenced in the fact that she: has experienced postgraduate contexts (which contributed to expanding her TPKMM); has conducted studies on MBT (which led her to like, defend and teach using this teaching perspective); has participated in studies developed in her RG; has recognized changes in her ways of understanding and promoting MBT (which helped to broaden her view of MBT); and be convinced of the potential of MBT in Science Education.

Even agreeing with Wertsch (1998) that the definition of an *"ideal end point"* when dealing with *"development"* is intellectually, ethically, and politically complex, in Figure 6, we present the TPKMM related to Lizi's understanding of MBT from the perspective of the present. Like the author, we consider that this can *"provide the background for an account of development. In short, one cannot coherently speak of development without positing an ideal end point"* (p. 36).

By taking into account the elements that have influenced Lizi's TPKMM of MBT manifested in all contexts stated in the interview and previously analyzed, we produced Figure 7. As well as the others that precede it and are related to it (Figures 2-6), Figure 7 is important for this discussion because it helps us to visualize aspects of development based on a set of representative figures (models) that show the TPKMM manifested by her in all contexts. Intending to represent such TPKMM, which were consolidated in the defined contexts, we sought to be coherent with the MBT framework, as models of this nature are useful in helping to explain abstract or difficult-to-understand aspects (Gilbert & Justi, 2016). In turn, do so by adapting the RCM proposed by Carlson et al. (2019) helps us to attribute meanings related to how TPKMM become dynamic in terms of their path of socio-historical development throughout history (Vygotsky, 1978; 1997; Wertsch, 1998).

Based on the RCM (Carlson, & Daehler, 2019) and assuming a socio-historical perspective (that based the design of Figure 7), we better understand mutual influences between Lizi's distinct TPK that were built, expanded and modified throughout the process. In the situation of discussions about MBT, it was clear that information was sharing between her and other people, especially Mary. On the other hand, her cPCKMM influenced the expansion of her pPCKMM and CKMM, something that can be considered from the dynamics related to the TPKMM that the RCM suggests and considers. It is also possible to make evident the influence of the different contexts in which such TPKMM manifested themselves, as well as of idiosyncratic situations and factors that contributed to this panorama. This is in line with the claims that TPK are dynamic and flexible (Carlson, & Daehler, 2019; Carlson et al., 2019; Schneider, 2019; Shulman, 2015), cumulative (Carlson, & Daehler, 2019) and complexes (Alonzo et al., 2019; Schneider, 2019).

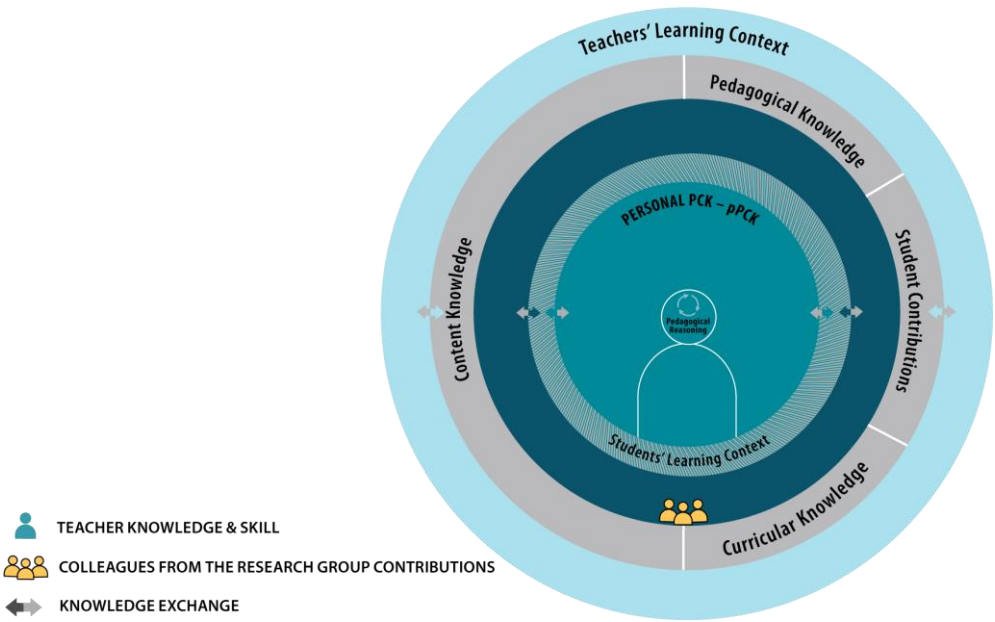

Figure 6 – Characterization of Lizi's TPKMM in the context of understanding MBT from the perspective of the present (after Carson, & Daehler, 2019, p. 83).

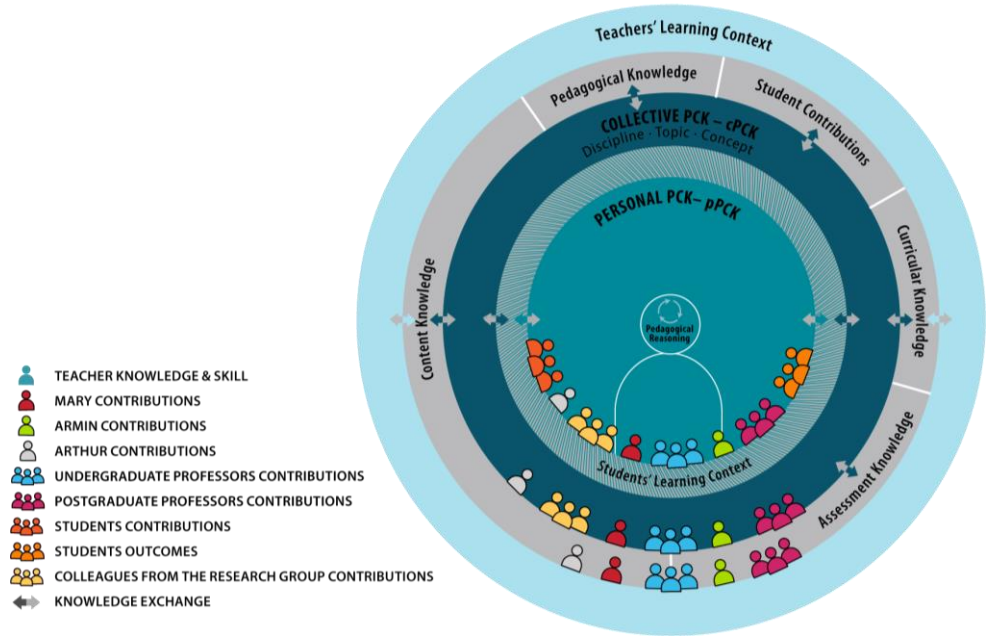

Figure 7 – Characterization of Lizi's TPKMM in her whole path in MBT (after Carson, & Daehler, 2019, p. 83).

CONCLUSIONS

In this study, we investigated the manifestation of TPKMM in the school, academic and professional trajectories of Lizi, an experienced Chemical Education associate professor, who is a specialist in MBT. By analyzing her statements, we identified and delimited critical didactic contexts of MBT in all her trajectories from a socio-historical perspective which, when analyzed together, allowed us to retrace, even partially, the developmental paths (Wertsch, 1998) of these TPKMM.

Our RQ1 asks: Which teacher professional knowledge on models and modeling were manifested in statements made by an associate professor involved in teachers' education about her life trajectory, from secondary education to university teaching profession? We identified and characterized all types of TPKMM adapted from the RCM that characterize the Professional Knowledge Bases on Models and Modeling (CKMM, CuKMM, PKMM, KSMM and AKMM) and the two types of PCKMM possible to be evidenced in an interview (cPCKMM and pPCKMM).

Our set of figures (models) used to characterize the teacher's TPKMM helps us to discuss important aspects of the developmental paths of these TPKMM in their trajectory and make sense of them. It became evident that, in contexts in which Lizi was only a student (Figures 2 and 3), she could built initial TPKMM (CKMM, CuKMM and pPCKMM). They were constituted from the observation of practices of her teacher and professors who taught about models. In the context of her postgraduate studies (Figure 4), such TPKMM were expanded – which was evidenced by both their mobilization and the incorporation of AKMM, KSMM, PKMM and cPCKMM in her repertoire of TPKMM. It was mainly during the Master's course that her PCKMM expanded due to her involvement in promotion of MSBE in professional practices (Figure 5).

Lizi's TPKMM manifested themselves in the narrative she produced about her path in MBT in different levels of detail, as commented below:

- Professional Knowledge Bases on Models and Modeling: CKMM (for example, characteristics and views about models and modeling), practices of modeling (description of the processes or stages that compose it), MBT as a teaching perspective (theoretical-methodological aspects based on it); CuKMM, mainly in terms of educational levels and curricular organization, subjects, courses or workshops for MBT; PKMM, related predominantly to the teaching perspective based on MBT, the practice of modeling and other teaching approaches and strategies that integrate it; KSMM, predominating the survey of students' previous knowledge and their main difficulties in MBT; and AKMM, manifested when Lizi gave us details about her doctorate study (related to student assessment in MBT);

- PCKMM: cPCKMM, from collaborative studies with Mary, other professors and members of her RG; and pPCKMM, from learning experiences that occurred mainly with Armim, in secondary education, some of her university professors, colleagues, Mary, members of her RG and through theoretical studies.

In relation to RQ2 (How did such knowledge manifest and change in the contexts and paths experienced and declared by her?), from a socio-historical perspective, we identified stages of a developmental path (longitudinal), mapped in contexts in which TPKMM (and factors that influenced them) manifested and became more complex and specialized in subsequent spaces and times. This can be characterized as development in terms of construction, mobilization, expansion, modification and/or resignification of TPKMM in two main movements: *gradual*, as she constructed and mobilized TPKMM in the experienced contexts; and *progressive*, with regard to the expansion, modification, transformation and resignification of TPKMM.

These results illustrate the emphasis that Wertsch (1998) gives to the fact that *"Agents, cultural tools, and the irreducible tension between them always have a particular past and are always in the process of undergoing further change"* (p. 34). Over time, as Lizi internalized and appropriated the MBT teaching perspective and taught Science from this perspective mobilizing TPK, the developmental paths in terms of mediated action was consolidated in the transformation of her teaching practice. This is consistent with Wertsch's ideas, based on Vygotsky's theory, that *"we can understand many aspects of mental functioning only if we understand their origin and the transformations they have undergone"* (Wertsch, 1998, p. 34).

In Lizi's report of these processes, the manifestation of TPKMM occurred from idiosyncratic groupings, with a predominance of TPKMM from Professional Knowledge Bases, cPCK and pPCK. We understand that this may be a trend when teachers declare their TPK (Mazibe et al., 2020) in narrative interviews. For example,

when commenting on situations in MBT, Lizi focused on more general or contextual aspects of her experiences, such as teaching approaches, practices and strategies.

Lizi became aware of how she started to construct CKMM, CuKMM, cPCKMM and pPCKMM related to models in secondary education (Figure 2), and expand her CKMM, cPCKMM and pPCKMM) also related to models when she was an university student (Figure 3). In the postgraduate contexts (Figure 4), the development of the Lizi's TPKMM took place: (i) from the Master's admission process, when she expanded CKMM and pPCKMM from studies in the literature that integrated aspects of modeling and MBT, in addition to cPCKMM on these aspects; (ii) in the rich context of the Master's course, fundamental to increase her understanding of MBT and marked by situations of creation, mobilization, expansion and development of CKMM, CuKMM, KSMM, PKMM, and cPCKMM; (iii) in the Doctorate, in which creation and/or expansion of her CKMM, AKMM, cPCKMM and pPCKMM were evidenced; (iv) in the postdoctoral context, in which the manifestation of other important CKMM, cPCKMM and pPCKMM supported our identification of the expansion and resignification of her view on aspects of MBT and on how this teaching perspective is related to other science education topics (as NOS). Finally, by teaching in both secondary schools and universities, Lizi had opportunities to develop her TPKMM (especially pPCKMM) when planning and conducting activities, subjects and workshops aimed at MBT. In such a process of TPKMM development, we characterized *filters,* basically concerning the promotion of MBT from the teaching perspective, and *amplifiers*, related to learning from this perspective (from the teacher or in relation to her view on student learning).

Wertsch (1998) considers that studies on developmental paths point out some final point(s). In the current study, what characterized such point were the statements of Lizi about her views on ways of practicing and conceiving MBT from the perspective of the present (Figure 6), which showed a very broad understanding of this teaching perspective. In this scenario, we also identified evidence of transformation and resignification of TPKMM and the factors that influence them. This is in line with the theory of mediated action since Wertsch explains that it is generally when we look at forms of mediated action that we have carried out in the past, comparing them with similar actions that we have carried out in the present, that we are able to understand how they develop either in terms of restriction or in terms of expanding their possibilities.

In order to favor the visualization of the process, in Figure 8[5] we represent the TPKMM developmental path taken by Lizi, that goes back to the process narrated by her. In it, we emphasize the turning points in her trajectory in terms of TPKMM and contexts of their occurrence.

The identification of the turning points was based on Schneider (2015), according to whom, in terms of TPK, they mean the existence of *high leverage generative* situations that can help in understanding aspects related to teacher learning. Therefore, the turning points and their associated critical didactic contexts involved changes in epistemological and practical perspectives, and are represented to characterize how the development of Lizi's TPKMM occurred over the time.

By both reflecting on the figures that characterized the critical didactic contexts and the one that characterizes the turning points in the development throughout her life trajectory, and associating them, we were consistent with the notion of development advocated by the theory of mediated action. This is so because, according to Wertsch (1998), development in terms of mediated action implies: (i) the idea that such development is not based solely on aspects of the individual's mind or any elements of mediated action considered in isolation, but takes into account the irreducible tension between agents and mediational means in every socio-historical framework; (ii) the assumption that aspects of mediated action are not always empowering or arise only in response to the needs of agents, but that they can also be restrictive and arise from unforeseen circumstances (or accidents); and (iii) a notion of intrinsic directionality of the process that serves to distinguish it from chance or directionless change. Furthermore, one cannot speak coherently about development without postulating an ideal end point (Wertsch, 1998, p. 36).

Thus, these issues also allow us to state that, holistically, the developmental path of Lizi's TPKMM has been progressive (but not linear) up to the present time. This may be generalized to any developmental path of TPK, since teachers have diversified experiences throughout their professional lives. Therefore, we emphasize the importance of unprecedented educational situations in the development of TPK (because, based on them, a teacher can modify or expand his/her pedagogical education), since they may be crucial for changes in perspectives, postures or educational actions. Such situations are marked by tensions and intensive learning and, sometimes, characterized by the transition between preparing for acting as a teacher, and starting to do so.

[5] This graph does not follow the time scale of occurrence of critical didactic events. Orders of magnitude are approximately ordinal and not proportional.

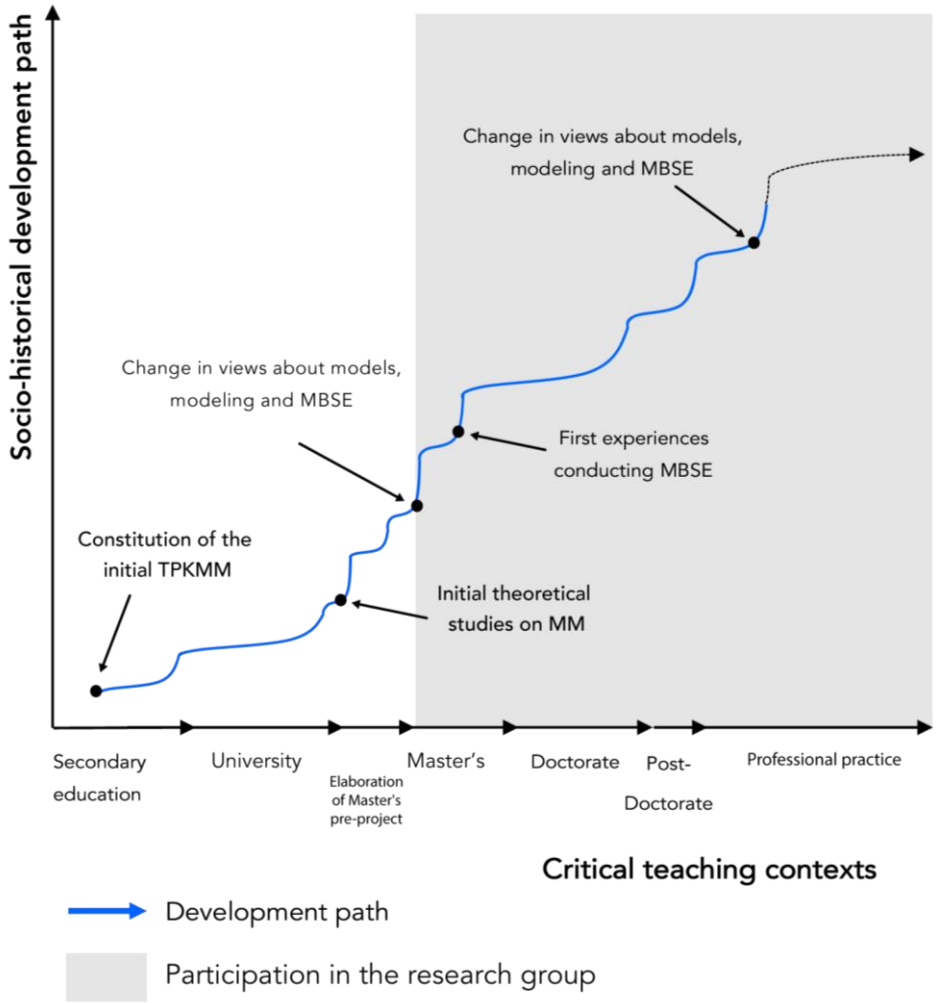

Figure 8 – Turning points in the development of Lizi's *TPK* throughout her life trajectory.

Finally, we emphasize that the Theory of Mediated Action (Wertsch, 1998) was essential in this study because it allowed us to carry out the analysis without losing sight of the unit of analysis it proposes. This reflected a broader, and at the same time coherent, vision of TPK development processes in a procedural and historically situated way.

FINAL THOUGHTS AND QUESTIONS

Life trajectories are sets of complex processes, consisting of practices, life stages and contexts that are interconnected (Bolzan, & Isaia, 2010). Revisiting science teachers' life trajectories from their memories can be a way to understand aspects that influence and are part of the development of their TPK, without losing sight of specific and fundamental details such as their primary experiences as students. When the gaze falls on long periods of time (as happened in our study that went back more than 20 years of Lizi's history), interviews are useful instruments for recovering information, sometimes forgotten or lost in memory, but important for the characterization, even partial, of such development.

Specifically concerning the MBT context, Gilbert and Justi (2016) emphasize the importance of teachers experiencing MBT situations to build a comprehensive understanding of this educational perspective by constructing and developing

> "a flexible and dynamic network of knowledge, skills and abilities related to all the elements and epistemic practices involved in modelling. This means much more than what the literature describes as teachers having to learn about models and modelling in exposition-based 'science methods' courses. That is certainly necessary but not sufficient" (Gilbert, & Justi, 2016, p. 258).

Returning to the Science Education literature, TPKMM have already been focused on other studies (for instance, Crawford, & Cullin, 2004; Justi, & Gilbert, 2002; Justi & van Driel, 2005). However, almost all of them investigated teachers' professional development in initial or continuing education when they participate in short term courses. Therefore, our study advances a little further by: (i) investigating the development of TPKMM of an experienced professional and specialist in MBT by considering teaching in terms of human action [in mediation], on the one hand, and the cultural, institutional and historical contexts in which this action occurs, on the other (Wertsch, 1998, p. 24); (ii) investigating her different learning contexts and those of the students to whom she taught, as well as different modes and sources of construction, mobilization and modification of her TPK, both in theory and in practice; (iii) presenting results of such a development over an extensive period of time (about 20 years) and contemplating so many and varied contexts of manifestation of such knowledge without losing sight of the property of the mediated action developmental paths and how it characterized her teaching trajectory in terms of TPKMM; (iv) using a model for teachers' knowledge – the RCM (Carlson, & Daehler, 2019) – that, to our knowledge, had not been used for studies on the development of TPKMM of science teachers educators; (v) considering the context of the basic education of the subject when analyzing the overall development of her PCK, since such context shed relevant lights on both details of early origin of her PCKMM and its development; and (vi) identifying, characterizing, and relating transitional points in her history that influenced or were part of the development of her TPKMM.

By assuming the theoretical, methodological and content related issues above identified, the current study can have possible implications for the field of teachers education mainly derived from its innovative focus on studying a teacher's sociohistorical life. This may support a comprehensive understanding on how both situations in teachers' life and revisiting such situations may be decisive for the development of their TPK on a specific topic. Therefore, we advocate that studies from similar perspectives can offer opportunities and facilities for teachers to reflect on regular teaching experiences and be able to articulate and share experiences to articulate their TPK (Henze et al., 2008).

By also assuming the Vygotskian socio-historical learning perspective in teachers' education contexts, identifying and understanding important situations and turning points of teachers' history on certain classes related Science Education topics may favor the recognition of the ways in which we learn to teach. This may become a strategy used by teachers' educators who intend to distance themselves from obsolete practices focused on traditional canonical training, generally and almost exclusively based on theoretical studies on Science Education topics (Roth & Jornet, 2014). As such educators value teachers' idiosyncratic personal developmental paths, the meanings of shared teaching and learning experiences can either be expanded (for instance, by giving visibility to different forms of PCK) or help them understand how TPK can be identified and characterized from their own educational stories. If we think about this articulation in terms of MBT classes, this seems to make a lot of sense, as it is a teaching approach that, despite being little widespread in our country, deserves special attention in teachers' education contexts mainly due to its potential to promote learning *of* and *about* science.

Thus, one of the general questions that we raise from this study is whether we, researchers, are taking due care in not excluding and/or dissociating teachers reflective practice from their socio-historical contexts of diverse educational practices when trying to analyze aspects of their TPK development. If such a development is a dynamic and non-linear process – as emphasized by Carlson and Daehler (2019) and van Driel and Berry (2012) – and that occurs in the long term (van Driel et al., 2014), are we attentive to these aspects when investigating changes in TPK over time? From what our study demonstrates, if we do not take these aspects into account within a framework that considers cultural, institutional, and historical contexts (Wertsch, 1998), we would be reductionists and would lose sight of important aspects of this development.

Thus, the current study helps to fill a gap pointed out by Park (2019) about the existence of few studies in Science Education that highlight contextual factors or situations related to TPK in terms of teacher's life stories. According to Park, most studies on TPK are limited to addressing specific science classroom environments and do not include descriptions of broader contextual factors, such as curricular influences, school environment and interactions between subjects. As suggested by Justi and van Driel (2006), such descriptions may help us to identify direct and superficial changes in their knowledge from more complex but specific and lasting changes, as the existence of turning points (something that we made evident in this study).

As future developments of this study, we envision possibilities of analyzing how Lizi's teaching identity was constituted during the development of her TPKMM, as well as how her current practice is influenced by the whole developmental process lived by her – which will be focused on additional analysis of our broad case study. We also recognize the importance of analyzing developmental paths on aspects of TPKMM in other science education topics, which could support the establish of relations between TPKMM and TPK on NOS, for instance. This last point is particularly promising as intersections of different approaches with MBT were

observed elsewhere in our broad study. Future research may also seek to investigate, for long periods of time, how TPKMM are manifested in the paths of beginning teachers in MBT when they promote it, which would allow the establishment of relationships with results such as those obtained in the current study. We view the identification of new aspects to be studied (in the data themselves or related to them) as another important contribution, since additional questions are essential for the production of new knowledge, so that the understanding (of each of them and the TPK in general) is expanded in the literature on Science Education.

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