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Models in Engineering Design as Decision-Making Aids

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ABSTRACT

Although models and modeling are central to engineering design, they have received much less attention than models or modeling in the philosophy of science. This paper draws on insights from the philosophical literature on models in science to elucidate models in engineering. Many of the apparent differences are a matter of degree. Models in engineering design do not function solely as representational or more general epistemic vehicles. Rather, models are central to facilitating decision making. This seems to be less pronounced in laboratory practices for scientific research than in engineering design. In engineering, often only the designers understand and determine the relation between the model and its target system. In this, they serve as truth makers and truth keepers. This social process of design is essential to understanding the role of models and modeling from a meta perspective, but is also relevant to engineer when models are reused. A better understanding of these roles can help to illuminate the roles of models in engineering. To illustrate these points, this paper uses the design of a 3D printed kayak as an example that shows how even a fairly modest engineering design project requires the creation of a multitude of different models.

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Introduction: plethora of models

Creating functional products is fundamental to engineering design activity. This involves complex processes that engineers need to understand. These processes are studied by engineering design researchers with the concrete aim of developing tools and methods to improve them, but they are also examined by scholars in reflective disciplines, such as philosophers of engineering and science. Models play a central role throughout all stages in engineering design; indeed, the entire design process and the decisions made in it are driven by and crucially rest upon models. The design process can arguably be seen as a process of creating, manipulating and using models, in which the models themselves evolve and are repurposed multiple times. Engineers interact with their products and processes largely through models. Models also play a central role in knowledge generation that, like the (applied) sciences, is not directly aimed at design. In this paper we stress the relevance of

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models to design as a social process and argue that models are central to making decisions in engineering processes.

Design is regarded by some as an ongoing process of decision making. Those who defend this view¹ take a purely formal approach to decision making that reduces it to a sequence of mathematical decision models. Hence this view is not uncontested because, as its opponents argue, it ignores the social nature of design processes. As we will illustrate in the following discussion, decision making understood in a broad and not purely formal sense does play a central role in design. Models are an essential part of many decision-making activities in engineering design, but their inherent ambiguity can cause misunderstanding.

Models are abstractions that visualize the current state of a design. However, engineers rarely reflect on the nature of these models, or on how technical possibilities and actions are affected by the models' properties and characteristics. Among the aspects of modeling that would benefit from such reflection is the problem of iteration.²

Divergent interpretations of the context, content, purpose or role of models are a significant cause of (sometimes unnecessary) iterations in design processes; differences of interpretation thus have a profound effect on the product itself and the effectiveness and efficiency of the design process. Iteration plays an important role in exploring design alternatives and resolving problems that arise in design processes. For example, designers create multiple models of the shape of a kayak to provide individual kayakers with the desired balance between maneuverability and stability. These models may be instantiated materially (e.g. in clay or plastic) or as computer aided design (CAD) models. However, (unnecessary) iterations often arise from incomplete or ambiguous information contained in the models,³ as well as a lack of understanding of the nature of models and the relationship between a model and reality.⁴

Taking the design of a personalized 3D printed kayak as an illustrative example,⁵ this paper describes the creation of a parametric model of a kayak. We also build on experimental findings of the creation of personalized prototypes with a 3D printer to illustrate the variation of models and the interplay of a multitude of models within a simple component design. The resulting parameterized model is used as a base model that is adapted to the individual measurements of specific kayakers.⁶ In this paper, we contend that one cannot account for the complex nature of modeling in engineering design by considering models solely as representational or more general epistemic vehicles; rather, the analysis reveals that models also—and sometimes primarily—function as decision aids for individual designers and design teams.

Engineers employ a plethora of different types of models throughout the design process. From material models to sophisticated computer renderings, engineers use different models to create, visualize and analyze the entire product, a specific part of it or a single aspect of the product. For example, in designing a kayak, engineers create models of the entire kayak, individual parts such as the seat, or a specific aspect such as the form, to analyze its hydrodynamic properties. Many of the models used in design are scientific models, such as a model of the boat's fluid-dynamic properties in a wind or water tunnel or a computer simulation of its behavior in various waves.

A lively debate has emerged within the philosophy of science over the nature and role of models in the sciences. By contrast, although models play a central role in engineering just as they do in the sciences, models in design have not yet been examined widely by

philosophers or the design community itself. What is written about engineering models is typically found in introductory chapters on modeling in engineering design textbooks (see, e.g. Vanja et al.,⁷ who also include a summary of other authors). This paper is a step towards a debate of models in engineering akin to models in science.

The paper is structured as follows. As designers make use of scientific models, this paper begins with a brief overview of recent philosophical insights into scientific modeling. For a more detailed and comprehensive overview, the reader is referred to Frigg and Hartmann.⁸ The paper focusses on two perspectives that are central to debates on models within the philosophy of science community, namely models as representations and models as epistemic vehicles. We then discuss some of the types of models that engineers use and the role that they play, illustrated by the kayak example, before we turn to models in the engineering community. We also comment on some of the differences from and similarities to modeling in sciences. Engineers make numerous choices when modeling and can model one aspect of an engineering product in many different ways. The role of models in decision making is discussed from two perspectives: that of individual designers deciding on the next steps in the design and carrying out activities, and that of teams reviewing designs and selecting alternatives. We contend that in engineering, the designer acts as a kind of truth maker or truth keeper. Note that the term 'truth' is used in a loose sense here. While we endorse a view that sees indirect representation as central to models in one way or another, we do not suggest that models are truth-apt (i.e. that it is possible to establish whether they are true or false) in a strict sense; however, (certain) statements in the model description may be true or false. The paper concludes with a summary and an outlook.

Models as vehicles for representation

Models of phenomena and indirect representation

While models have always been part and parcel of scientific reasoning, it took the philosophy of science a surprisingly long time to recognize the importance of models in the scientific process. At first glance the abundance of different types of models may be overwhelming, and it may seem far from clear, for example, what the mouse model in the life sciences shares with a computer simulation in quantum chemistry. One unified approach to models is to recognize that all models seem to share certain semantic features. Since at least the beginning of the 2000s, within philosophy of science the research on scientific models has been dominated by investigations of the representational function that models perform. A model represents a specific target system. This target system may be some real-world phenomenon, where 'phenomenon' is an umbrella term for relatively stable and general features of the real world.⁹ For example, weather models aim to represent certain aspects of the atmosphere such as temperature variations in a certain region. The target system may also be an abstract system or even another model. Examples are SU(2)-gauge theoretic models that are used as (toy) models to understand SU(3) models. Sometimes the target system may not even be specified in detail.¹⁰ The focus on the representational aspects of models is seen as a turning point in the philosophical debate on models: Models had long been seen as mere heuristic devices in scientific practice since, among other shortcomings, they may incorporate inconsistencies or assumptions that contradict accepted



Figure 1. Indirect View on Model Representation: model descriptions determine a model, the model represents the target or target system

knowledge. This was seen in contrast to theories or law of natures that were, roughly speaking, linked to truth. However, theory or laws of nature are not in fact directly connected with real-world target phenomena; they require additional information and assumptions to be connected with the target system. This is where the representational turn in philosophy of science has revealed the strength of models.

It was only fairly recently that representation became a topic of discussion in philosophy of science, while in other areas of philosophical research such as artificial intelligence or philosophy of mind it has been discussed for quite some time. Many different questions are considered in thinking about how models represent, and many different views on representation have been proposed. As others have noted, one must at least distinguish various representational *styles* (e.g. a scale model of a kayak represents the kayak differently than various geometric models) from the question of the respect in which something is a representation of something else (e.g. because the model and the target system are similar in certain respects).¹¹ Note that when the description of the model is identified with the model itself, the latter issue would be essentially equivalent to the long-standing question of how language relates to reality, and thus be part of philosophy of language. Only when the model is seen as a separate entity from its description, the question of representation becomes a unique one in philosophy of science or another discipline being concerned with models.

Many philosophers of science, indeed, contend that model descriptions specify models, rather than equate description with the model itself. This so-called indirect view is indicated in Figure 1. Consider an example of a prototypical model in the sciences: Bohr's model of the atom. The mathematical equations *specify* the mathematical structure of the model system, which then represents the target systems, the (outer) electron layers of an atom. Or take a concrete model like the mouse model in the life sciences. There is some understanding that the metabolisms in model mice and humans are similar in certain respects. But what exactly this representational relation is and what features are actually represented is exceedingly unclear.

This latter view construes scientific representation as a relation between two entities, the model and the target, where models are understood as non-linguistic entities. Here the model descriptions determine a model; then it is the model that represents the target. Toon calls this the *indirect* view of representation.¹² This view is not only the most popular among contemporary philosophers of science (Toon himself being a noteworthy exception). Weisberg¹³ even views this indirectness as *the* defining feature of modeling. In the indirect view models cannot be true or false, as they are not descriptions. This intuitively seems to square well with tangible physical models or engineering models (like the scale model of the kayak) as tools, but for the indirect view this also holds for abstract models that are described with sentences in a formal language like Bohr's model of the atom. The indirect view of model representation raises a new question, namely how can an object that is not a word or a sentence scientifically represent a phenomenon. The focus on this question

is one reason so much of the philosophical literature on scientific models revolves around models' representational function.

The various philosophical views on how models represent fall into two main camps. While one group sees representation as a two-part relation between a model and its target, the other stresses that this relation is a manifold concept that includes the model's intended audience, the modeling purpose, the modeler, or even other potential audiences. The first camp is commonly referred to as an informational (or strong) account of scientific representation, while the latter is described as a pragmatic (or deflationary, or functional) account.^{14,15}

Informational views on model representation emphasize that in order to explain representation, one need only examine the relations between models and their corresponding target systems. Central in this debate is a discussion about the nature of the representational relation, which in its strongest form is seen as an isomorphism, or more loosely as some unspecified similarity function.¹⁶ In contrast, pragmatic views focus on scientists' activities. In these pragmatic accounts of models, the representational relation comprises not only the model and the target system, but also the modeler, the model's audience, etc. According to this view, the relation is constituted only after individual scientists or groups of scientists have offered intended uses for the model.

Another account of models that has recently gained some prominence in the philosophical discussion on models in engineering design is known as the fictionalist account. By viewing models as 'initiating' a 'game of make-believe' (as suggested in a different context by K. Walton¹⁷), this account aims, among other things, to address the observation that just as in the sciences, design models employ highly idealized and simplified assumptions such that the model and the potential target system may not have much in common at first glance but nonetheless are central in design as well as scientific enterprises.

The cart and the horse, or: models as epistemic agents

Debates on models in philosophy of science revolve around the question of how models can be central in the epistemic enterprise when they make use of distortions, idealizations, simplifications, etc. Addressing this issue by focusing on how models represent may seem like putting the cart before the horse, because we seek to learn about the real world by studying models. In this sense, accounts that view models as epistemic agents aim to put the horse where it belongs, namely before the cart.¹⁸ One recent example of such an epistemic account is Knuuttila's artefactual approach. Arguing that the representational aspect alone is insufficient for understanding how models work, Knuuttila explicitly develops her artefactual approach to scientific models to complement representational accounts.¹⁹ The artefactual approach views models as epistemic agents, which includes representation but is not solely focused on models' representational function. Models as epistemic tools 'are built by specific representational means and are constrained [to] facilitate the study of certain scientific questions, and [we] learn [...] from them by means of construction and manipulation.'²⁰ The seminal and most influential approach here is Morgan and Morrison's account of models as autonomous agents, known as the models as mediators account, which we will discuss in more detail in the following.

Models as mediators

In what is known as the semantic view of scientific theories, models are derived (more or less) straightforwardly from some overarching theory.²¹ This relationship between a theory and its models has been criticized.²² The ‘models as mediators’ account, proposed by Morgan and Morrison,²³ contends that models are autonomous agents in that they ‘(1) [...] function in a way that is partially independent of theory and (2) in many cases [...] are constructed with a minimal reliance on high level theory.’²⁴ On this view, models are able to mediate between theory and the real world by virtue of their partial independence from high-level theory. Through this mediating role, models function as tools or instruments that enable us to learn more about both theories and the real world.

The independence of models in the ‘models as mediators’ account features two aspects, namely construction and functioning.²⁵ On the one hand, models do not follow straightforwardly from the observation data of a given phenomenon. The underdetermination of theoretical descriptions by available data is a long-recognized problem in the philosophy of science and in the sciences themselves. At the same time, models are not derived straightforwardly from theories. For example, even the simple Newtonian model of the earth orbiting the sun is not derived directly from Newton’s theory and Newton’s law of gravitation. These general theories must be supplemented by modeling assumptions that are not entailed by the theories, such as a homogenous mass distribution of the sun and the earth, neglecting other planetary objects, etc.

Models in engineering design and in design research

While engineers continually interact with models throughout the life cycle of a product or during the design process, they usually do not reflect much about the nature or properties of models. The engineering design community largely emphasizes the representational character of models but does not question what, exactly, the models represent. In particular, they do not differentiate between models of existing products and models of emerging designs.

Illustrative example: design of a kayak

To illustrate these points, the following discussion draws on models that were generated by a group of students and their instructor in the process of designing personalized kayaks in collaboration with a kayak manufacturer as part of the students’ master projects.²⁶ The students came on an Erasmus exchange to carry out their master project research and submitted the project as a team. The kayak builder provided them with CAD models for various kayaks. The students adapted them to create parametric models for customization, which could be used to print personalized kayaks on a 3D printer.²⁷ At present, the kayak company has begun producing 3D printed kayaks and is hoping to recruit another group of master students to develop the service elements of the personalized 3D printing using the models described here as a starting point.

This is a low-tech product and a fairly simple production process with very few components compared to, for example, a car or an aircraft. Even so, this example illustrates how

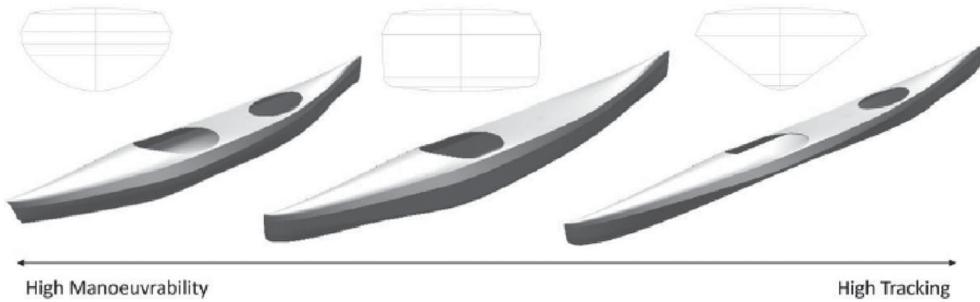


Figure 2. Geometric models and visualization of kayak designs

mathematical and computer models are used in contemporary practice to create personalized products, which would have once required the considerable expertise of a master boatbuilder. It also illustrates how design often begins with existing models, in this case the CAD models, and ends with new models that are then passed on to others, whose needs are not yet clear. The paper reports that the project selected kayaks 'because they need to suit the environment of use, the experience level of the kayaker and anthropometric measurements of the user.'²⁸ To enable cost effective customization, the project made use of additive manufacturing techniques—also referred to as 3D(imensional) printing—such as fused filament fabrication. The students used state-of-the-art commercial software and are now in discussions with a company to commercialize the approach. The range of models and use of modeling techniques are typical of models used in industry, but since the work was published the authors were kind enough to share their models. Lithgow et al.²⁹ discuss a model-based approach to automating the design of the body of the kayak and include illustrations of the models they use. They used state of the art commercial modeling software. The models selected as illustrates can be found in most industrial processes as well. However, as this was a student project, the models are not commercially sensitive.

Engineering products are modeled in many different and complementary ways. Engineers also generate and interact with models that do not relate directly to the products but provide information that is needed for the product development process, like the functional models presented in the following section. Today, many of these models are computer models, which connect different forms of models. For example, feature-based CAD models combine mathematical and geometric models, which allows for the specification of parametric ranges and defines the relationship between these parameters in mathematical equations that in turn define a product, from which multiple instances can be generated. Figure 2 shows three different instances of the parametric model. Although it is a student design project and thus quite simple compared to most industrial design cases, the kayak example clearly displays the blurring of ontological categories (see Figure 3). The project combines several ontological categories that involves structural as well as narrative elements (cf. Morgan³⁰).

The complementarity of models in engineering: the mode of the models

Engineering models can be classified in various ways. Until the product design is complete and all relevant information is coherent, it is very difficult to describe even a simple product

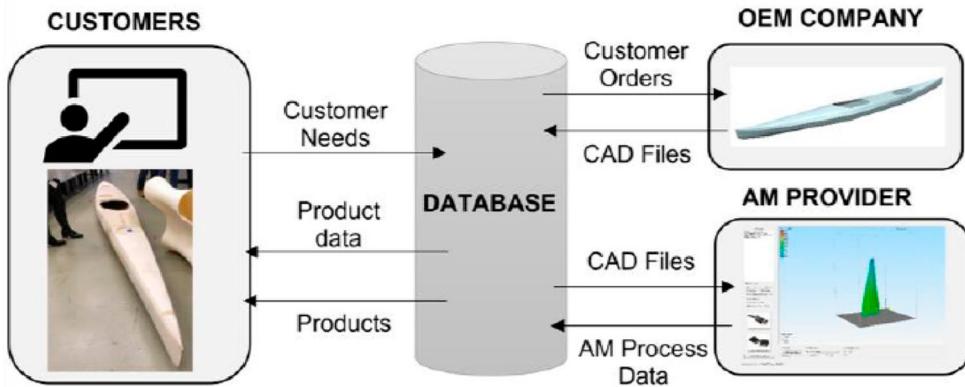


Figure 3. Rendering and prototype of a kayak

like a kayak in a single integrated model. Different modes of models are required throughout the product development process. As we will argue, these different modes play an important role in the collective decision-making process in engineering.

In our illustrative example, the following model modes, which are also discerned for example by Vanja et al.³¹, are central:

- **Mathematical models:** These include equations and statistical models of the form or performance of the product. For example, there are equations to determine the length of the kayak based on the size of the kayaker and the intended use, such as competition or wildwater paddling, as well as equations that calculate the drag of the kayak in the water. This is the one of the parameters that the engineers want to minimize.
- **Product visualizations:** These show how the product might or would look, from simple sketches, which indicate the high-level properties, to detailed renderings, which simulate the final appearance of the product. For example, Figure 3 show various 3D models of kayaks. Figure 2 is a rendering and gives an impression of what the final product would look like. Note that while philosophy of science commonly distinguishes between visualizations and models, for the design community visualizations also act as models.
- **Geometric models:** These typically show cross sections of the geometry or embodiment of a product, as illustrated in Figure 3.
- **Physical models:** These may be full-size or scale models of the product and can be purpose-made prototypes of the whole product or parts of it. Existing products also stand in as physical models. Figure 3 (right) shows a kayak emerging from a 3D printer. The printed kayak (Figure 3, left) could serve as a full-scale prototype to conduct user tests prior to production or (as intended in the Lithgow et al.³² paper) as a key component of a one-off personalized product to which some fixings need to be added.
- **Data models:** These contain data about the product, the user or its use captured in databases or, as is often the case now, in spreadsheets.
- **Abstract models:** These models, such as functional models, show abstract relationships between different aspects of the product, its users or potential uses.

- Numerical models: Particularly for complex geometries or for turbulent flows (e.g. in the boundary layer), the models are implemented on a computer. Sometimes the governing equations can directly be solved numerically; most often, however, approximations are needed.

Gero and Kannengieser³³ describe the process of design in terms of determining a product's function (i.e. purpose), its behavior, what it does (intended or unintended) and its structure, which describes the embodiment of the product. Functional models are typically abstract models (see next section); form models are geometric or mathematical models, where the form is typically shown in product visualizations. The behavior of a product can be derived from mathematical models and physical models. Many data models are also generated from the behavior of existing products.

Representational aspects

The engineering design literature recognizes the enormous importance of models in the development of products. Particularly the representational view on models seems to square well with engineers' own view. For example, the widely used textbook on engineering design by Pahl and Beitz³⁴ sees a model as a representation of the target system and modeling as creating or modifying a model in its entirety or in parts. Roth³⁵ picks up on the idea that models are analogous and defines a model *M* to be in a relation with an object *O* that allows inferences about *O* to be drawn from *M*.

Industry guidelines also often stress the representational features of models. For example, the German industry guideline VDI-Richtlinie 2206 (development methodology for mechatronic systems)³⁶ defines a model as a physical or mathematical representation of a real-world component or system. The industry guideline for data processing and calculation in engineering design (VDI-2211)³⁷ has a broader notion of models and expands the possible target system. Models here are defined as material or immaterial constructs, created for a specific purpose to represent the target system, which itself can be a model. They also see a model as a substitute for the target system that stands in its place. The VDI 2209 guideline for 3 D product modeling³⁸ addresses digital data capture from 3D physical models, which might be scaled, e.g. a clay model for a wind tunnel, and 2D graphic models such as technical drawings and formal models. These industrial guidelines explicate slightly different views. We contend that VDI-2211 seems most applicable because, just as in the sciences, models may represent target systems that are either real-world systems or other models.'

The VDI guidelines draw on two general views of models: Minsky³⁹ sees a model as an object that allows a viewer to draw inferences about another model. For Stachowiak⁴⁰ there are three aspects that define a model: the representational aspect, the reductionistic aspect and the pragmatic aspect, which is the purpose of the model. Vanja et al.⁴¹ offer a synthesis by defining a model as an abstract material or immaterial construct created to represent an object or system for a specific purpose. In addition to the classification of VDI-2209 they also include mental models in the list of potential models. According to Roddeck⁴² models must be defined unambiguously, be free of contradiction and redundancies, and be easy to use.

Returning to the kayak example, a physical, rescaled model of a kayak in a towing tank aims to reproduce the flow of water around a real kayak in a river. Generally speaking, when

it comes to representation, there seems to be a genuine difference between models in science and models in engineering design. As Poznic⁴³ points out, this difference relates to the direction of fit. While models in science represent some real-world target system or phenomenon, models in design aim to construct new artifacts or processes. The design relation therefore has a target-to-model direction of fit (see Figure 5a), i.e. the target is constructed to match the model.

In contrast, as is typical in scientific models, the epistemic artifact is a representational model—a vehicle—that stands in a relation with an inverse direction of fit to a corresponding target system. The users adjust the model to match the target and thus the relation of representation has a model-to-target direction of fit (see Figure 5b). While this adequately captures some aspects of engineering design that seem to differ from models in the sciences, it offers only a crude depiction of design. Design processes are often much more complex. Only the final manufacturing models are complete instructions for producing the product, which have been developed through many other models. Generally speaking, research in the area of design is much more attentive to the complexities of the actual process of modeling than the philosophical literature, particularly the literature on scientific models. This general claim should not, however, distract from the fact that even in the sciences the relation between theory and target is often much more complex than the representational view (as presented above) would suggest. This not only holds true for applied or interdisciplinary fields, but also for areas such as particle physics, where scientists have no direct access to the phenomenon of interest, but can only access it through what is referred to as a data model. Here scientists make use of data reduction and curve fitting. Moreover, in complex experimental settings, the scientist also needs to understand the data generation process such as the experimental measurement apparatus and the experimental setup. From the other direction, i.e. how mediating models relate to theory, again various modeling strategies and models are involved. For particle physics, for example, Karaca⁴⁴ has shown that various models are involved in deriving results from underlying theories, which can be compared to the experiment.

Eckert and Hillerbrand⁴⁵ draw a distinction between generative models that describe a future design and evaluation models used to assess whether a proposed design has the desired properties before it goes into production. Figure 4 illustrates the relationship between different generative and evaluation models and highlights the fact that the target system of many models in engineering is another model. The relationship between intermediate models and the final product can be quite tenuous because the design is modified throughout the product development process and engineers carry out many activities to validate the design and thereby gain confidence in it. Note that the models themselves carry no information about whether the target system was actually built or not, though this information may be relevant for future reuse and repurposing of the model (see discussion in the following sections).

To summarize the discussion, we can say that in both science and engineering some models (a) precede the target and others (b) are created to represent the target. As Figure 5 illustrates, the predominant direction of fit varies. All the kayak models have a direction of fit from the model to the target. No physical kayak yet exists, but the models are generated so that a kayak can be produced following the sequence of models illustrated in Figure 3. In the process of generating these models, multiple analyses will have taken place to understand aspects of the kayak such as hydrodynamics. These analysis

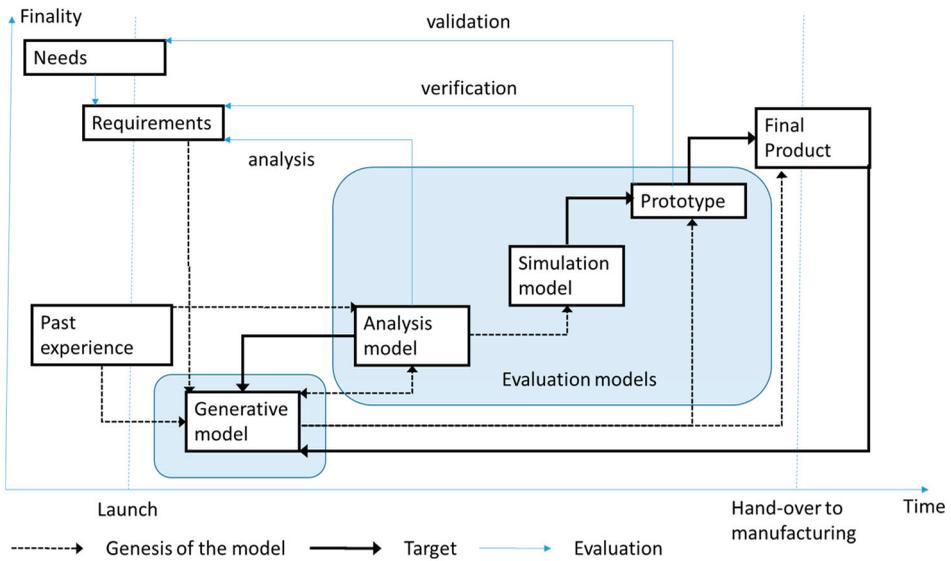


Figure 4. Relationships of fit between different models throughout the design process (black lines), the genesis of models (dashed line) and the evaluation criteria (thin lines) from Eckert and Hillerbrand⁶⁵



Figure 5. Direction of fit in models in design (a) and in the sciences (b)

models are very similar to scientific models, like those used to analyze river water flowing over stones.

Novelty of models

In practice, the pace of engineering design development is different for different types of products or different elements of the same system. Most products are a combination of:

- Reused components: These are fully specified. Companies have experience with these components and usually also have performance data for them. However, while much is known, they still need to be reassessed in a new context. In this case, complete and accurate models exist.
- Adapted components: These are modifications of existing components, for which parametric models often exist. There might also be knowledge gained from their use, but companies must judge the extent to which this information is relevant for the new product. Here, engineers can make use of existing models that they adapt.
- New components: These components are newly created. Some might be based on library components, in which case models can be adapted, but others must be designed from scratch with new models created for them.

- Innovative components: these embody innovation in terms of the solution principles, the materials used or the functions provided. Companies know much less about them and therefore have to put considerable effort into evaluating them.

The kayak example illustrates this combination of components: It is made as a single component and therefore can be understood as an adapted component. However, the details are a mixture of elements that the students reuse from traditional designs and adapt to 3D printing. The parametric design generates new designs, which would require new testing. They also make use of standard libraries of components, solution principles and materials.

In engineering practice, very few components are based on genuine innovation; rather, companies want to use existing technologies or materials and often designs. For example, they build prototype innovative designs as pilots and back-up solutions for tried and tested technology in order to gather empirical knowledge. This concept, increasingly conceptualized as TRL (technology readiness levels), originally derives from NASA and the aerospace industry⁴⁶ and describes the process of maturation from innovative technology to established technology, where level 1 is an innovation developed, for example, at a university and level 10 is a highly mature solution that has been deployed in commercial products. In practice, companies rarely use any technology below TRL5.

Models in the engineering design process

Different aspects of the same feature of a product can be expressed in different and complementary ways. Features can be expressed as:

- Incomplete: important aspects are not expressed, such as the materials to be used;
- Inconsistent: contradictory information; or
- Divergent in scope: the models cover a different scope or aspect of a product.

Throughout the design process, designers and engineers have to interpret the models and make multiple decisions independently or collectively. However, at the end of the entire design process, the product needs to be fully defined in order to go into production.

Most engineering products are designed by large teams developing parts of the product in parallel. In the kayak example, three students worked together under the supervision of their instructor. One of the important functions of models is coordination between different team members. As Bucciarelli⁴⁷ points out, engineers approach problems from their own object world, i.e. their own set of assumptions, experiences and knowledge, which can make a coherent understanding of models and their underlying assumptions difficult. In the kayak example the team was very small, but the members came from different countries and had to negotiate different academic traditions. Models usually have a modular structure, in which the model as a whole represents the final product with various 'interacting' sub-models; components or subsystems are also often modeled independently. In practice, the structure of the models often mirrors the team structure, as individuals and teams work on their own sub-models, which are later integrated. Whole system models often apply to a particular aspect of a product, e.g. a wooden scale model of the kayak that

could be used in a water tunnel represents the entire surface of the product, which is usually made up of multiple parts. These whole system models are typically owned by specific experts or teams, who need to collate information from other models. As modern products typically are mechatronic or cyberphysical, it is necessary to combine models from different disciplines. Such modular models are also integral to many sciences in current practice. Current climate models that couple models for certain dynamics in the atmosphere and hydrosphere (and possibly other systems) offer a case in point.

Moreover, scientific modeling, like most scientific research, is often a highly collaborative endeavor. While this is centrally addressed particularly in STS or social epistemology, the philosophical literature on scientific models has thus far largely neglected these collaborative aspects (as well as many other aspects of what one may refer to as the context for discovery).

Design processes are highly iterative,⁴⁸ requiring engineers to go over similar ground several times and revise provisional decisions. These iterations either arise externally, e.g. from the customer's changing requirements, or in response to problems with aspects of a design that emerge during the evaluation or in the integration of different product elements. In general terms, however, it is possible to say that as the process progresses, models shift from vague models, like sketches or the functional models seen in Figure 6, towards detailed and accurate models similar to the maintenance sketch of the pump or the parametric model of the kayak. Over the course of the design process, the emphasis shifts from generative models that define the emerging design to evaluation models that enable the designers to validate the properties of the design (see Figure 4).

Salience and background knowledge in design

Background knowledge and modeling choices

In design, the same entity, such as a component, function, or process, may often be modeled in different ways. The case is similar in science and even before models were studied in philosophy of science, scholars studied this idea under the heading of two related but distinct effects: the underdetermination of theory by observational data and the theory-ladenness of observation. Just as theories are underdetermined by observations, so too are scientific models. The history of science as well as contemporary sciences provide a plethora of examples in which very different models all represent a given phenomenon with the same amount of accuracy. Like underdetermination, the theory-ladenness of observation also shows up in modeling. Consider the following example from the nanosciences: when modeling surface effects, a scientist *chooses* to model interactions on the surface in a classical, quantum-mechanical or semi-classical way; this preliminary decision precedes the modeling itself and fundamentally defines the model. In what Kuhn refers to as normal science, scientists find themselves in a very different model environment. Even so, the choice to use a specific theory likewise fundamentally defines the model, though there is still room for various models within one theoretical framework.

Similarly, designers often have a choice about how to model a given aspect of their design. A variety of tools and modeling environments are available for designers. For example, there are many different commercial CAD systems with various functionalities. Even when a certain modeling environment has been selected, modelers still have to choose

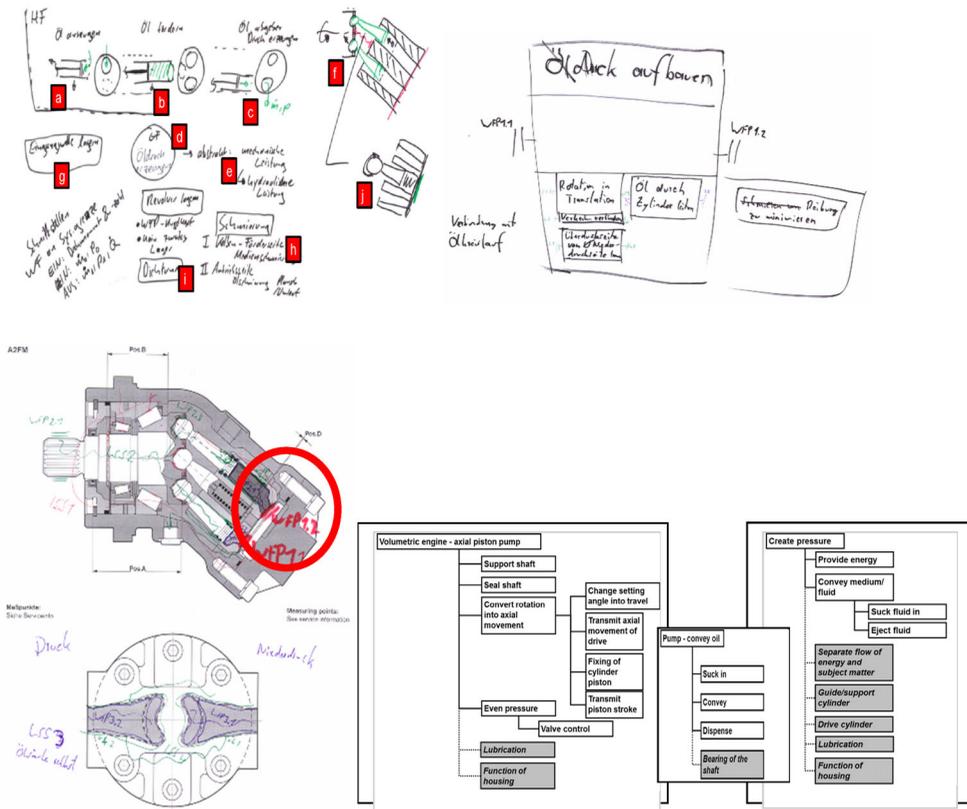


Figure 6. Different functional models for a pump from Eckert et al. (2011)

how to generate the model; the model environment does not fully determine the model. Both the freedom that the modeling environment allows and the constraints entailed in the choice of a specific modeling framework are often not fully realized in practice.

In engineering practice, the reasons for the choice of a modeling framework are often undocumented and may become problematic when models are reused in (even slightly) different contexts. For example, the authors of the kayaking paper advocate using a parametric approach as opposed to modeling each individual kayak. If a team knew from the beginning that they would only design one kayak, it might be faster to use a classical geometric model instead of a parametric approach. An even more fundamental decision that precedes the modeling practice, which becomes very apparent in the kayak example, is whether to model the artifact with a physical or geometric model or with a numerical simulation. Also, what exactly is to be modeled is a presupposition that influences the modeling and precedes it to some extent.

Fundamental suppositions frequently precede modeling and are often made unconsciously. In principle, this is similar in design and in the sciences, but there seems to be a difference in practice. Scientists most often work in what may be called ‘normal science’ following Kuhn, i.e. they answer scientific questions within the paradigm of a given discipline. Note that this holds even when scientists work with multi- or interdisciplinary

approaches, as each scientist within a collaboration is always an expert in a specific field. A model in theoretical chemistry, for example, is fundamentally defined by whether the phenomenon is to be modeled classically, semi-classically or quantum-mechanically. But the respective scientists are most likely familiar with the relevant background knowledge. By contrast, there seems to be nothing akin to a normal science in engineering design practice. More often than not, designers make use of very different models for which they and their audience do not possess (sufficient) knowledge of the relevant background. Models sometimes are taken from their original contexts simply to start conversations in the team.

In engineering design, fundamental choices that correspond to the choice of a different scientific paradigm seen in the quantum chemistry example can take various forms. Vermaas⁴⁹, for example, analyzes differences between various functional modeling approaches. Following Brown and Blessing,⁵⁰ he points out that some functional models describe the goals of an agent: the state of the world the agent wishes to achieve, the actions the agent executes with the device, the functions or roles the device should play in the environment, or its behavior, i.e. what it does when it is used.

Saliency

What is modeled and how it is modeled influences how the models are used, and the decisions based upon them. The kayak in the student project, for example, was modeled in such a way that it is readily available for additive manufacturing. While this unspoken presupposition is rather benign in this particular case, not reporting it explicitly may create certain challenges as the models used in this process would need to be adapted to generate molds of kayaks.

Figure 6 shows the results of an experiment in which several engineers (all with mechanical engineering degrees) were asked to analyze the function of a pump (bottom left corner). They chose different modes of expressing their functional model, different notations and a different logic of modeling.⁵¹ The participants' analyses diverged significantly not just in their details, but in more fundamental aspects as well. The participants did not agree on the role that some elements of the pump (e.g. the casing) play in its overall function. They had different notions of functions and expressed functions in fundamentally different ways. They also interpreted how the pump works very differently. For example, the details of the connection between the piston and the concave seal were interpreted in different ways (see the red circle in Figure 6). While some participants assumed that the curvature of the end of the piston pressed the piston onto the seal, others saw no significance in the curvature of the piston.

The illustrations in Figure 6 were created in an experimental setup, but similar models are generated to sketch out functions in industry. These models, like others used in industry, rarely contain an explicit description of their purpose, as this is clear in the context in which they are first produced. However, as the models are later reused, the original purpose might be lost. It therefore might be advisable in some circumstances to include the purpose of the model in the model description. However, as models are adapted and reused, version management might become complicated and misleading, and the ambiguity of purpose might also serve as a source of inspiration,⁵² allowing designers to see a new purpose for an existing or modified model.

The participants' interpretations of functions in the experiment depended on the training they had received, such as at different universities, or which part of their training they had focused on. Problems arising from different interpretations of concepts are further aggravated when engineers come from different disciplines, e.g. software and mechanical engineering. The need to collaborate across multiple disciplines occurs, of course, not just in engineering design, but also in contemporary sciences.

Figure 6 clearly displays how the background knowledge of the modeler, which may even be tacit, influences not only the modeling itself, but also what modelers see in a model. Borrowing a term from Kuhn,⁵³ we refer to this as a *salience*, i.e. different designers do not observe the same things in the same model—some pay attention to the curvature of the piston while others do not. When generating models, engineers are making many assumptions about the use and purpose of the model, as well as the elements and behavior of the future design. For example, while most participants assumed the pump was used to pump, some pointed out that it could be reversed and act as a type of motor. The kayak designers made assumptions about many aspects of the kayak, like the size and skills of users or the properties of the 3D printed material. While some of this information might be captured in documentation, it is neither inherent in the models nor universally shared among the engineers. Engineers in industry also have to understand the functions of the existing products and their components when they modify products. Here, salience can cause significant problems for subsequent activities as engineers need to understand the models of how the product works.⁵⁴

Models as decision making aids

Design can be seen as an ongoing process of decision making. Those who defend this view take a purely formal approach to decision making that reduces it to a sequence of mathematical decision models. As opponents argue, however, this view overlooks the social nature of design processes. As we will illustrate in the following discussion, decision making understood in a broad sense does indeed play a central role in design and models are an essential part of many decision-making activities in engineering design. Moreover, serving as a decision-making aid is often the primary purpose of models in engineering design. Most engineering models also have a strong representational aspect and serve as decision-making aids precisely *because* they represent a potential product or an idea for it. However, engineers also generate models that express the main functions of a class of projects, such as an aircraft, as an expression of concepts. These models do not represent a specific target system, but assist engineers in structuring conversations.

Unlike scholars, who argue for design as formal decision making processes, we contend that models contribute to communication and thus play a central role in the social nature of the design process. While models in design often aim primarily at decision making, they may nonetheless fulfill other epistemic functions, such as structuring engineering knowledge. Quite often, this may even be the very reason models are used as decision-making aids.

Note that just as many other apparent differences between science and engineering design are ultimately a matter of differences in degree, the same can be said for the roles that models play. While the decision-making aspect seems to be present in most design models, models may serve as decision-making aids in science as well,⁵⁵ such as when high

energy physics models provide information about whether and precisely how the next particle collider is to be built. Moreover, just as engineering models of traffic flows serve as aids in political decision making, scientific models likewise influence political decisions, such as those concerning the spread of a pandemic or on the consequences of greenhouse gas emissions.⁵⁶ Furthermore, though the focus in philosophy of science is mostly on models as epistemic devices, models in the sciences, just as in engineering, also fulfill other functions. The standard model of particle physics provides the current standard explanation and understanding of the most fundamental physical processes at a subatomic scale. It is thus an important epistemic device today, while other models may be used mainly for pedagogical or didactic purposes. Bohr's model of the atom, which describes the motion of electrons around the nucleus in analogy to the motion of the planets around the sun, is clearly outdated. However, even today Bohr's model proves useful in teaching science and thus fulfills a pedagogical function. It helps students to understand, for example, how subatomic movement distinguishes itself from classical planetary motion, i.e. that electrons do not move in fixed orbits.

Models as externalizations

The design of most engineering products is too complex to hold in one's mind, so it is necessary to externalize ideas. Together with other vehicles of representation like graphs and sketches, 3D images or tables and diagrams, models are a central means of externalizing ideas in engineering designs. Here details may really matter. For example, as shown in Figure 3, the fine details in the curve of the kayak determine its maneuverability, or the exact shape of the convex plate at the bottom of the pump ensures that it seals and therefore pumps efficiently.

The core of some modeling activities in engineering design lies not in models' role as a means to represent some not-yet-existent target system,⁵⁷ but in the fact that models are externalizations. Externalizations play a very important role in the design process because they enable designers to reflect on the design for purposes of assessment, but also to see the potential for further development and new ideas.⁵⁸ The reinterpretation of ambiguous externalization has been recognized as a primary mechanism for creativity in design.⁵⁹ When designers interact with an externalization of a design, they make a conscious or sometimes unconscious decision about how to proceed with the design. Externalizations enable designers to decide on the next steps in creating the design or the actions that are triggered by the current state of the design. For example, engineers might realize that they need to obtain further information and then decide how to obtain this information or plan steps to evaluate the design.

As engineering design is usually a collective activity, externalizations play an important role in communicating and sharing design ideas or the state of the design with other designers, users or clients. Without an externalization of a design idea, it is not possible to share it; however, the model is also a central source of misunderstanding and resulting problems in the design process. As all models are abstracted and only express selected elements, other details are filled in by those who interact with the models based on their own experiences and perspectives. As we argued in the previous section, background assumptions that are not explicated further and salience may be a source of misunderstanding where each modeler and user of a given model perceives a very different model. The same

ambiguity that can trigger creativity can also cause inefficiency and repetition of tasks in teams collaborating on a design.⁶⁰

Engineers also need to update their clients or customers on the progress of their work to obtain feedback on the evolving design. They often share the engineering models created as part of the design process; however, they also create models specifically to interact with their customers.⁶¹ For example, with a personalized kayak, the customer could be shown a 3D model as seen in Figure 3, but designers might also create a more detailed rendering that depicts the potential boat with full color and surface texture, as shown in Figure 2. As 3D technology advances, engineers are also creating full size or scale 3D models for their clients, and external parties usually require visual or tactile models rather than mathematical models. These are commonly referred to as visualizations rather than models in the philosophy of science literature, while the design community itself views them as models.

Externalizations therefore enable individual as well as collective decision making. In particular, they allow external stakeholders like clients to be brought into the design process.

The various roles of models in engineering design

Engineering processes are set up to have many formal decision-making points. Many current processes are structured as Stage-Gate processes.⁶² Companies make a formal decision about whether to proceed with a project based on evidence that the design has reached a particular milestone. These milestones are usually demonstrated through models or the results of an analysis of models. Engineers have regular 'design review' meetings, where teams come together to assess the progress of the design, flag problems or identify outstanding tasks. These discussions are conducted around models of the design, which different team members use to illustrate specific points. Engineers also generate specific models in or for decision-making meetings, where they collate information about a specific aspect of a design. For example, most companies carry out failure mode and effect (FMEA) analyses,⁶³ where they collect potential failure modes on a large spreadsheet, assess the likelihood and effect of the potential failures and identify actions to mitigate them. FMEA models are generated and reviewed regularly in meetings and are used to prioritize design tasks and decisions about changes to the design.

During early stages of the design process, engineering companies often develop multiple alternative designs before they decide which alternative to carry forward. Through the design process, engineers are often challenged to think through or develop alternative solutions to overcome specific design problems. For example, before parametric models were used, kayak designers would have offered the alternatives shown in Figure 3 as design options, and one would have been chosen for production. At these points, engineers select between various alternatives, which are potentially developed to the same extent. In this case, all design alternatives have the same kinds of models associated with them, and these models are used to select a suitable design. In practice, engineers often have a preferred design that they want to develop further; they then select the alternative designs to put forward in such a way that their preferred option appears as a more obvious choice.

Many selections also involve users or customers, who are presented with multiple solutions at different stages of development. They can then select an option. The models associated with these design alternatives are also an important way for users and customers

to understand what they want and what their requirements are. Seeing and interacting with models is an important way to understand whether a design meets their requirements and could be a viable product.

'Truth-making' and 'truth-keeping' in engineering modeling

In philosophy of science one of the key concerns is the relationship between models and their target systems. The underlying assumption is that the phenomenon being modeled exists in reality, or at least has existed or might exist in the future. In engineering design, this relationship is essentially determined by the decisions made by the engineers. The engineers decide between two equally well-developed alternatives. As soon as the decision is made, one set of models will become associated with the emerging design and the other will not (discarded design alternatives are usually seen as an opportunity to learn and might be used as the starting point for future designs). Later, when the design has become a product, the design models that have been selected form part of the representation of an existing object, which can then be objectively compared with the models. In this sense, engineers act as truth makers, who decide which model will represent a real design. Here it is important to note that in complex institutional settings, not everyone who is involved in the modeling may be involved in these decisions. The power that is given to some and not others may reflect the institutional setup rather than the role that engineers play in the modeling.

An engineering model of an alternative that has been discarded looks exactly like the model selected for further use. Models do not contain information about how they are related to their target system, unless this information is explicitly annotated (salience). While the relation might be clear to the engineers who develop the models, as the target system develops the relationship becomes tenuous. The models are reused, and the information about which models ultimately led to a prototype or a design eventually gets lost. For example, the models of kayaks developed by the student team could be used as a starting point by a kayak maker or a 3D printing company. There is an intention for what should be reused, which is clear to those who create the models, but not to others. These engineers thus become truth keepers with regard to the relation of the models to the target system.

Neither the pragmatic accounts of representation nor more general accounts of models as epistemic vehicles can elucidate the notion of engineers as truth makers or keepers, as they overlook the fact that in the design process models are often used primarily as neither epistemic nor representational vehicles. Augmenting these views by acknowledging the role models play in decision making gives us a better understanding of engineering design processes. This may also directly benefit the design process because of the implications for epistemic practice, such as when models are reused or repurposed and salient features cause problems or provide inspiration for new creative ideas.

In our interview studies on engineering change in helicopter design⁶⁴, engineers voiced a frustration that in large design teams, knowledge about the intention and relevance of these models is relatively local to specific engineers, teams or parts of teams. Therefore, the relationship between the set of models and the target is opaque to others until a set of manufacturing instructions is transmitted. Theoretically, these instructions describe the product that is to be produced. However, in practice this design is often amended to address issues that arise in the manufacturing process. Design models are also often not updated as the

design changes. Functional models in particular are created at the beginning of a project to define the structure or to carry out FMEAs, but rarely updated later; yet they are used throughout the design process after the design has been changed. As the previous section has illustrated, the interpretation of a product and the resulting model also diverge for different people. Therefore, it is debatable whether in practice there is ever a single set of models that truly represent the product. Decisions are made by combining the models and the background knowledge of the decision makers. The engineers know many aspects of the design, such as cost constraints or manufacturing processes, and therefore they know which alternatives might be beneficial to them personally or to their organization. This background knowledge gives the engineers power over those who only see the models.

Conclusion

Without doubt, engineering design is concerned with representations of the artifacts or processes to be designed. But not all models have the primary function of representation. The different visualizations of the kayak primarily serve to aid communication between the future users of the kayak and the designer. Similarly, architects make some sketches specifically to communicate with clients. Models are interpreted differently by the people who interact with them depending on their background and interests. This different focus makes different aspects of models salient, which requires discussion to reach a shared understanding.

The design community highlights the importance of sketches and other representations as externalizations in enabling designers to reflect about the design or to discuss it with others. One of the purposes of reflection is to support designers in deciding how to proceed. This paper has elucidated the complex relationship between models and their target systems, where only the designer knows which aspects of models have been or will be present in a future design because, for example, some elements will be carried over from a past design and others are only tentative but not indicated as such on the model. In this sense, the designer or engineer becomes the truth keeper. At the same time, the engineers or designers also actively make decisions about which elements they will carry forward or which option to pursue. This makes them truth makers.

Epistemic aspects are central here, but as we have argued, focusing on the epistemic aspects alone—for instance, by concentrating on models as representational vehicles or more generally as epistemic tools—obscures certain challenges in modeling. Particularly when models are reused and repurposed (as is common in design), the relationship between the models and the target systems is far from clear.

Design processes are often embedded in hierarchical decision structures. At one point of the design process, someone on the design team decides in favor of a certain product feature (as in our simple case when a certain visualized kayak model is selected for printing). Then the model is not only used for the specific purpose that the designer had in mind, but reused and repurposed in multiple ways. The decision for specific modeling assumptions is often tacit. Some explicit decisions are not shared because knowledge about the model may be a matter of power. This implies that explicit decisions to use a certain design are masked as epistemic choices, while they may in fact be motivated by a broad range of considerations. Design is fraught with epistemic uncertainties; these decisions reduce uncertainty, but they are not necessarily based on epistemic grounds.

Notes

1. Hazelrigg, "Decision-Based Engineering Design"
2. Wynn and Eckert "Perspectives on Iteration"
3. Stacey and Eckert, "Against Ambiguity," 153–183
4. Eckert and Stacey, "What is a process model?"
5. Lithgow et al., "Design Automation Additive Manufacturing"
6. Bonham et al., "Digital Thread"
7. Vanja et al., *CX für Ingenieure*
8. Frigg and Hartman, "Models in Science"
9. E.g. Bailer-Jones, *Scientific Models Philosophie Science*, van Fraassen 2008, *Scientific Representation*
10. Suárez 2010, "Scientific Representation"
11. Cf. for example Frigg and Nguyen 2020, "Scientific Representation"
12. Toon 2012, *Models as Make-Believe*, 43
13. Weisberg, "Who is a Modeler," 207–233
14. Knuuttila, "Isolating Representations Credible Constructions"
15. Knuuttila, "Models, Representation, and Mediation", Knuuttila, "Isolating Representations vs. Credible Constructions", Chakravartty, "Informational Functional Scientific Representation"
16. Poznic, "Representation and Similarity" Suarez, "Scientific Representation"
17. Walton, *Mimesis as Make-Believe*.
18. Morgan and Morrison, *Models as Mediators*, Knuuttila, "Isolating Representations Credible Constructions"
19. Note that Knuuttila's account of models is sometimes referred to as an artefactual account of model representation.
20. Knuuttila, "Isolating Representations Credible Constructions"
21. Suppes, "Models of Data," 252–261, Mayo, *Error Growth Experimental Knowledge*
22. E.g. Cartwright, *How Laws Physics Lie*, Morgan and Morrison, *Models as Mediators*
23. Morgan and Morrison, *Models as Mediators*
24. Morgan and Morrison, *Models as Mediators*
25. Frigg and Hartmann, *Models in Science*
26. Lithgow et al., "Design Automation Additive Manufacturing"
27. Bonham et al., Digital Thread
28. *ibid*
29. Lithgow et al., "Design Automation Additive Manufacturing"
30. Morgan and Morrison, *Models as Mediators*
31. Vanja, *CX für Ingenieure*
32. Lithgow et al., "Design Automation Additive Manufacturing"
33. Gero and Kannengiesser, "Function–Behaviour–Structure Framework"
34. E.g. Pahl and Beitz, *Konstruktionslehre*
35. Roth, *Konstruieren mit Konstruktionskatalogen*
36. VDI-2206
37. VDI-2211
38. VDI-2209
39. Minsky, "Matter, Mind and Model"
40. Stachowiak, *Allgemeine Modelltheorie*
41. Vanja et al., *CX für Ingenieure*
42. Roddeck, *Einführung in die Mechatronik*
43. Poznic, "Modelling Organs with Organs on Chips"
44. Karaca, "Theory-Ladenness of Experimentation"
45. Eckert and Hillerbrand, "Models in Engineering Design"
46. Mankins, "Technology Readiness Levels"
47. Bucciarelli, *Designing Engineers*
48. Wynn and Eckert, "Perspectives on Iteration in Design and Development"
49. Vermaas, "The Flexible Meaning of Function in Engineering"

50. Brown and Blessing, "Relationship between function and affordance"
51. Eckert et al., "Different Notions of Function"
52. Schon and Wiggins, "Kinds of seeing"
53. Kuhn 1962, *The Structure of Scientific Revolution*
54. Eckert et al., "Different Notions of Function"
55. An interesting example in this context is also provided by maps; cf. Contessa 2013 or Vertesi, "Mind the gap." Subway maps, for example, represent certain features of infrastructures and are used to decide which path to take, etc.
56. Hillerbrand, "Climate Simulations"
57. Poznic, "Representation and Similarity"
58. Schön, *The Reflective Practitioner*
59. Goldschmidt, "The Dialectics of Sketching"
60. Stacey and Eckert, "Against Ambiguity"
61. Eckert et al., "Sketching Across Design Domains"
62. Cooper, "Perspective: Stage-Gate[®] Idea"
63. Stamatis, *Failure Mode Effect Analysis*
64. Eckert et al., "Change and customization"
65. Eckert and Hillerbrand, "Models in Engineering Design"

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