Chapter 1
Introducing a Framework for Modeling Competence

Annette Upmeier zu Belzen, Jan van Driel, and Dirk Krüger

1.1 Introduction

The purpose of this chapter is to locate the book's idea within a larger context regarding the definitions of models, modeling, and competence, beginning by describing the increasing relevance of models over time and resulting in the presentation of a competence-based approach for structuring different aspects and levels of modeling competence.

The "career" of the term "scientific models" began in the 1980s[1] and was related to shifts "[…] *from disregard to popularity, from formal accounts to a functional characterization of models, from the role of models in science to their role in human cognition*" by Bailer-Jones (1999, p. 24).

The disregard is related to the substitutive role of models as appendices to theory without their own relevance to scientific thinking. The gain in popularity began when models were considered relevant for scientific discovery and thus theory change, which led to an increasing focus on the functions of models in research

[1] A database research study in Scopus revealed an increasing number of publications on the terms "scientific models," "models," and "modeling" OR "modelling" between 1980 and 1990 at the time of this writing (query dated 10.01.2019).

A. Upmeier zu Belzen (✉)
Department of Biology, Biology Education, Humboldt-Universität zu Berlin, Berlin, Germany
e-mail: annette.upmeier@biologie.hu-berlin.de

J. van Driel
Department of Education, Melbourne University, Melbourne, Australia

D. Krüger
Department of Biology, Biology Education, Freie Universität Berlin, Berlin, Germany

A. Upmeier zu Belzen et al. (eds.), *Towards a Competence-Based View on Models and Modeling in Science Education*, Models and Modeling in Science Education 12, https://doi.org/10.1007/978-3-030-30255-9_1

processes. In this, a universal conception relying on formal accounts of models was displaced, and a characterization open to a diversity of conceptions corresponding to different functions arose. But still, understanding the different roles of models in science means understanding the epistemology *of* science in the sense of a property of science. However, from a rather constructivist perspective, research is more about sensemaking and figuring out personal epistemologies *for* science. In the latter, the function of models is considered not just within science but also in human cognition so that models are now also viewed as tools of actual scientific thinking (Bailer-Jones, 1999; Russ, 2014).

Nevertheless, the roles of models remain twofold. Models as media are needed to communicate about scientific research and to convey content learning in schools. Using models in the sense of a modeling practice means using models and modeling as research tools for inquiry purposes to gain insights into previously unknown aspects of a phenomenon (Krüger, Kauertz, & Upmeier zu Belzen, 2018; Upmeier zu Belzen & Krüger, 2010).

1.2 Theoretical Background

1.2.1 Relationships Between Modeling and Other Inquiry Practices

The process of modeling can be considered a concrete inquiry practice in which hypotheses about a phenomenon are derived from an initial model with a certain theoretical focus about a structure, process, or system (Upmeier zu Belzen & Krüger, 2010). In science education, basic inquiry practices consist of observing, comparing, and classifying as well as experimenting (Nowak, Nehring, Tiemann, & Upmeier zu Belzen, 2013). Against this background, the question of the position of modeling arises and can be answered from either an explicit or implicit position. Scientific modeling might be seen explicitly as one method alongside others (Fig. 1.1). Alternatively, modeling steps might be considered integral within all inquiry processes (cf. Hartmann, Upmeier zu Belzen, Krüger, & Pant, 2015; cf. Lehrer & Schauble, 2015, p. 707). In the latter, inquiry practices in general are considered modeling activities, each with specific characteristics of scientific thinking that depend on the content and scientific question and result in specific hypotheses and investigations (Fig. 1.1). Both trains of thought are allowed, each with a different main emphasis. Treating a modeling process as a practice of inquiry is helpful for teaching and learning because models and modeling can be experienced in their epistemological functioning as research tools for human cognition. From a philosophical point of view, the two ideas focus on the reasoning behind the modeling activities and, at the same time, the semantic view of models and modeling (Sect. 1.2.3).

Scientific thinking / Inquiry practice	Observing	Comparing/Classifying	Experimenting	Modeling
Research question on …	… functional relationships between systems (e.g. structure and function)	… criteria, categories, orders	… causes and effects	… modeling variables of phenomena
Hypothesis on …	… relations	… differences	… causes and effects	… all kinds of hypotheses
Investigation as …	… systematic observations of features with feature types or over time	… comparisons, categorizations, systematizations	.. controlled experiments	… all kinds of investigations
Results in terms of …	… correlations between variables, descriptions of features, structures, and systems, possibly over time	… categories and category systems, possibly hierarchical, matrices of objects and superior comparison criteria	… relations between causes and effects, causal explanations	… findings about a phenomenon or changing of the model

Fig. 1.1 Matrix of scientific thinking and inquiry practice

More recently, the idea of using models and modeling as personal cognitive tools for inquiry has become increasingly prominent. Therefore, different types of inquiry and reasoning have been discussed, such as modeling pedagogies (Campbell & Oh, 2015), reasoning styles (Osborne, 2018), and modeling frames (Louca, Zacharia, & Constantinou, 2011). These alternative structures of cognitive strategies during inquiry processes help in both school practice and science education research and can be applied to models and modeling as well as to other methods of inquiry.

1.2.2 Teaching and Learning with Models and Modeling for Inquiry and Thinking

To use models and modeling for scientific thinking and inquiry practices in schools, it is necessary to consider the perspective of learners and learning. Science education curricula (e.g. KMK, 2005; NGSS Lead States, 2013; NRC, 2012) entail standards to bring knowledge into action in terms of skills, performances, or competences. Research findings have suggested that models are used as media to describe and understand content rather than as research tools to gain new knowledge and to understand the role of scientific inquiry (Grünkorn, Upmeier zu Belzen, & Krüger, 2014). When using models and modeling for inquiry, expressive and exploratory modeling are the most commonly used pedagogies in science education, whereas cyclic modeling is used the least (Campbell & Oh, 2015; Krell & Krüger, 2016).

Against this background, one reason to publish this volume is to strengthen the systematic application of models and modeling in science education to go beyond their use as media. Their use as media will always remain important for teaching and learning content knowledge, but this use of models is not sufficient and must be complemented with the use of models as research tools when the goal is to acquire competence in scientific thinking and inquiry practices (Fig. 1.1).

1.2.3 Modeling Student Learning in Competence Models

At this point, models of student learning must come into play. For example, student learning can be modeled with competence models or learning progressions, two prominent examples from different cultural backgrounds (Upmeier zu Belzen, Alonzo, Krell, & Krüger, 2019). They have in common that they model a skill or a competence to be acquired. This book broadly discusses the competence-based approach to models and modeling. Along with Koeppen, Hartig, Klieme, and Leutner (2008, p. 68), Rychen and Salganik (2003, p. 43) defined the construct of competence coherently as "domain-specific cognitive dispositions that are required to successfully cope with certain situations or tasks, and that are acquired by learning processes." An essential element of this definition is the contextual specificity and learnability of competence, as it has been introduced as an alternative to the focus on context-independent cognitive dispositions that are limited in learning (e.g. McClelland, 1973; "Testing for competence rather than for 'intelligence'"). "In contrast, competences reflect a person's potential to meet cognitive demands in specific areas of learning and behavior" (Koeppen et al., 2008, p. 62) in order to successfully solve problems in various situations (Klieme, Hartig, & Rauch, 2008). Competences "are, thus, more closely related to 'real life.'" Connell, Sheridan, and Gardner (2003, p. 142) concisely characterized competences as 'realized abilities'" (Koeppen et al., 2008, p. 62). In other words, competences are latent and complex constructs that encompass both the knowledge and skills that manifest during performance. However, according to Ropohl, Nielsen, Olley, Rönnebeck, and Stables (2018), the concept of competence is still under discussion due to its many components. Whereas cognitive aspects are always considered part of competence and therefore included in competence models, volitional components are often not considered (Koeppen et al., 2008).

Competences or performance expectations describe current goals for education rather than content lists students should learn (Koeppen et al., 2008). Models of student learning provide information about educational goals, curricula, teaching, and assessment (e.g., Gotwals, 2012; Reusser, 2014). As such, they mediate between standards, educational goals, teaching activities, and student learning. Thus, they can support lessons tailored to students' learning needs (e.g., Alonzo, 2011).

Competences in terms of an expected outcome of learning processes are empirically investigated, and competence characteristics are diagnosed as clearly as possible using test procedures. With a focus on models and modeling in science education, modeling competence has been defined and structured in a framework for modeling competence (FMC) that incorporates both, models as media and models as research tools. Empirical studies have shown that the assumed structure is predominantly supported and can thus be used as a basis for the evidence-based promotion of modeling competence (Krell, Upmeier zu Belzen, & Krüger, 2016). As models and modeling are the central constructs of the FMC, we offer a theoretical clarification of them in the following.

1.2.4 The Term "Model"

Models are the central tools and resources of science. Models are used as tools to gain new insights and as media to communicate already known facts (Gilbert & Justi, 2016; Giere, Bickle, & Mauldin, 2006; Gouvea & Passmore, 2017; Passmore, Gouvea, & Giere, 2014). The scientific importance of models also explains their use in the science education curricula of schools around the world (e.g., in Germany (KMK, 2005); in the U.S. (NRC, 2012; NGSS Lead States, 2013)).

Given the importance of models, it may be surprising that in interdisciplinary discourses, no general classification systems are available for models (Mittelstraß, 2005), and even within the sciences, different classifications of models have been proposed in education research (e.g. Crawford & Cullin, 2005 for Biology; Justi & Gilbert, 2002 for Chemistry; Kircher, 2015 for Physics, pp. 804ff). These categorizations, which are phenomenologically oriented (Ritchey, 2012) or ontologically oriented (Oh & Oh, 2011), do not produce a satisfactory result because they provide only a one-criterion-based system without demonstrating insights into the functions and epistemologies of these models. However, what these models do have in common is that they are all connected by subject, purpose, and time (Giere, 2010; Stachowiak, 1973). People can therefore judge and interpret models as representations of original objects, phenomena, or systems of the experiential world. These representations depict the experiential world and also allow a person to derive and test hypotheses for a particular purpose and for a limited period of time. From the need to optimize models when needed, it follows that no one can claim that there is only one valid model. Because of this, models have focused meaning and a limited scope, that is, a special theoretical focus.

Despite the recognition of the scientific importance of models and modeling, there is no unified definition of the concept of the model in science and science education (Agassi, 1995; Gilbert & Justi, 2016; Sect. 1.2.2) nor is there a unified modeling theory (Ritchey, 2012). Mittelstraß (2005, p. 65) provided a general framework: "Models are replicas of a real or imaginary object with the aim of learning something about it or learning something from it." Mittelstraß pointed to both the descriptive and the research function of modeling. Special approaches to the concept of models have been presented by scientists in Cognitive Psychology (e.g. Nersessian, 2008), Philosophy (e.g. Bailer-Jones, 2003; Giere, 2010), Computer Science (e.g. Mahr, 2012), and subject-related Education Research (e.g. Gilbert & Justi, 2016; Gouvea & Passmore, 2017; Upmeier zu Belzen, 2013). Different terms have been used in their definitions of models: e.g. mental model (Nersessian, 2008), representation (Giere, 2004), theoretical model (Upmeier zu Belzen, 2013), abstractor, or analogy (Oh & Oh, 2011). Nersessian (2008, p. 93) defined a mental model as a "structural, behavioral, or functional analog representation of a real-world or imaginary situation, event, or process." In Giere's (2004) early view, models were described as representations of natural objects, processes, or phenomena that have been developed for a particular purpose and have a similarity to what they represent. When such models relate to the world, hypotheses arise with regard to adapting a model to a particular section of the world. In the most recent discussions (Mahr, 2015), this ontological definition of the concept of models is based on the existence of the represented steps of the model object in the background, and an epistemological position is taken in which models are used to understand the experiential world. For example, Giere (2010, p. 269) wrote: "Agents intend to use model M to represent a part of the world W for some purpose P." In this definition, the role of the modeler is significant when an object is used as a model. From this point of view, there are two conclusions that can be drawn: Depending on the purpose, there can be several models for a phenomenon that allow different applications so that one and the same representation can be used for different purposes (Gilbert & Justi, 2016, p. 21). To account for this epistemological function of models, models should not solely be considered as representations that are judged by how well they fit the particular phenomenon (Gilbert & Justi, 2016; Gouvea & Passmore, 2017). Rather, the nature of models as cognitive tools should be emphasized. Gouvea and Passmore (2017) suggested talking about *models for* (as method) instead of *models of* (as media). According to Gilbert and Justi (2016, p. 21), it helps to conceive of models as substitute systems (see Mäki, 2005) or to describe models as epistemic tools (Ritchey, 2012). This opens the tool-like character of the models for exploration (Gouvea & Passmore, 2017; Passmore et al., 2014).

1.2.5 The Idea of Model-Being

More and more authors are approaching the concept of models from an epistemological point of view (Gilbert & Justi, 2016; Mahr, 2012, 2015; Passmore et al., 2014). In this case, something becomes a model when it is used (Giere, 2010), developed (Ritchey, 2012), or conceived (Mahr, 2015) by a subject as a model because the subject made a judgment about model-being. A consistent epistemological perspective is presented through Mahr's (2015) model of model-being in the following approach. It can be used as a basis for theoretical justifications in the levels of modeling competence (Upmeier zu Belzen & Krüger, 2010).

Because the term "model" is a homonym with different meanings (e.g. for people from the fashion industry or art, true-to-scale organ sculptures, mathematical systems of equations, architectural designs, or map drawings), Mahr (2015) refrained from investigating and defining the ontological properties of models. Rather, he tried to epistemologically elucidate why an object is conceived as a model. He distinguished between an imagined (mental) model (e.g. climate change) and a model object that represents the model in the broadest sense (computer simulation of climate change). According to Mahr (2015), the mental model is thus represented by the model object, where it has two relationships to the perception of a subject: it is both a model *of* something and a model *for* something (cf. Gouvea & Passmore, 2017). These constructive relationships, being a model *of* something (perspective of construction; Fig. 1.2) and being a model *for* something (perspective of application; Fig. 1.2), justify the judgment of model-being (Mahr, 2015; Passmore et al., 2014).

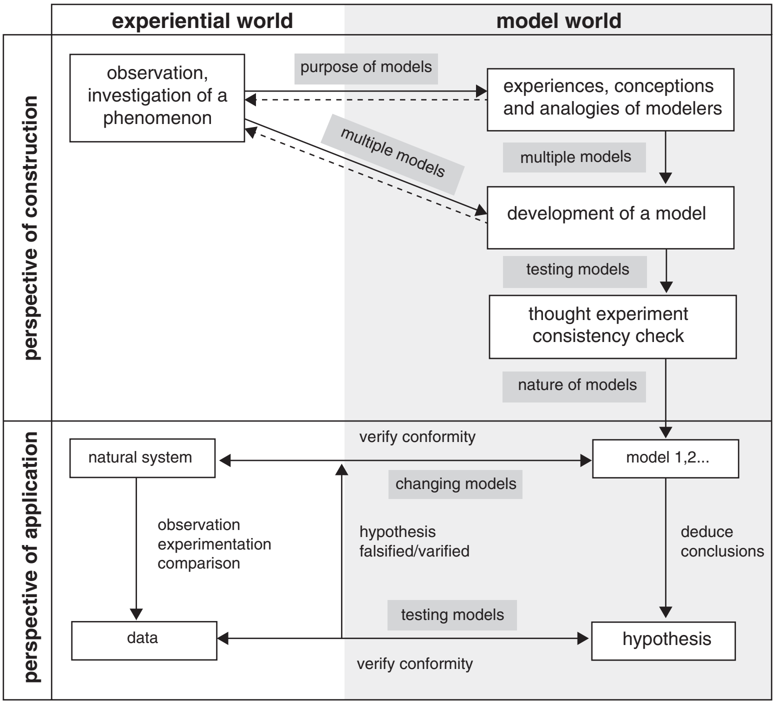

Fig. 1.2 Framework for the modeling process (Krell et al., 2016). Gray boxes indicate aspects of the FMC (Fig. 1.3) when going through inquiry processes

With this definition, Mahr (2015) provided conditions that, separated from inherent properties permanently associated with the model object, conceived of an object as a model that can be used by a person or group as a model *of* something and *for* something for a given time. The described aspects, that is, the model object that is a model *of* something (representative of a phenomenon) and, from an application perspective, a model *for* something (a medium in a mediation situation or a tool in the process of knowledge realization), can be used to think about how models are used to describe levels of competence. The relationship between a person who makes or uses the model and the model itself plays a central role. Giere (2010) described the subject as an *agent*, the person who decides both the focus of the similarities (intent) and the goal of that focus (purpose). In his approach to model-being, Mahr (2012) also consistently thinks with the subject when he distinguishes between the mental model that is modeled by the subject and the model object (i.e., the mental model externalized by the subject) as well as the creation and application of the model object. The perspectives of model-being on the model object, on the construction and application of the model provide descriptions for levels of competence. They are based on the fact that these perspectives can be considered in problem-solving situations when creating and using models (Upmeier zu Belzen & Krüger, 2010).

1.2.6 Models as Media and Models as Research Tools

Models are used in science classes when, for example, structures, processes, or systems are not immediately accessible due to their size, speed, abstractness, or ethical considerations. Models are both physical and theoretical representations of an initial object filtered through a theoretical perspective for a particular purpose. They have a representative function and are used to describe structures or to understand processes. In this perspective, models act as media that support communication and the learning of sound scientific knowledge.

Gaining new insights through scientific thinking with modeling not only explains retrospectively known processes to uninformed people by using models or modeling but also requires new hypotheses with models of phenomena that have yet to be investigated. Such uses of models and modeling allow theoretical or empirical investigations to be conducted to test hypotheses. At the center of this process is not the content-related answer that has been generated, but in order to understand and question, the generation process itself. A predominantly medially oriented ontological use of the features, structures, and categorizations of a model is therefore extended by a methodologically oriented epistemological perspective on the function of the model and modeling in a cognitive process. Models that are used methodologically as research tools contribute to the development of competences in three ways: (1) when the cognitive process of generating new knowledge is reflected through models and through modeling itself, (2) when an understanding of the nature of science is developed, and (3) when content knowledge is gained.

1.2.7 Modeling as a Process

Thereby, the particular importance of modeling becomes clear when it is recognized that modeling can be linked to scientific practices (e.g. observing, comparing, classifying, or experimenting; Mäki, 2005; Morgan, 2005; Fig. 1.1). Whereas in the case of an experiment, the isolation and manipulation of variables in the modeling process is done on a theoretical level in the model world (Clement, 2009), the isolation and manipulation of selected variables follows a material transformation in the experiential world (Mäki, 2005). This allows an empirical examination of predictions in the experiential world, predictions that have been derived from modeling (Giere et al., 2006; Fig. 1.2).

If the hypotheses derived from the model contradict the data, then the conclusion that the model and the system are mismatched can be drawn. In this case, the model has to be optimized or the concept of the modeled phenomenon has to be changed. This requires a new test and demonstrates the cyclical character of the modeling process. In the hypothesis-based comparison of the theoretical model world and the experiential world (Giere et al., 2006), the functions of modeling are recognized as a method of finding scientific knowledge.

Modeling is a complex process that is fundamental to both scientific knowledge generation and people's problem-solving skills (e.g. Nersessian, 2008). Various authors have described the purpose-oriented design as well as the corresponding testing and modification of (mental) models from different perspectives, for example, cognitive-psychological (e.g. Nersessian, 2013) or the school context (e.g. Clement, 1989; Fleige, Seegers, Upmeier zu Belzen, & Krüger, 2012; Gilbert & Justi, 2016).

In principle, the process of modeling dispenses with a strict procedural description and the definition of certain rules because modeling can be seen as an art with creative elements (Morrison & Morgan, 1999). Therefore, it is not only theory or data that determine modeling, but modeling also depends on the intuition and experience of the modeler, as in the case of the hypothetical-deductive approach to knowledge generation (Clement, 1989). Nevertheless, it is possible to identify recurring elements arranged according to the ideal type of research logic (Popper, 2005), which can also be used in other practices, for example, in a scientific observation or an experiment. The starting point of the modeling process is an observed phenomenon, which, taking into account the purpose of the model and the prior knowledge and experience of the person doing the modeling, leads to a first draft of a model that presents the relevant variables of the phenomenon. This step is referred to as the construction of a mental model (Nersessian, 2008), initial model (Clement, 1989), or proto-model (Gilbert & Justi, 2016) and is performed on a mental level. First, an attempt is made to identify a known suitable or analogous (professional) model by means of an observation. If this cannot be achieved or is insufficient, new model elements and links are generated on this basis. In the development of the model, the internal consistency and fit to the phenomenon are examined. The process results in one or more externalizations, which can be referred to as the model object(s) (Mahr, 2015). The model object as a medium focuses on selected variables of the system. In addition, hypotheses can be derived from the conceptual model or model object about how the system will behave under certain conditions. Experimental investigations, comparisons, or systematic observations then lead to results that confirm or falsify the hypotheses that are being considered (Krell et al., 2016; Figs. 1.1 and 1.2).

As explained above, there are several approaches for describing modeling. So far, the process of modeling has been described rather generally. An attempt to develop a unified theory for this purpose was made by Ritchey (2012). He first defined a scientific model as consisting of at least two mental constructs (e.g. light as a physical variable and photosynthesis rate as a chemical variable) that can be interpreted as variables or dimensions and can be experimentally investigated. The modeler has to build relationships between these constructs or variables, e. g. a causal relationship. In addition, Ritchey (2012) characterized five features of modeling: The constructs can take on values or be nominal (no value), the contexts can be directed or not, their relationships can but do not have to be quantified, the relations can be cyclic or acyclic, and the type of relation can be mathematical/functional, probabilistic, quasi-causal, or non-causal (logical, normative). Ritchey (2012), however, allowed additional attributes to be assigned to a modeling process (e.g., continuous/discrete), but he left it with these five properties and identified 42 plausible modeling types with specific combinations of these properties.

In summary, models and modeling in science have two main functions. By externalizing a conceptual model in the form of a model object, scientists can communicate their ideas about a phenomenon and discuss it with others. Models are primarily used as media that transport and communicate the state of research. In addition, science gains new knowledge by applying and testing these models. In this sense, models are used as research tools for gaining knowledge and allow to reflect about the inquiry process.

1.3 The Framework for Modeling Competence

The FMC was developed for science education purposes and involves the use of models as research tools and modeling as a research practice. This notion of models and the reflection of the modeling process are interdisciplinary and considered part of a scientific understanding (Gobert et al., 2011; Reinisch & Krüger, 2018) that has been conceptualized as “a type of nature of science understanding” and encompasses “how models are used, why they are used, and what their strengths and limitations are in order to appreciate how science works and the dynamic nature of knowledge that science produces” (Schwarz et al., 2009, pp. 634–635). Therefore, modeling competence includes the ability to gain insightful knowledge with models, to be able to judge models with regard to their purpose, and to reflect on the process of gaining knowledge through models and modeling (Krüger et al., 2018; Upmeier zu Belzen & Krüger, 2010). Thus, the framework provides a theory-based overview of how students and pre- and in-service science teachers should understand models and modeling in science.

1.3.1 Competence as an Ability to Reflect on Models and Modeling

Building on different structural approaches in the natural sciences (e.g., Crawford & Cullin, 2005; Grosslight, Unger, Jay, & Smith, 1991; Justi & Gilbert, 2003), Upmeier zu Belzen and Krüger (2010) differentiated between five theoretical aspects of modeling competence (Fig. 1.3). These aspects were based on the results of international studies on students’ (e.g., Grosslight et al., 1991) and teachers’ (e.g., Crawford & Cullin, 2005) conceptions of models and modeling: *nature of models, multiple models, purpose of models, testing models,* and *changing models* (Krell et al., 2016; Krüger et al., 2018; Upmeier zu Belzen & Krüger, 2010). Further, for each aspect, they identified levels that are based on Mahr’s (2015) conceptualization of model-being. The proposed structure (five aspects with three levels each)

Aspects	Level I	Level II	Level III
Nature of Models	Replication of the phenomenon	Idealized representation of the phenomenon	Theoretical reconstruction of the phenomenon
Multiple Models	Different model objects	Different foci on the phenomenon	Different hypotheses about the phenomenon
Purpose of Models	Describing the phenomenon	Explaining the phenomenon	Predicting something about the phenomenon
Testing Models	Testing the model object	Comparing the model and the phenomenon	Testing hypotheses about the phenomenon
Changing Models	Correcting defects in the model object	Revising due to new insights	Revising due to the falsification of hypotheses about the phenomenon

Fig. 1.3 Framework for modeling competence with five aspects and three levels

has been extensively investigated (cf. Krell et al., 2016); nevertheless, it should be interpreted as a nominal category system until it can be regarded as an empirically validated developmental model (cf. Kauertz, Fischer, Mayer, Sumfleth, & Walpuski, 2010). The levels (Fig. 1.3) are theoretically described as follows:

Level I: The ability to assess the appearance of the model object (cf. Mahr, 2015) from an aesthetic point of view or technical functionality without putting the phenomenon in relation to the model object, except in its capacity as a copy or for the purpose of illustrating; the model object is judged as such.

Level II: The ability to assess the process of model construction; primarily, there is a focus on the model as media use of the model object as a more or less accurate representation of a phenomenon; the model object is representative *of* something already known in the natural sciences.

Level III: The ability to use a model in an application as a tool for investigating a phenomenon and thereby assessing its productivity; the model object as a model *for* something leads to the processing of new, thus far unexplained, scientific questions.

The aspects and their gradations can be described as follows:

Nature of models: The ratio of the similarity between the model and the phenomenon is assessed as a model *of* something. Competence is expressed in the different meanings of the model object as a true-to-life replica (level I), as an idealized representation (level II), or as a theoretical reconstruction of a phenomenon (level III).

Multiple models: Reasons are assessed for the existence of several models that represent one phenomenon. The variety of models is characterized by differences between the model objects (level I), different areas of focus in the construction of the models (model *of* something, level II), and various assumptions about a phenomenon and the application of the models in further examinations (model *for* something, level III).

Purpose of models: The purpose of models is to guide the corresponding process of modeling. If the purpose of models is to illustrate (level I) and explain (level II) something with educational intentions, then models are used as media (models *of* something). However, if the purpose of models is to derive a prediction from them, they become a model *for* something with the perspective of application as a tool in the generation of knowledge (level III).

Testing models and *changing models*: The levels describe different ways and reasons to test and to change models. Level I is about tests and optimizations at the model object only. On level II, the model object is often parallelized with the phenomenon and is improved in the case of misfit. On level III, the model object as a model *for* something is tested through the verification of previously derived hypotheses and changed when the hypotheses are rejected.

The aspects and levels represent perspectives of reflection, which not only receive their meaning in an abstract, cognitive reflection on the term model but are relevant under the competence-based perspective in subject-related problem-solving situations at different stages of the cyclic process of modeling (Fig. 1.2).

1.3.2 Empirical Investigations

The theoretically based FMC (Fig. 1.3) has been empirically examined and the results have been incorporated into its further development (cf. Krell et al., 2016). The framework is based on qualitative interview studies on the perceptions of students and teachers with regard to models and modeling and the roles of models and modeling in an inquiry process (e.g., Crawford & Cullin, 2005; Grosslight et al., 1991; Krüger et al., 2018). Furthermore, when using open-ended tasks, initial levels have been identified for the aspects of *multiple models* (rejecting the existence of multiple models), *testing models* (rejecting the testing of models), and *changing models* (rejecting the changing of models; Grünkorn et al., 2014).

Using quantitative methods, the extent to which the structure of the FMC (aspects, levels) can be empirically supported (e.g. Terzer, Hartig, & Upmeier zu Belzen, 2013) has been examined. From an educational point of view, the organization into the aspects has great diagnostic potential (Fleige et al., 2012). Empirically, however, it has not yet been conclusively clarified whether modeling competence can be viewed as a five-dimensional (Krell, 2013) or one-dimensional construct (Terzer, 2013). By contrast, the assumption of three ordinal levels was substantiated except for the aspect of *testing models* (Krell, 2013; Terzer, 2013).

A longitudinal study for evaluating the FMC as a development model in Grades 7 to 10 has shown that students' (13–16 years) modeling competence results in a significant development, but the effect sizes were small (Patzke, Krüger, & Upmeier zu Belzen, 2015). Also, the modeling competence of pre-service biology, chemistry, and physics teachers has demonstrated development throughout several studies in the aspects *purpose of models, testing models*, and *changing models* (Hartmann et al., 2015; Mathesius, Upmeier zu Belzen, & Krüger, 2014).

Successfully training pre-service biology teachers with an explicit reflection of the FMC (Fig. 1.3) led to a significant increase in modeling competence in all five aspects with average effect sizes (Günther, Fleige, Upmeier zu Belzen, & Krüger, 2019). However, students who were taught by these trained teachers did not benefit from the increase in their teachers' modeling competence. The results showed that teachers with an elaborate modeling competence did not have adequate diagnostic competences to foster students' modeling competence (Günther et al., 2019).

Additionally, a tool with forced-choice tasks to receive immediate feedback was developed and validated in order to diagnose students in the aspects *nature of models* and *purpose of models* (Gogolin & Krüger, 2015, 2018). The tool makes it possible to offer individual support measures and to evaluate students' success directly.

1.4 Conclusion

In summary, with the FMC, we structure the different theoretical aspects and levels of modeling competence as a basis for teaching and learning. In order to use the FMC for evaluation purposes in certain domains, it has to be adapted with regard to content because the FMC is content free. Bearing in mind the presented perspectives (Fig. 1.3), it is possible to evaluate whether students or pre-service or in-service biology teachers exhibit more or less elaborated performances while solving tasks with certain contents. The FMC allows a person's potential to solve problems in varying situations with models and modeling to be assigned to different levels of the five aspects (Upmeier zu Belzen & Krüger, 2010). Whereas cognitive aspects are considered in the FMC, volitional and behavior-related components are not directly included although they are needed to show modeling competence.

The FMC is located between the theory of competence and competence-oriented teaching in special domains, (Upmeier zu Belzen et al., 2019). It is derived from teaching methodology, the psychology of learning, and the philosophy of science. Although the FMC has been conceptualized as a structural model, empirical evidence that the levels are hierarchically ordered still has to be provided before it can be considered a developmental model (cf. Schecker & Parchmann, 2006).

The FMC provides a strong foundation for empirically testing the structure of modeling competence, and it can support the understanding of the aspects and levels of modeling competence and student learning as well as the development of curricular materials (Fleige et al., 2012; Rahmenlehrplan Berlin/Brandenburg, 2015). Two main functions of models need to be highlighted in this context: By developing a model object as a representation of the model, scientists are able to communicate their conceptions about a phenomenon and discuss it with others. In this case, models are primarily used as media (level I and level II) that carry the state of scientific knowledge. In addition, science is gaining new knowledge by applying and testing models. In this sense, models are used to generate hypotheses about unknown phenomena (level III). Models in this sense are research tools that are used to gain new knowledge. The FMC provides an integration of ontological, procedural and epistemological functions of models and allows researchers to determine students' and pre-service and in-service teachers' modeling competence.

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