TOWARDS A CATEGORIZATION OF SCIENTIFIC MODELS

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ABSTRACT: In this paper, we discuss the existence of a specific criterion on which modern scientists and philosophers could focus to determine the basic categories of scientific models. We first examine why the categorization of scientific models is considered significant and why this type of research might be useful for modern philosophers. Moreover, we critically approach Susan G. Sterrett's scientific models' categorization, as an initial point for further discussion on this issue. Sterrett's models' categorization is based on the nature of the system under study and the operation of the representation mechanism. Instead, we propose that the most appropriate criterion of scientific models' categorization is the nature of the model itself, as this criterion is clear, fundamental, and succeeds in eliminating the influence of the human factor during the process of classifying models as it indicates in which category every scientific model may be classified. To support our approach, we present a classification scheme of five general categories of models, which are comprehensive and distinguishable. Classifying models in such a manner can potentially impact the process of understanding and defining the notion of the scientific model in general.

KEYWORDS: theoretical models, physical models, fiction models, mathematical models, models of informatics

1. Introduction

Scientific models are significant experimental tools of modern science, widely used in various scientific fields, with dominant that of natural sciences, during the process of drawing inferences, explaining relations, controlling, and predicting the objects, systems, phenomena, or situations of interest (Frigg and Hartmann 2020; Rogers 2012). Their importance in the natural world's description, explanation, and prediction is recognized worldwide and widely accepted by researchers in different scientific fields.

The beginning of the systematic exploitation of models in scientific methodology was detected in the mid-17th century, as a consequence of the development of experimental methodology in the 17th century after the Scientific Revolution and the Enlightenment. Since the early 18th century, scientists have devoted much time to constructing, testing, comparing, and revising models (Frigg and Hartmann 2020). Typical examples of models developed at that time are the scale models used in several engineering fields and mathematical models widely used in physics. From the 17th to 19th century, scientific models were integrated and systematically applied in the experimental methodology of the natural sciences, engineering, and other scientific fields while the period from the 20th to 21st century corresponds to an attempt to understand, define, and classify scientific models as well as extending their application to many other scientific fields.

Although the technique of scientific models was an indispensable part of the experimental methodology of the natural sciences, engineering, and various other fields throughout the 18th and 19th centuries, the concept of the scientific model had not been examined by philosophers until the early 20th century when the first theories on the subject emerged. Philosophers have provided several definitions and categorizations of scientific models in recent decades. In this context, two core questions arose. The first question is: *why should categorizing scientific models from the field of philosophy of science be considered important?* The first chapter of this paper includes an attempt to address this issue. The second important issue is *the existence of a specific categorization of scientific models, capable of overcoming some important limitations due to the long-established misconceptions of the notion of the scientific model in the field of philosophy of science, such as the issue concerning the scientific nature of models-physical setups* (Bell and Machover 1977; Giere 1988, 319-323; Hesse 1967, 354-35; Hodges 2020; Sterrett 2002, 59-63, 2003, 2006, 69-80, 2017(a), 857-860). In the second chapter of this paper, the innovative and quite sufficient for the first years of 21st-century models' categorization proposal addressed by the modern philosopher of science Susan G. Sterrett is presented and analyzed. One important reason that led to the distinction of Sterrett's approach is that, through her models' categorization proposal, a long-standing fragmentary view is addressed, according to which only theoretical models can be accepted as scientific tools in contrast with physical models, which are perceived as educational tools rather than scientific techniques by a significant number of 20th-century philosophers. In this context, Sterrett's categorization of models could be considered an initial point for our critical discussion.

The notion of the scientific model is often defined as the representation of a natural object, phenomenon, or system, or as the interpretation of a theory (Frigg and Hartmann 2020; Rogers 2012). Scientific modeling is a powerful technique applied to examine a system, a phenomenon, or an object that the researcher often does not have access to, due to space or time distance of it, because of its size, or various other reasons, even ethical. A core functional mechanism of scientific models is the mechanism of similarity, which allows transferring knowledge from the model to the target system. Scientific models are connections of thoughts with reality. Even if the researcher does not have access to reality per se, these links allow him to approach reality, understand, describe, control, and make predictions about specific parts of the real world. All these parameters can justify the widespread use of models and their incorporation as an integral part of modern scientific methodology, although they also generate further complexity and questions related to the nature, classification, and operation of these tools, a fact that requires more adequate examination from the field of philosophy of science.

Modern philosophers and scientists recognize the importance of models and explore their role in scientific practice. They observe that various entities are commonly used as models, such as physical objects, physical devices, natural phenomena, imaginary constructions, and sets of theoretical structures or equations (Frigg and Hartmann 2020; Rogers 2012). Consequently, philosophers recognize a wide range of types of models utilized by a continuously growing number of scientific fields. Some categories of models that are systematically exploited in natural sciences research are theoretical models, analogue models, scale models, phenomenological models, computational models, explanatory models, testing models, imaginary models, mathematical models, mechanistic models, iconic models, etc. (Frigg and Hartmann 2020; Rogers 2012).

The huge number and the variety of scientific models that have been developed last decades often lead to confusion about their definition and categorization. Moreover, scientific models are a constantly evolving technique since existing models are often adjusted to new parameters, and new types of models are invented. Consequently, understanding, conceptualizing, and defining the notion of the scientific model are considered demanding endeavors. The categorization of existing knowledge on basic types of models is crucial to perceiving the concept of the scientific model. Especially, the classification of models into basic categories can contribute to the organization of the existing knowledge concerning models, thus, further clarifying the notion of the scientific model, regardless of the subcategory to which every single model falls. The achievement of a sufficient categorization of models can contribute to the organization and classification of models' categories and knowledge concerning models in general.

The classification of scientific models depends on the criterion that the researcher has chosen to distinguish different kinds of models. In other words, the key question that attracts the researcher's interest regarding the models determines their categorization criterion. For example, the question "*What kind of things can be considered as models?*" leads to the adoption of an ontological criterion or the question of *how we learn and explain with models* to an epistemological criterion (Frigg and Hartmann 2020; Rogers 2012).

In this context, the core question that motivates our work is: *on what criterion should modern scientists and philosophers focus to distinguish the basic categories of scientific models, which could be capable of encompassing all kinds of models?*

Thus, this paper aims to address these issues by participating in the ongoing dialogue concerning the categorization of scientific models that modern philosopher of science Susan G. Sterrett introduced during the first years of the 21st century.

2. The Significance of the Categorization of Scientific Models

Although considerable efforts have been made in recent decades to conceptualize and categorize models in the field of philosophy of science, we cannot yet consider the theoretical documentation for this technique sufficient. The rapid and continuous evolution of models along with the general acceptance of some misconceptions and fragmentary perceptions of the meaning and types of scientific models highlight the necessity for a more systematic investigation of the concept and the categories of the scientific models in the field of philosophy of science. At this point, one question arises: *why is the examination of the concept of the scientific model and the categorization of scientific models by philosophers of science considered important?* We support that the study of the concept of the scientific model and the classification of scientific models into basic categories by philosophers of science can be considered significant mainly for two reasons. The first reason arises from the detection of common misconceptions that were presented mainly during the 20th century and related to the concept, nature, function, and role of scientific models in scientific methodology. These misconceptions reveal that the conceptualization and the definition of the notion of the scientific model were fragmentary in the field of philosophy of science until the first decade of the 21st century when the discussion concerning the models enhanced and new more sufficient theories emerged. The second reason is traced to one of the basic objects of the field of philosophy of science which is the analysis of scientific methods (Losee 1993, 13).

According to a common misconception, models, specifically material models, are often treated as measuring instruments (Eran 2020; Krantz 1971, 9). This perception degrades the value and importance of the technique of scientific modeling and confirms that the understanding of this concept by some philosophers and scientists is fragmentary. A scientific analogue or material model is not just a measuring instrument, it often has the potential to provide measurement information through its application; however, it cannot be compared to a microscope, which covers the inability of the human eye to observe microscopic systems. Their main difference lies in the functional mechanism of the model that differentiates it from the microscope and measuring instruments, in general. Since a core mechanism of function of the model is the similarity. The main purpose of its function is the representation of an inaccessible or a difficult-to-access system (Sterrett 2002, 59-63, 2003, 1-3, 2006, 69-80, 2017(a), 857-860), therefore a model is not just an instrument that has been properly configured to help us observe the system of interest itself, but it has been configured to represent a system that we cannot observe directly. The scientific model might often carry quantitative information, although it does not exclusively constitute a measuring instrument, but a powerful scientific technique widely applied to various fields. Thus, a more extensive examination of this technique by philosophers and scientists could contribute to overcoming this fragmentary perception, concerning mainly the function of analogue models.

Another fragmentary perception of the concept and nature of the model, which derives from the field of philosophy of science, is found mainly in the theories developed from the first decades until the middle of the 20th century. During this period, most philosophers accepted only theoretical structures as scientific techniques (Bell and Machover, 1977, ch. 5; Giere 1988, 319-323; Hesse 1967, 354-35; Hodges 2020, ch. 1, 2, 3). According to this view, the only acceptable kinds of scientific models are theoretical models, such as theoretical or mathematical structures, while the models that are physical setups are perceived mainly as tools assisting in the educational process. This perception of the scientific model is insufficient and fragmentary, as it rejects multiple important techniques that are structured based on strict scientific criteria and are extensively used in modern scientific methodology (Sterrett 2002, 59-63, 2003, 1-3, 2006, 69-80, 2017(a), 857-860). Therefore, scientific models are not only theoretical structures but also physical setups, widely known as analogue models (Sterrett 2002, 59-63, 2003, 1-3, 2006, 69-80, 2017(a), 857-860). However, it should be mentioned that contemporary philosophers (such as Susan Sterrett, Roman Frigg, etc.) accept the scientific nature of various types of material models and several modern philosophers study this wide category of models, their operation mechanisms, and the possibilities that their application provides in modern science.

Another dogmatic but widely accepted attitude towards models emerged at the end of the 20th century. Many philosophers of science, such as Margaret C. Morrison, place the model in an intermediate stage between theory and the real world. The structure of this perspective is based on theory and leads to conclusions about real-world situations (Morgan and Morrison 1999, 10-13; Morrison 1996, 6).

This approach, although extremely interesting, is quite fragmentary as it overlooks that models are not necessarily placed on intermediate stages but, in some cases, consist of theoretical structures or components of the real world, as Susan G. Sterrett observed (2003, 1-15). Thus, the perception of a model as something different or separate from theory or reality could be characterized as limited and arbitrary to some extent. The model operates as a link between human thought and the real world, but it doesn't need to be placed in an intermediate stage or to be perceived as something different from the theory or the real world. Understanding and accepting different forms that models take can contribute to a more comprehensive and adequate understanding of the concept, the role, and the capabilities of the scientific model in scientific practice. It is also important to note that the nature of each model (whether it is a theoretical structure, an imaginary construction, or a physical device) does not affect its basic role as a link between thought and reality, or between research hypotheses, and target systems. Therefore, the scientific model is a stable connection between thought and reality, regardless of its nature.

Accordingly, a more adequate and comprehensive philosophical approach to the concept of the scientific model is considered necessary as it could contribute to further clarifying the concept of the model, contribute to its theoretical documentation, and succeed in the clear and sufficient categorization of models into basic categories.

One other reason that imposes the more systematic examination of the concept of scientific models, their role in scientific methodology and the organization of related knowledge derived from the field of philosophy of science, is defined by one of the basic objects of this field, which is the analysis of scientific methods (Losee1993, 13). In other words, the philosophy of science investigates scientific techniques, such as scientific models, analyzes them, and provides theories entailing knowledge about them, which could be used as the necessary theoretical context, upon which, the design and the conduct of their experimental application can be based (Losee1993, 15). The theoretical approaches derived from the field of philosophy of science can contribute to the collection, organization, and categorization of existing knowledge regarding models, and consequently lead to their definition and the achievement of their theoretical documentation.

According to John Losee, one of the subjects of the philosophy of science is the analysis of scientific methods while the corresponding subject of science is the interpretation of facts (Losee1993, 13). Under these conditions, the philosophers of science attempt to acquire knowledge regarding the scientific techniques or the mechanisms themselves, while natural scientists mainly focus on finding the most appropriate and effective way to apply them, to ultimately acquire knowledge concerning the natural world. In other words, in the philosophy of science, the concept of scientific models is treated as the subject under investigation while in the natural sciences, medicine, and even the economic and social sciences, these techniques are treated as scientific means, used to investigate inaccessible systems or phenomena of interest, or as interpretations of theories. The philosophy of science shapes the theoretical framework, which includes the techniques and mechanisms under consideration. This theoretical background could be understood by researchers in different scientific fields. This is an important advantage of philosophical approaches, concerning scientific techniques and mechanisms such as the technique of scientific models.

A core question concerning the concept of the scientific model in the philosophy of science is: *How could philosophers understand and define the concept of the scientific model?* To understand and define the meaning of the scientific model, an important step is to gather, organize, and categorize existing knowledge regarding models. To this end, it is considered important to gather knowledge regarding this scientific technique and various types of models, to classify them into basic categories. This process will provide important information on the various forms that this technique takes in modern scientific practice, and lead to a comprehensive understanding of the nature, role, and operation of different types of scientific models in modern science. Thus, the categorization of scientific models enhances the understanding of the concept, the role, and the capabilities that modeling techniques provide to modern science. How could this be achieved? With the overall presentation of all the basic subcategories of scientific models, frequent misunderstandings regarding the nature and function of scientific models could be addressed. Finally, if a philosopher achieves an adequate categorization of scientific models, it would be easier and more feasible to contribute a more sufficient definition for the concept of scientific models, a holistic definition corresponding to every existing scientific model.

Due to the above reasons the philosophical investigation and the achievement of an adequate categorization of scientific models can be considered an important step during the process of perceiving the concept and effectively applying the corresponding technique during the experimentation. In this framework, in the early 21st century an innovative proposal for model categorization was introduced by the modern philosopher of science Susan G. Sterrett, which succeeded in initiating a dialogue concerning the categorization of scientific models in the field of philosophy of science.

3. A Critical Approach to Susan G. Sterrett's Perspective

Since the beginning of the 21st century, Susan G. Sterrett[1] has extensively studied the concept of scientific models and has made considerable efforts to clarify that a more meticulous examination of the concept and categories of scientific models in the field of philosophy of science is required. She expressed her doubts about the degree of understanding of the concept of scientific models in the field of philosophy of science and therefore the possibility of an adequate categorization of the scientific models derived from this field. At the beginning of the 21st century, Sterrett considered the philosophical approach to the concept of models fragmentary, as it did not include a wide range of models, which are not theoretical tools of an intermediate stage but parts of the real world, such as scale models in physics and mechanics or animal models in biology (Sterrett 2002, 56-59, 2003, 1-2). However, she mentioned that philosophers did not ignore this models' category, but they perceived them more as applied art rather than formal scientific techniques (Sterrett 2003, 1-2, 10-12).

After Sterrett defined that she is not studying all kinds of models but especially models used in reasoning, models employed in making inferences, providing explanations, or promoting understanding (Sterrett 2003, 2-3), she attempted to identify the cause of inadequate categorization of models in the philosophy of science and to overcome this barrier by revising the criterion of models' categorization. Sterrett supports that the criterion of models' categorization should be the nature of the system under study, the relation between the model and the target system, and the operation of the representation mechanism. She is referring to in her article entitled Kinds of Models (Sterrett 2003, 2):

> What makes these two kinds of models disparate is not the disparity that exists between the things that serve as a model --e.g., not the disparity between a living animal and an abstract mathematical structure -- but with the difference between these two models in terms of their relationships to what is modeled and in how they are used to model. To put it briefly, what makes these two kinds of models disparate are the things in virtue of which each is a model.

[1] Susan G. Sterrett is a History and Philosophy of Science Professor at Wichita State University in Kansas. Her published research focuses on issues related to the methodology of science with her major contribution highlighting the importance of concepts of similarity and scientific models in the field of Philosophy of Science, the significance of which had already been recognized in natural sciences and engineering. A great deal of her research efforts is related to scientific models and analogical logic in natural sciences, geophysics, biology, ecology, cognitive science, and artificial intelligence from the view of a philosopher of science (Sterrett 2019, 1-12).

Therefore, Sterrett focuses on what a model represents and proposes the classification of scientific models in two wide categories, the category "realm of thought" and the category "using one piece of the world to tell about another." The first category includes models of abstract, mathematical structures, algorithms, or mechanism descriptions. These tools are considered models because of their relation to some equations or formal scientific proposals (Sterrett 2003, 1-2, 9-11; Grigoriadou, Coutelieris, and Theologou 2021, 115-118). According to her, examples falling in this category are the Mechanical Models of Electrodynamic Equations, The Models of Axioms – Arithmetic and Geometry, and the Mathematical Models Used for Simulation. As she mentioned (Sterrett 2003, 9):

> The models are abstract in that they are mathematical structures, algorithms, or descriptions of mechanisms. They are something grasped in thought (as Frege might put it), rather than something located in time and space.

Models that fall into the second category represent parts of the real world. These models are commonly known as analogue models (Sterrett 2017(a), 857-878; Grigoriadou, Coutelieris, and Theologou 2021, 115-118). Analogue models are physical set-ups that are utilized as models of other physical set-ups, which cannot be observed by researchers due to limitations such as their size, space, or time distance from them. Their basic functional mechanism is "similarity" which is validated by a ratio of physical quantities or by a ratio of relations observed between physical quantities of two phenomena or objects. The analogue relations between the model and the target system are selected based on the direction and purpose of the research (Sterrett 2002, 59-63, 2006, 69-80; Grigoriadou, Coutelieris, and Theologou 2021, 115-118). The similarity is defined by criteria that are determined by the phenomenon of interest and the problem to be solved. Formal methods, principles, and scientific laws are involved in establishing criteria for the similarity between two situations and in verifying that these criteria are satisfied. Thus, as Sterrett observes, there is a formal methodology involved in reasoning employing the "piece of the world" kind of model (Sterrett 2003, 9). This is her main argument facing the conviction coming from the field of philosophy of science of the middle 20th century that analogue models are more an applied art than a formal experimental method.

For example, in the case of scale models, the methodology for establishing physical similarity is dimensional analysis. Therefore, the similarity between the model and the object of interest is usually not absolute, as it is defined concerning a particular characteristic, which is always defined in the light of a scientific hypothesis (Grigoriadou, Coutelieris, and Theologou 2021, 115-118). This was one of Sterrett's strongest arguments for the scientific nature of material models and one of the most important contributions of her theory to the effort of understanding the concept of the scientific model in the field of philosophy of science. Examples of "pieces of the word" models are the Models of Organisms in biology, the Experimental Scale Models, and the Re-enactments of Events used in criminology. These kinds of models are considered models because of a specific similarity to some other physical object or situation. Sterrett has extensively examined the kind of scale models that are usually used in engineering and physics. Scale Models are physical objects or systems that are used to control or predict the behavior of a machine, an object, or a system of different dimensions. They are constructed in such a manner that there is a specific proportion to an object in the physical world (Sterrett 2002, 59-63, 2003, 9, 2006, 69-80, 2017(a), 857-860). An interesting example of the application of this kind of model is William Froude's experimentation with ship scale models to solve major problems encountered in the construction of ships for the English Navy, which were related to stability, speed of ships, and their interaction with water in motion or stillness. Froude carried out experiments with ship scale models and extended the inferences of his experiments, through the appropriate calculations, to full-size ships (Froude 1874, 36-73).

Sterrett's contribution to highlighting the significance of the concept of the scientific model in the field of philosophy of science is obvious. Throughout her research, she highlighted how neglected and fragmented the concept of scientific models was until the first years of the 21st century in this field. Sterrett's contribution is not limited to her theories on similarity and scientific model concepts, or on her models' categorization proposal which was undoubtedly important too. One of the core contributions we recognize in this work is highlighting the importance of further investigating these concepts in the field of philosophy of science. If the enumeration and analysis of existing knowledge throughout the research are considered important, then the detection of absent knowledge should be accepted as a powerful motive, able to trigger new research steps, reveal new research directions, and contribute to the development and evolution of science over time.

Furthermore, Sterrett introduced a different criterion for the categorization of scientific models: "what a model represents and how the mechanism of representation functions." This criterion led to an interesting, innovative, and adequate classification of models in two wide categories, especially for the first years of the 21st century when the material models were not extensively examined by philosophers. This way Sterrett placed the discussion about the categorization of scientific models at the center of interest in the field of philosophy of science.

Although the categorization of scientific models proposed by Sterrett is considered particularly innovative for the field of philosophy of science at that time, we can discern some specific limitations arising from it. Firstly, the philosopher points out that she does not study all kinds of models, but specific models utilized in reasoning, employed in making inferences, providing explanations, or promoting understanding (Sterrett 2003, 2-3). For example, Sterrett discerns theoretical models and models physical setups, but she does not discuss at all the category of fiction or imaginary models. Therefore, through Sterrett's models' classification, it is not clear into which category fiction models, like the atomistic model by N. Bohr, fall or if this kind of model could be included in one of Sterrett's two proposed general categories.

Moreover, considering the range and variety of types of scientific models, Sterrett's categorization of models into only two basic categories can be considered restrictive. On the one hand, as we have already mentioned, the philosopher points out that she does not study all kinds of models (Sterrett 2003, 2-3). On the other hand, Sterrett includes mathematical models in the same category as theoretical models based on the opinion that both are *grasped in thought, rather than located in time and space* (2003, 9). However, these two types of models could be identified as two distinct entities. Furthermore, Sterrett does not discuss some possible differences between mathematical models and models of informatics. Thus, throughout Sterrett's categorization proposal, details considering the core features of each model subcategory are not estimated and cannot be presented. Thus, a need for a more elaborate categorization of scientific models emerges and, the following question arises: *what criterion should modern scientists and philosophers focus on to distinguish the basic categories of scientific models so that all kinds of models can be encompassed?* We are trying to address these issues through our scientific models' categorization proposal which is presented on the next pages.

4. The Categorization of Scientific Models: a Five-class Scheme

The definition and the categorization of scientific models are demanding processes. Scientific models are extended methodological tools utilized by a wide range of scientific fields around the world. That fact has as a result a huge variety of kinds of models and a corresponding variety of models' definitions, which can easily lead to confusion. Moreover, the modeling technique is continuously developing, and new models are formed and included in the methodology of various scientific fields. In other words, the notion and the categories of scientific models are constantly evolving. It becomes clear that if a researcher wants to examine the concept and categorization of scientific models, he must face a great deal of information and developments.

An important question faced here is *which categorization of scientific models could be considered sufficient. What do we expect from such a categorization?* We strongly believe that an adequate categorization of scientific models must provide the opportunity to include all types of scientific models in their basic categories. In this context, throughout our approach, we accept Sterrett's argument, according to which formal scientific models could not only be perceived as theoretical or abstract entities but also as physical set-ups. This kind of scientific model is a powerful technique of modern science and its research in the field of philosophy of science should be supported.

Moreover, an adequate categorization must be clear, comprehensive, and detailed. Therefore, it is important to succeed in defining some core features of every subcategory of models, as well as presenting the main differences between different types of models. Such a categorization of scientific models could contribute to a more comprehensive understanding and a more sufficient definition of the notion of the scientific model.

What is the criterion that could succeed in such a categorization of scientific models? The categorization criterion should be strict, fundamental, and capable of ensuring a clear and sufficient categorization, a categorization that meets the above conditions while limiting the role of the human factor in classifying models as much as possible. The criterion should be strict to indicate the classification of models in specific categories so that the criterion itself supports in which basic category or categories each model can be included.

Against this demanding background, we suppose that a researcher owing to categorize scientific models, must start his work with one crucial question: *what is the appropriate criterion of scientific models' categorization?* In the context of our models' categorization proposal, we chose as the most appropriate criterion "the nature of the model" and supported that it can lead to a clear, safe, and sufficient classification of scientific models. In other words, our categorization is based on the fundamental question: *what kind of things are used as models?* Focusing on this criterion, we can ensure that all types of models can be included in the proposed categories, while at the same time, each model can be placed in one or more categories according to its nature. This criterion essentially is specific, clear, easily identifiable, and unequivocally defines the categories each scientific model falls into.

Through our study, we propose a five-category distinction of scientific models (figure 1). The first category is theoretical models, which are theories or sets of theories that are developed to explain a situation or a phenomenon or contribute to the prediction of a situation or a phenomenon. Models included in this category are theoretical structures whose formation is based on formal proposals, principles, and laws, and they are used in the scientific methodology of different fields such as physics, medicine, psychology, financials, sciences of education, etc. (Hodges 2020 ch.5; Frigg and Hartmann 2020 ch.2, 2.3, 3.4, 4.2). An interesting example of theoretical models is the kind of conceptual models, which are widely used in fields such as theoretical physics. Another example is cognitive models, which are based on the knowledge we are acquiring about a process or a phenomenon. Researchers observe a phenomenon, study it, and rely on their experience to make forecasts and suggestions (Frigg and Hartmann 2020, ch.3). This process is called cognitive modeling. Other kinds of theoretical models are models of learning used in psychology and models of economic growth in finances.

The second category is the category of models' physical set-ups, widely known as material, physical or analogue models. Scientific models included in this category are physical objects, physical systems, organisms, and scenes (Grigoriadou 2024, 138-139). These material models are usually chosen or constructed by researchers to describe, explain, or predict a similar target set-up placed in the real world, in the light of a specific scientific hypothesis. This model's category is extensively used by different scientific fields with the dominant being that of natural sciences and mechanics. Moreover, this category includes a significant number of kinds of models such as scale models in mechanics, physics, geology, ecology, hydrogeology, or animal models in biology, medicine, or pharmacology (Sterrett 2003, 6-9; Frigg and Hartmann 2020, ch.2.1). An interesting example of this kind of model is the ship scale models were constructed and utilized by William Froude during the 19th century to solve problems related to stability, speed of ships, and their interaction with water in motion or stillness. Other examples are building models constructed and used to predict the stability of buildings, but also cars, airplanes, or other kinds of mechanical scale models. Scale models are also used during the experimentation of geosciences such as volcano, and eco-system scale models (e.g. lake models), and of astronomy such as models that represent celestial bodies and their movement. Another example of physical setup models is animal models widely used in biomedical sciences such as the well-known guinea pigs which are mainly used to test experimental treatments.

The third category we have discerned is that of fiction or imaginary models referring to mental constructions, mental representations, which are neither theoretical nor material models but fiction set-ups, that represent physical objects, phenomena, situations difficult or impossible to be observed, or possible systems (Frigg and Hartmann 2020, ch.2.2). Although the utilization of fiction models is often observed in scientific practice, fiction modeling has not been explored in the context of scientific models' research. Several researchers, such as Sterrett too, place fiction models in the same category as theoretical models. In the context of our approach, adopting as a categorization criterion the nature of the model, we distinguish these two categories concerning that they are two different entities. On the one hand, a theoretical model is a theory based on formal proposals, principles, and laws, contributing especially to the description, and explanation of a phenomenon, situation, or system on the other hand, a fiction model is an imaginary construction used to represent physical set-ups, possible systems, or scenarios (Frigg and Hartmann 2020, ch.2.2; Gelfert 2017, 8-9; Nersessian 1998, 11-12; Sterrett 2003, 9). One interesting approach to this model's category is attributed to Nancy Nersessian, a 21st-century philosopher, physicist, Professor of cognitive science at the Georgia Institute of Technology, and Research Fellow at the Harvard Department of Psychology. She suggested that (Nersessian 1998, 11-12):

> Much of human reasoning proceeds via "mental models", that is thought experiments on internal models. A mental model is a structural analog of a real-world or imaginary situation, event, or process as constructed by the mind in reasoning… it embodies a representation of the spatial and temporal relations among, and the causal structures connecting the events and entities depicted and whatever other information that is relevant to the problem-solving tasks.

Interesting examples of the application of fiction models come from the fields of physics, finance, sociology, and other fields even from antiquity. For instance, Leucippus' and Democritus' atomic structure can be perceived as a fiction or imaginary model as it is a mental construction that represents the structure of atoms that are tiny particles, invisible, in constant motion that is impossible to observe (Grigoriadou 2023, 574-582). Leucippus and Democritus invented an imaginary arrangement, a fiction model, based on which they sought to describe particles that due to their size could not be observed directly and gave an acceptable answer, specifically for this period, regarding the structure and changes of matter (Grigoriadou 2023, 574-582). Another example of a fiction model is Bohr's model of the atom (Frigg and Hartmann 2020, ch.2.2).

Another extensively used category of models is that of mathematical models. Mathematical models are representations in mathematical terms of the behavior of real devices, objects (Dym 2004, 4), phenomena, and different kinds of processes. Mathematical models are systematically used by different scientific fields such as engineering, natural sciences, economics, social sciences, medicine, etc. According to some categorizations mathematical models are placed in the same category as theoretical models depending on the idea that they are abstract entities with the main aim of describing or predicting mechanisms, systems, or phenomena. This perspective can be considered acceptable. However, it is important to highlight that mathematical models' strength is traced in providing representations of real systems' behaviors in mathematical terms. More specifically, their main advantage which justifies their significantly extended exploitation by different fields is that they describe systems using the language of mathematics, which is concise and precise with well-defined rules for manipulations (Glenn, 2008, 1-2). These rules allow accurate and efficient examination and management of systems under investigation, significantly reducing the possibility of error in describing, explaining, and predicting them, especially in the case of natural systems and phenomena that are characterized by determinism. Mathematical models also have solutions, which consist of mathematical representations of the behavior of the metrics under investigation. These solutions are self-evident because they arise from mathematical descriptions of natural phenomena and systems. Examples of mathematical models are: statistical models, differential equations, and linear models (Glenn, 2008, 7-35). The most famous example here is Maxwell's equations which provided a mathematical model for electric, optical, and radio technologies, including the most important laws of electricity and magnetism. Maxwell through his mathematical model succeeded in a complete description of electromagnetic phenomena, developing an entire electromagnetism theory.

The last category is that of the models of informatics, a widely extended category of scientific models in modern science with a variety of appliances in different areas of engineering, natural sciences, economics, social sciences, and other fields. In informatics, a model consisting of programs and their meaning explains the reality of computers and what their screens display (Bertot 2009, 560-565). Although models of informatics are based on algorithms, they often provide additional properties from mathematical models for various reasons, one of which is that the results of data processing are displayed on computer screens. Thus, this kind of model represents specific systems or provides explanations and descriptions of real-world systems or situations through computer screens. Two popular kinds of models of informatics are data models and models of simulation. A data model is a description of the objects or systems represented by a computer system with their properties and relationships (Mo and Sinha 2015, 51-55). It is an abstract model that organizes data elements and standardizes how the data elements relate to one another, and it represents reality (Mo and Sinha 2015, 51-57). Moreover, a data model is specified in data modeling notation, which is often a graphical form. These kinds of models are usually characterized as data structures, especially in the context of programming language (Mo and Sinha 2015, 51-73). Data models can either refer to abstract formalizations of the objects and relationships found in a particular application's domain or to the concepts used to define such formalizations (Mo and Sinha 2015, 51-73). Another category of models of informatics is computer models of simulation which are computer programs or algorithms which simulate changes in a modeled system in response to input signals (Ifenthaler 2012). Computer simulations are techniques for studying mathematically complex systems and have applications in almost every field of scientific study. Simulations are typically classified according to the type of algorithm that they employ (Smith 1999, 1-3; Winsberg 2003, 107-108). A simulation model allows the examination of a system's behaviors without requiring construction or experimentation with the real system. This kind of model operates through a process of creating and analyzing a digital prototype of a physical model to predict its performance in the world such as flight simulators (Smith 1999, 1-4). Models of informatics are the most advanced category of scientific models, combining features of other categories such as mathematical, theoretical, and physical setup models, a reason that explains its extended utilization during the experimentation of various scientific fields.

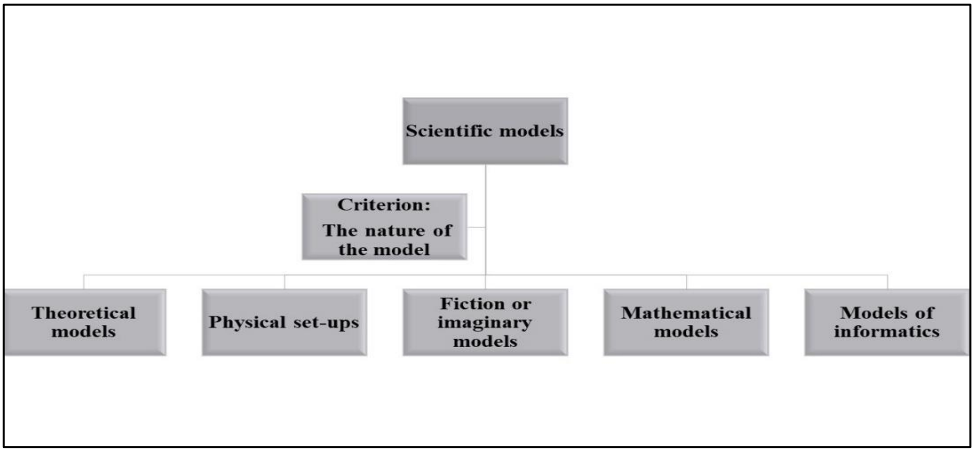

Figure 1: The categorization scheme.

The above categorization scheme (figure 1) is clear enough, and adequately comprehensive as it carries the potential to encompass all scientific models in the proposed basic categories, revealing at the same time some core differences between these five basic kinds of models. In this respect, the proposed categorization material can enhance the effort spent in scientific models' notion conceptualization and thus, the definition of this powerful scientific tool. Moreover, the proposed categorization criterion, the nature of the model itself, is fundamental and simultaneously can be easily used when classifying models into general categories. We could say that this criterion succeeds in limiting the role and the influence of the human factor during categorizing models as it indicates in which category every scientific model should be classified. This proposed categorization scheme could be used as a tool by scientists and philosophers, to support their research. Through this categorization, scientists from every scientific field could categorize different choices of appropriate models for their experiments, they could be assisted in selecting the model that best meets the needs of their research, and easily describe their methodological tools, during the stage of presentation of their methodology.

Having distinguished the proposed five general categories of scientific models, we will endeavor to describe the identity, towards a general trial of defining this complex and heterogeneous scientific tool, known as the scientific model. So, the core questions here are*: what is a scientific model? What features, that are common in all these models' categories, make up the identity of this powerful tool?* As arises from the above analysis, the scientific model is a constantly evolving scientific tool that succeeds in connecting our thoughts with the real world, and our research hypotheses with the target systems. Scientific models can be theories or sets of theories, mental representations, equations or sets of equations, physical setups, or computer programs, that are utilized to contribute to a specific research hypothesis testing, mainly to describe, explain, or make predictions about an inaccessible or difficult-to-access part of real-world or to support, interpret or extend a theory. A core mechanism that determines the representational function of scientific models is similarity, which is utilized during the invention, selection, or construction of a model and the transfer of the conclusions drawn from the model's application to the system under the study. In this manner, scientific models through their representational function succeed in translating the *unfamiliar into familiar terms*, operating as links between the research hypotheses and the systems in the study.

5. Conclusions

The variety, the extended exploitation, and the continuous evolution of scientific models sometimes result in uncertainty concerning their definition and categorization. The achievement of a sufficient categorization of models is considered crucial as it can contribute to the organization and classification of the types of models and the related knowledge to a certain degree. Understanding, conceptualizing, and defining the notion of the scientific model can be enhanced by a comprehensive, detailed, and clear categorization of scientific models into specific basic categories. Such a categorization of models can contribute to the limitation of common misconceptions concerning the concept of the scientific model and, thus, enhance its comprehension and definition.

Against this demanding background, a philosopher of science or scientist aiming to categorize scientific models must choose a specific criterion to succeed in a sufficient classification of scientific models. An interesting model categorization proposal is attributed to the modern philosopher of science Sterrett G. Susan, who distinguished and defined two wide model categories focusing on what a model represents and how its representation mechanism operates. These two categories she proposed are the category "realm of thought" and the category "using one piece of the world to tell about another," Sterrett's approach was innovative considering that until then the material models were not extensively examined by philosophers. However, if we consider the variety of scientific models used in modern science, her models' categorization into only two basic categories is somehow restricted. At this point the need for a more comprehensive and detailed categorization, capable of overcoming the limitations of Sterrett's categorization, and contributing to understanding the concept of the model in general, became apparent.

On this basis, throughout this paper, we proposed as the most appropriate criterion of scientific models' categorization ''the nature of the model,'' a fundamental criterion capable of reducing the role of the human factor during the categorization of scientific models.

This criterion can be easily used during models' classification into general categories. We firmly believe that the criterion we chose can lead to a sufficient categorization of scientific models as it contributes to encompassing all kinds of models in the proposed categories. In other words, the chosen criterion indicates the classification of the models in specific categories. Thus, we classified the models into five categories. Through the proposed categorization, details considering the core features of each model subcategory are estimated and presented, while differences between models' subcategories are pointed out. In this context, the proposed classes of scientific models are theoretical models, physical set-ups, fiction or imaginary models, mathematical models, and models of informatics. Estimating all these kinds of models increases the chances of clearly understanding and more adequately defining this powerful scientific tool.

Surely, many models' categorization proposals have been offered today based on different criteria, and the result may be different proposed categories of models. One of our scopes was to participate in the dialogue concerning the categorization of scientific models in the field of philosophy of science and provoke other proposals, which could contribute to the general effort of enhancing the understanding and the theoretical documentation of the concept of scientific models in modern philosophy of science.

References

Bell J. and Machover, M. 1977. *A Course in Mathematical Logic*. Amsterdam: North-Holland.

Bertot, Y., Huet, G., Levy J-J and Plotkin, G. 2009. "The tower of informatic models." In *From Semantics to Computer Science: Essays in Honour of Gilles Kahn* (1st edition), 559-572. USA, New York: Cambridge University Press.

Dym, C. L. 2004. *Principles of mathematical modeling.* Burlington, USA: Elsevier Academic Press.

Eran, T. "Measurement in Science." In *The Stanford Encyclopedia of Philosophy* (Fall 2020 Edition), edited by E. N. Zalta, 2020. URL = https://plato.stanford.edu/archives/fall2020/entries/measurement-science/.

Frigg, R. and Hartmann S. 2020. "Models in Science." In *The Stanford Encyclopedia of Philosophy* (Spring 2020 Edition), edited by E. N. Zalta. URL = https://plato.stanford.edu/archives/spr2020/entries/models-science/.

Froude, W. 1874. "On Experiments with H. M. S 'Greyhound'." In *Transactions of the Royal Institution of Naval Architects* 15: 36-73.

Giere, R. 1988. *Explaining Science: A Cognitive Approach*. Chicago: University of Chicago Press.

Glenn, M. 2008. *An Introduction to Mathematical Modelling*. Courses text for Bioinformatics and Statistics Scotland. Given by Daniel Lawson and Glenn Marion, 2008.

Gelfert, A. 2017. "The ontology of models." In *Springer Handbook of Model-Based Science,* edited by L. Magnani and T. Bertolotti, 5-23. Springers.

Grigoriadou, V. 2023. "The Precursors of Scientific Models in Ancient Egypt, Mesopotamia, and Ancient Greek World: A Comparative Study." *European Journal of Theoretical and Applied Sciences 1*(4): 574-582.

———. 2024. "Sacrifices on the Altar of Science: The Case of Model Organisms"*. European Journal of Arts, Humanities and Social Sciences 1(3), 137-46.*

Grigoriadou, V., Coutelieris, F. and Theologou, K. 2021. "History of the concept of similarity in natural sciences." *Conatus-Journal of Philosophy* 6(1): 101-123.

Hesse, M. B. 1967. "Models and Analogy in Science." In *Encyclopedia of Philosophy* edited by P. Edwards, 354-359. New York: Macmillan.

Hodges, W. "Model Theory." In *The Stanford Encyclopedia of Philosophy* (Winter 2020 Edition), edited by Edward N. Zalta, 2020. URL = https://plato.stanford.edu/archives/win2020/entries/model-theory/.

Ifenthaler, D. 2012. "Computer Simulation Model." In *Encyclopedia of the Sciences of Learning,* edited by N. M. Seel. Boston: Springer, 2012.

Krantz, D., Duncan L., Suppes, P. and Tversky A. 1971. *Foundations of Measurement Vol 1: Additive and Polynomial Representations*, San Diego, and London: Academic Press.

Losee, J. 1993. *Φιλοσοφία της επιστήμης*. Μεταφρασμένο στα Ελληνικά από τον Θεόδωρο Μ. Χρηστίδη. Θεσσαλονίκη: Εκδόσεις Βάνιας.

Mo, J. P. T. and Sinha, A. 2015. "Systems design." In *Engineering Systems Acquisition and Support,* edited by J. P. T. Mo, C. Bil, and A. Sinha. UK, 51-73. Cambridge: Woodhead Publishing Series in Mechanical Engineering.

Morgan, M. S. and Morrison M. C. 1999. *Models as Mediators: Perspectives on Natural and Social Science.* Cambridge: Cambridge University Press.

Morrison, M. C. 1996. *Models as Mediators: based on a contribution to a seminar under the auspices of the Otto und Martha Fischbeck-Stiftung*, Wissenschaftskolleg, May 20-22, 1996.

Nersessian, N. J. 1998. "Model-Based Reasoning in Conceptual Change." In *Model-Based Reasoning in Scientific Discovery,* edited by L. Magnani, N. Nersessian, and P. Thagard, 5-22. Pavia, Italy: Springer.

Rogers, K. 2012. "Scientific modeling." In *Encyclopædia Britannica*. URL = https://www.britannica.com/science/scientific-modeling.

Smith, R. D. 1999. "Simulation: The Engine Behind The Virtual World." *The Simulation 2000 series* 1: 1-24.

Sterrett, S. G. 2002. "Physical Models and Fundamental Laws: Using One Piece of the World to Tell About Another." *Mind and Society* 5, 3: 51-66.

———. 2003. "Kinds of Models": based on a talk presented at an STS Interdisciplinary roundtable: "The Multiple Meanings of Models", Duke University: John Hope Franklin Center, March 20, 2003.

———. 2006. "Models of Machines and Models of Phenomena." *International Studies in the Philosophy of Science* 20(1): 69-80.

———. 2017(a). "Experimentation on Analogue Models." In *Springer Handbook of Model-Based Science,* edited by L. Magnani and T. Bertolotti, 857-878. Switzerland: Springer.

———. 2017(b). "Physically Similar Systems – A History of the Concept." In *Springer Handbook of Model-Based Science*, edited by L. Magnani and T. Bertolotti, 377- 411. Switzerland: Springer.

———.2019. *Curriculum Vitae*. URL = https://wichita.academia.edu/SusanSterrett/CurriculumVitae

Winsberg, E. 2003. "Simulated Experiments: Methodology for a Virtual World." *Philosophy of Science* 70(1): 105-120.