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ARTICLE

Scientific Modeling Versus Engineering Modeling: Similarities and Dissimilarities

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Abstract
This article aims to answer what I call the "constitution question of engineering modeling": *in virtue of what does an engineering model model its target system*? To do so, I will offer a category-theoretic, structuralist account of design, using the olog framework. Drawing on this account, I will conclude that engineering and scientific models are not only cognitively but also representationally indistinguishable. I will finally propose an axiological criterion for distinguishing scientific from engineering modeling.

Keywords Scientific modeling · Engineering modeling · Structuralism · Design representation · Final value · Instrumental value

1 Introduction

Modeling is extremely common among scientists. By using models, they explain why the world is the way it is, predict future events, subsume seemingly disparate phenomena under a law of nature and do other cognitive activities. Given that explaining, unifying and making predictions are truth-conducive practices, scientific models may be conceived of, at first sight, as *epistemic* (or cognitive) means. Whatever their nature, from the iconic model of the solar system to the group-theoretic models of quantum particles, philosophers of science have closely scrutinized the *relation* between scientific models and the world, the so-called *scientific representation*, and also proposed several accounts to answer the constitution question of scientific representation (Callender and Cohen 2006): *in virtue of* what does a scientific model represent its target system?[1] But it is not just scientists who use models; engineers too utilize them to produce technical artifacts. As such, engineering models are usually taken to be *pragmatically* valuable tools. Like the scientific case,

[1] The philosophical literature on scientific representation is so vast and growing that I can mention only the surveys. Frigg and Nguyen (2017) have examined almost all views. Chakravartty (2010) has categorized them into the two groups of informational and functional theories. Boesch (2019) has recently developed a unifying picture of functional or agent-based accounts. For a brief sketch, see Frigg and Nguyen (2018).

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and irrespective of their nature, from the scale model of a bridge to the computer simulation of an aerospace vehicle, the parallel question is: *in virtue of* what does an engineering model model its to-be-built artifact? I call this question the *constitution question of engineering modeling*. Philosophers of technology, who usually refer to an engineering model as *design*, however, have often examined the nature of design, rather than its relation to the world, and developed several theories of design.[2] In this article, the constitution question about engineering modeling would be in focus: what is *engineering modeling* as a relation between a model and its target?

To address the question, I will turn to the more familiar question, i.e. the constitution question of scientific representation, and then try to make clear in what ways scientific and engineering modeling are similar and dissimilar. After all, several philosophers have defended the distinguishability between pure and applied sciences (including engineering sciences), and many philosophical accounts have been proposed to explain this distinction (Bunge 1966; Niiniluoto 1993; Boon 2006; Poznic 2016; Roll-Hansen 2017; Yaghmaie 2017).[3] However, here I will particularly focus on the distinction regarding the sorts of their modeling—which has been considered earlier by Poznic (2016)—and argue that in engineering modeling, like scientific representation, cognitive aims are pursued. In other words, engineers before everything else are going to predict the properties of a to-be-built artifact, to explain its future mechanism and to understand its prospective behavior. So engineering models like scientific ones are cognitive tools. Thus understood, these two kinds of modeling are *cognitively* alike. The similarities between them, however, are not limited to the cognitive considerations. Next, and more importantly, I will show that engineering modeling, once again like scientific representation, is partially grounded on the structural similarities between models and their targets. So cognitive aims are achieved *in virtue of* this sort of similarity. Thus in this sense, the two sorts of modeling are also *representationally* similar. But if they are both representationally and cognitively indistinguishable, what would differentiate them? Drawing on the two well-known, defended distinctions in moral philosophy (Korsgaard 1983; O'Neill 1992; Kagan 1998), namely extrinsic versus intrinsic and final versus instrumental goodness, I will argue that while reaching cognitive goals via scientific representation is *finally* valuable, achieving them through engineering modeling is *instrumentally* good. Therefore, their *axiological* features characterize them.

The paper is structured as follows. In the second section, I will briefly survey the main theories of scientific representation and then categorize them into three groups: full-blown structuralist, full-blown agent-based and hybrid accounts. I will next argue that scientific representation is grounded on both structural and intentional aspects. Drawing on van Eck's analysis of the role of design in engineering (2016, Ch. 3), in Sect. 3 I will show that engineering models are cognitive tools. Next, a structuralist account of engineering modeling will be proposed. This account uses the *olog*; a category-theoretic framework developed by Spivak and Kent (2012). To distinguish engineering from scientific modeling, in Sect. 4 I will compare my account with Poznic's (2016) proposal upon which it is the direction of fit that differentiates them. I will argue that his criterion seems to be both too strong and

[2] Among them are the use plan analysis of Houkes and Vermaas (2010), the explanationist account of van Eck (2016) and Galle's (1999) action-based account in which the conception of design representation has a key role. Besides philosophical accounts, design theorists also have suggested several design theories, e.g. the concept-knowledge (C-K) theory of Hatchuel and Weil (2009), the Functional-Behavior-Structure account of Gero and Kannengiesser (2004) and the Functional Basis method of Stone and Wood (2000).

[3] Many thinkers attack such a distinction. For more on this, see footnote 20.

too weak in the sense that it identifies some engineering as scientific and some scientific as engineering models. Finally, I will adopt an axiological criterion for separating the two sorts of modeling.

2 Scientific Modeling

Of scientific representation, several philosophical questions are worth discussing (Frigg and Nguyen 2017) among which the so-called "constitution" one (Callender and Cohen 2006) has attracted much attention in recent years: *in virtue of what does the model M represent the target T*? Answers to the constitution question may be categorized into the following three groups. According to the first, scientific representation is nothing but a relation between what represents (the "source" of representation or the model) and what is represented (the "target" that is a selected aspect of the world). Furthermore, the relation is grounded on the similarities shared between the source and target. But the best way to understand similarity is to conceive of it as a structural relation, e.g. isomorphism (Ubbink 1960), homomorphism (Bartels 2006) and partial isomorphism (French 2003). More precisely, according to this approach, M represents T iff M is similar to T iff M is morphic to T.[4] So, for example, the iconic model of the solar system represents the solar system, since the structures associated with these two things are isomorphic. Consequently, scientific representation does not depend on other things such as the intentionality of the person who uses M to represent T. As such, the view may be called the *full-blown structuralist account* on which M represents T, denoted by $R_s(M, T)$, iff $SS(\mathcal{M}, \mathcal{T})$ where $SS(\mathcal{M}, \mathcal{T})$ means the structure associated with M, i.e. $\mathcal{M}$, is structurally similar to the structure associated with T, i.e. $\mathcal{T}$. The critics of the view have argued that, for instance, similarity due to its logical properties which representation lacks (e.g. being symmetric) and the problem of "mistargeting" (i.e. representing different target systems by structurally similar sources) provides neither necessary nor sufficient conditions for scientific representation and then cannot fully ground it (Suárez 2003).[5] Therefore, any adequate theory of representation should take into account another significant factor, i.e. the agent's intention.

According to the *full-blown agent-based accounts* as recently discussed by Boesch (2019), scientific representation is thought to be not a relation but an intentional action performed by a cognitive agent. The first instance of this view is of Callender and Cohen (2006) in terms of which scientific representation is the act of stipulation of the cognitive agent. In other words, $R_s(M, T)$ iff the agent C stipulates that M denotes T. For instance, if someone stipulates that the Einstein equations "represent" the structure of spacetime, then it scientifically represents it. However, other views under this category do not such trivially deal with the problem. According to Hughes' DDI account (1997), for instance, scientific representation is characterized by three actions: denotation, demonstration and

[4] For instance, Ubbink argues that "[t]he essential thing is that a model represents an object or matters of fact in virtue of its structure; so an object is a model ... of matters of fact if, and only if, their structures are isomorphic" (Ubbink 1960, 302), or French holds that "[e]ach of these claims [i.e. isomorphsim is not necessary for representation, isomorphism is not sufficient for representation and models denote and do not resemble] will be questioned and I will conclude by suggesting that, through appropriate modifications, a form of isomorphism [i.e. partial isomorphism] can serve to underpin representation in both the arts and science" (French 2003, 1473).

[5] The theories deploying non-symmetric morphisms such as homomorphism would meet the first objection (Bartels 2006). For more details about structuralism on representation, see Frigg and Nguyen (2017).

interpretation. In denotation, the agent uses the source to stand-in for the target. Next, she demonstrates some aspects of the source and finally interprets them to infer, explain, predict and do other cognitive activities. Suárez's inferentialism (2004; 2010; 2015) is another account on which $R_s(M, T)$ only if M has the capacity leading an "informed user" to consider T and the capacity allowing her to draw specific inferences concerning T. He calls the first capacity *representational force* and the second the ability to make *surrogate reasoning*. His view may be thought of as a full-blown agent-based account, because the capacities are not grounded on the properties of S and T, but only on the norms governing the scientific community (Suárez 2015, 42).[6]

The final category includes the *hybrid accounts* on which scientific representation is neither a dyadic relation between a source and a target nor an intentional action, but an n-ary relation between the source, the target and the intentional actions taken by an agent. The traces of this kind of thinking can be found in Bueno and Colyvan (2011), Bueno and French (2011) (in a vague manner, since they do not endorse the constitutive role of intention in scientific representation), Giere (2004; 2010a, b) and Van Fraassen (2010). According to Bueno and Colyvan's (2011) inferential account of the applicability of mathematics, for example, three steps, i.e. immersion, derivation and interpretation, together lead to representation. In immersion, a cognitive agent relates "the relevant aspects of the empirical situation" to "the appropriate mathematical structure" by *choosing* a map from the situation to the structure. Next, in derivation and regarding the mathematical structure associated with the physical situation, *appropriate* consequences are drawn from the formalism. And finally in interpretation, a cognitive agent interprets the mathematical consequences, using a *suitable* mapping from the consequences to the empirical situation. In all the three steps pragmatic and contextual considerations are involved in. As the authors have put it, in immersion and interpretation "there is considerable choice about the mappings used in both ... stages. In both cases the decision about the choice of mappings will be a matter of context, and pragmatic considerations come into play" (2011, 354), and about the idealization in derivation step "to be able to derive any results from [the] setting, an additional idealized move has to be made" (2011, 360). Unlike Hughes' DDI account, someone may consider their view as a sort of hybrid account, because the mappings chosen in these stages are all structure-preserving. So, within their view, the intentional aspects alone cannot ground scientific representation.

The main problem facing these accounts is how to share the representational burden between the source-target relation, supposed to be a structural one, and the intentional actions so that none of them becomes idle. For instance, according to Frigg and Nguyen's (2017) analysis of Giere's agent-based similarity account, which proposes "agents (1) intend; (2) to use model, M; (3) to represent a part of the world W; (4) for purposes, P. So agents specify which similarities are intended and for what purpose" (Giere 2010a, 274), the role of source-target relation becomes unnecessary, and the cognitive agent fills the whole of representational role, since similarity is neither sufficient nor necessary for representation (Giere 2004, 747). Here I do not adjudicate between these views. But regarding the objections against the full-blown structuralist and agent-based accounts, it seems that the most promising account should take into account both the intentional and structural aspects in a way both of which have their own grounding roles. Informed by the inferential account of Bueno and Colyvan, for instance, we may think of scientific representation as a

6 Suárez's account is deflationary in the sense that it aims not to answer the constitution question, but just to provide necessary conditions.

structural relation between the source and target, which itself is grounded on the intentional aspects at least in two ways. Firstly, one may ascribe different structures to a target. In other words, the target underdetermines the structure supposed to be represented by the model. So structural representation depends on the action of ascription. Secondly, that which relation (object) in the structure associated with the source should be assigned to which relation (object) in the structure associated to the target depends on agent's choices. Now, this is the action of assignment (in both immersion and interpretation stages) that grounds structural representation. Only the intentional aspects, however, cannot fulfill the representational role. After ascribing and assigning, to have scientific representation, there should be a sort of morphism between the two structures. To be more precise, let A be the set of all ascriptions and I the set of all assignments. The crucial point is that there may be no $a \in A$ and $i \in I$ such that the two structures are morphic.[7] Thus understood, structural representation is grounded on both the intentional actions taken by the agent and the structural relations. To define the hybrid account, these considerations may be molded in this way:

Scientific Modeling: Let M be a scientific model and T a selected part of the world. M scientifically represents T if and only if, regarding the intentional actions $A = \{A_1, A_2, ..., A_n\}$ taken by the agent C, there is a suitable morphism between $\mathcal{M}$ and $\mathcal{T}$, where they are, respectivley, the structures associated with M and T.

Now I would like to make a number of passing remarks concerning the characterization. First, the above description differs from the full-blown structuralist accounts in that it refers to the set of intentional actions as a partial grounding base. Second, I do not want to put forward a new theory of scientific representation here, nor defend the hybrid accounts against all attacks have been launched upon the full-blown structuralist accounts, but merely reconstruct them schematically to be compared more easily with engineering modeling.[8] And finally, I have not limited the intentional actions to the ascription and assignment—for I think every theory of scientific representation should be to some extent schematic and leaves room for other resources of implicit interpretations (Frigg and Nguyen 2019) and intentional commitments (Fletcher 2018) of users.

3 Engineering Modeling

In the previous section, it was argued that scientific models have a representational role on which scientists can attain cognitive goals. However, it can be shown that the cognitive-functional role of models is not limited to pure science disciplines; engineering models also are cognitively worthy tools (Boon and Knuuttila 2009). The architectural model of a bridge, the computer simulation of a wing and the paper plan of a circuit are all engineering models upon which engineers predict, understand and explain facts about the bridge, wing and circuit. Indeed, embodying these cognitive virtues, among others, allows engineers to produce technical artifacts *more effectively*. In the literature of philosophy of technology and design studies, an engineering model is usually treated as the production of a design process and referred to, for example, by "design plan" or "design representation". Among the theories of design within which the semantic and epistemic roles of a design

[7] To avoid Newman's objection, the set A is not unconstrained (Bueno 2017). Otherwise, we can always ascribe a structure, being morphic to the model, to the target. As such, the intentional acts merely would carry out the representational burden.

[8] For a detailed defense of a hybrid account, see Bueno and French (2011).

production are deeply explored is Per Galle's account (1999). In what follows, I will first introduce his proposal and its critique given by van Eck (2016, Ch. 3), which recognizes the cognitive role of design representation instead of its semantic role. Next, using the framework of olog, I will develop a structuralist account of design representation on which the representational status of engineering modeling appears to be more close to its scientific counterpart.

3.1 Design Representation and Its Cognitive Functions

In Galle's (1999) account, the *artifact production process* is a set of actions performed by the three types of agents: the client, designer and maker. In this process, designing is a central stage characterized by the triple <designer, design representation, t> in which the design representation and t are, respectively, the production of designing and its time. A design representation, i.e. *the plan or model of the artifact on which the artifact would be produced*, has two semantic and epistemic roles. As a semantic tool, the design representation driven by the designer's ideas about the artifact enables her, the client and maker to interpret it and consequently to communicate[9] with one another concerning whether or not the design representation would satisfy their criteria. Furthermore, it is supposed to solve the so-called "problem of the absent artifact". The problem is how an artifact when it has not yet been produced can make true/false a related proposition. Based on Galle's suggestion, the truth-making relation is not between the to-be-built artifact and the proposition, but between the client's, maker's and designer's ideas and the proposition. More importantly, what shape their ideas are their interpretations of the artifact's attributions as described in the design representation. For instance, when a bridge designer tells a mayor "the bridge just connects the highway A with B" and the mayor replies "it is better to connect A with C", the absent bridge does not enable them to communicate but their ideas of the bridge (or better stated their interpretations of the description of bridge as given in the design representation). So the design representation driven by the designer's aims enables the client and maker to communicate with the designer about whether or not it would satisfy their criteria. If not, the process of redesign will begin. Thus understood, a design representation in Galle's account has a *semantic role*, meaning that it makes meaningful the propositions concerning the design representation. However, it also has an *epistemic role*. Given a design representation, say, of the bridge, the designer *explains* to the mayor why it can carry a heavy traffic load, the mayor as a client *predicts* how it would like to be and the maker *knows* what material would be suitable to construct it. As such, a design representation allows the agent to achieve her epistemic or cognitive goals concerning the artifact which has not yet been produced.

According to van Eck (2016, Ch. 3), the view that a design representation is a semantic tool is doomed to failure for two reasons. First, assigning a truth value (in an objective or intersubjective way) to a given proposition through the agent's ideas and consequently having an effective communication between them need the ideas to be in accord with each other. But ideas are internally isolated and externally inaccessible. More precisely, for instance, there is no guarantee that the designer's idea of the bridge matches with the client's idea of it, that are both the production of their interpretations of the bridge as described in the design representation. Therefore, "it becomes impossible to

[9] Galle calls the communication of the designer with herself "self-communication" (Galle 1999, 63).

intersubjectively establish the truth or falsity of propositions expressed in terms of design representations in unambiguous way, since the true-false statements are (completely) relativized" (van Eck 2016, 47). The second problem, for van Eck, is more severe. Consider the statement "the bridge would carry a heavy traffic load". It is reasonable to conceive the statement as a predictive one which *would be* true if it would carry a heavy traffic. However, according to Galle's suggestion, the truth-makers of the statement, i.e. the agents' ideas, are present when the artifact is absent and make it true or false, that it is in contradiction with the predictive characterization of the statement. For van Eck, the semantic role of design representation should respect this intuition that this is the to-be-built artifact that makes true/false predictive statements. But Galle's account does not capture it.

After identifying the problem of the absent artifact as a pseudo-problem, van Eck attributes two other cognitive roles to design representation: "as means for counterfactual understanding and as means to make predictions with respect to the functional performance of redesigned systems" (van Eck 2016, 47). To do so, van Eck first uses Stone and Wood's (2000) functionalist account of design to model the internal structure of a design representation. Within this view, every artifact has an overall function driven by the client, which is represented in the design representation by operations on flows of materials, energies and signals. In a deeper step, each overall function is decomposed to more basic functions which are in turn represented by the associated operations on flows. Having a design representation which depicts the overall function of an artifact and its more basic functions, the agent is able both to predict how performing more basic functions would lead to the realization of the overall function and to understand counterfactually how the overall function would change if a more basic function were to be changed.

In addition to this sort of counterfactual understanding, the conception of design representation provides a frame making reasonable the process of redesign. Consider the artifact A with the overall function F and the more basic functions $f_1, f_2, ..., f_n$ represented in the design representation DR_1, respectively, by $G, g_1, g_2, ..., g_n$. Having seen DR_1, the client tells the designer that F supposed to be realized according to DR_1 would not be, say, energetically efficient. So the designer should begin the process of redesign. The designer produces a new DR, say DR_2, with the representational components $H, h_1, h_2, ..., h_m$. Given DR_1, DR_2, and the counterfactual understanding of how F and $f_1, f_2, ..., f_n$ would be fulfilled if it were to be built according to DR_1 or DR_2, the agents are allowed to know whether A modeled by DR_1 would be a more plausible artifact or A modeled by DR_2.

As we see, the role of design representation in engineering modeling is cognitive, as is the role of scientific representation in scientific modeling. At the end of the paper, I will provide an axiological criterion for distinguishing the two sorts of modeling, but in the next section I aim to answer the constitution question of engineering modeling: *in virtue of* what does the design representation DR represent its target T? In other words, like scientific representation, we are seeking sufficient and necessary conditions for representation. As a result, it will be shown that engineering modeling is also representationally similar to scientific modeling.

3.2 Design Representation as Structure

In this part, I will try to show that design representations as described by the functional basis method can be modeled within the olog framework. Spivak and Kent (2012) introduced it to model the entities and their relations embedded in an ontology. From a foundational point of view, an olog is a category-theoretic framework interpreted in terms of types

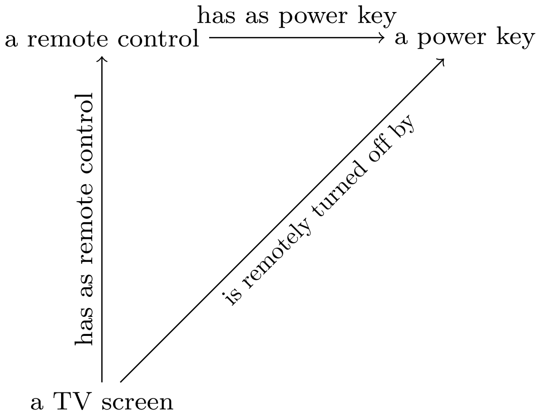

Fig. 1 In an olog, facts are represented by commutative diagrams

and tokens. In the following, I will first briefly introduce the basic notions of category theory[10] and then the olog. Next, I will present a simple design representation of an artifact within the framework.

A category $\mathcal{C}$ consists of the two types of objects: *objects* denoted by A, B, C, ... and *arrows* or *morphisms* denoted by f, g, h, ... To each arrow is assigned two objects named *domain* and *codomain*. For example, the arrow f with the domain A and the codomain B is denoted by $A \xrightarrow{f} B$ or $f : A \to B$. For each pair of arrows $A \xrightarrow{f} B$ and $B \xrightarrow{g} C$, there is an arrow $A \xrightarrow{g \circ f} C$ that is called *the composite of g following f*. Also, for each object A, there is an *identity* arrow denoted by $A \xrightarrow{1_A} A$. These objects satisfy the axioms of associativity, i.e. if $A \xrightarrow{f} B \xrightarrow{g} C \xrightarrow{h} D$, then $(h \circ g) \circ f = h \circ (g \circ f)$, and identity, i.e. if $A \xrightarrow{f} B$, then $f = f \circ 1_A$ and $f = 1_B \circ f$.

An olog is a category whose objects and arrows represent, respectively, *types* and *aspects* (or *functions* in the type-theoretic sense). For instance, the ontology having the two types `TV screen` and `remote control`, and the aspect `has as remote control`[11] is represented by *a TV Screen* $\xrightarrow{\textit{has as remote control}}$ *a remote control*. In an olog, *facts* are represented by commutative diagrams. For instance, the fact that `the power key of a remote control of a TV screen is equivalent with the power key that remotely turns off the TV screen` is represented by the diagram in Fig. 1.

As a transition from a type-theoretic framework to a set-theoretic one, Spivak and Kent define the *functor* $I : \mathcal{C} \to \mathbf{Set}$ as an *instance* of $\mathcal{C}$ that maps the type-theoretic object x of $\mathcal{C}$ to the set $I(x)$ of **Set** (i.e. the category of sets), and the aspect $f : x \to y$ to $I(f) : I(x) \to I(y)$. This instance satisfies a fact declared in $\mathcal{C}$, e.g. $f_{l_1} \circ f_{l_2} \circ ... \circ f_{l_i} = f_{k_1} \circ f_{k_2} \circ ... \circ f_{k_j}$, if $I(f_{l_1}) \circ I(f_{l_2}) \circ ... \circ I(f_{l_i}) = I(f_{k_1}) \circ I(f_{k_2}) \circ ... \circ I(f_{k_j})$. If we denote the fact by ϵ, we say that $I(\mathcal{C})$, the *category of instances*, is a model of ϵ and denote it by $I \vDash_{\mathcal{C}} \epsilon$. From an intensional point of view,[12] we may conceive of $I(\mathcal{C})$ as the *category of tokens*, $T(\mathcal{C})$, whose objects are

10 For more details, see Awodey (2010).

11 Since being aspect is a functional relation, we cannot simply denote the aspect by "`has`" (Spivak and Kent 2012, 4).

12 The mathematical notions to be introduced hereafter are not present in the olog framework.

structures $< \{a_1, a_2, ..., a_n\}, \{g^a_1, g^a_2, ..., g^a_m\} >$ where $a_1, a_2, ..., a_n$ are, respectively, the tokens of $x_1, x_2, ..., x_n$ and $g^a_1, g^a_2, ..., g^a_m$ are, respectively, the tokens of function types $f_1, f_2, ..., f_m$. If $I \vDash_{\mathcal{C}} \epsilon$, then each object satisfies ϵ, i.e. $g^a_{l_1} \circ g^a_{l_2} \circ ... \circ g^a_{l_i} = g^a_{k_1} \circ g^a_{k_2} \circ ... \circ g^a_{k_j}$. So, in summary, we have the three categories of olog, instances and tokens.

Given a design representation presenting some facts, and regarding the artifacts which would be built on the design representation, we may model the design representation by the structure $\mathcal{DR} =< \mathcal{C}, E >$, where $\mathcal{C}$ denotes the category of olog and E refers to the facts presented by the design representation. We may represent the artifacts to be built according to the design representation by $\mathcal{AC} =< T(\mathcal{C}), F >$, where $T(\mathcal{C})$ is the associated category of tokens and F is the (tokens of) facts satisfied by the objects of $T(\mathcal{C})$ representing the artifacts. These facts are nothing but the goals pursued by the client using the artifact. For instance, consider a client who asks a designer to design a TV with a remote control having a power key which can remotely switch off the TV screen. The design representation of this TV is an olog having the three types $x =$ `TV screen`, $y =$ `remote control` and $z =$ `power key`, and the three aspects $(f : x \to y) =$ `has as remote control`, $(g : y \to z) =$ `has as power key`, $(h : x \to z) =$ `is remotely turned off by`. So the design representation satisfying the fact ϵ mentioned above is modeled via $\mathcal{DR} =< \{x, y, z\}, \{f, g, h\}, \epsilon >$ in which $h = g \circ f$. Now consider the artifact with the TV screen a, remote control b and power key c that remotely switches off the TV screen. This artifact is represented by the structure $< \{a, b, c\}, \{f_{ab}, g_{bc}, h_{ac}\}, \delta >$ where f_{ab}, g_{bc}, h_{ac} are, respectively, the tokens of function types f, g and h, and δ denotes $h_{ac} = g_{bc} \circ f_{ab}$, representing the artifact satisfies the fact. Now we are ready to characterize the relation of engineering modeling being established between a design representation and its associated artifact:

Engineering Modeling: Let $\mathcal{DR} =< \{x_1, x_2, ..., x_n\}, \{f_1, f_2, ..., f_m\}, \{\epsilon_1, \epsilon_2, ..., \epsilon_l\} >$ be the structure of the design representation DR. The artifact A, represented by $\mathcal{A} =< \{a_1, a_2, ..., a_n\}, \{g^a_1, g^a_2, ..., g^a_m\}, \{\epsilon^a_1, \epsilon^a_2, ..., \epsilon^a_l\} >$, is an *artifact of DR*, or equivalently $\mathcal{DR}$ is a *model* of $\mathcal{A}$, iff regarding the functions mapping each type to its token, $TTO : \{x_1, x_2, ..., x_n\} \to \{a_1, a_2, ..., a_n\}$, where $TTO(x_i) = a_i$, and mapping each function type to its token, $TTF : \{f_1, f_2, ..., f_m\} \to \{g^a_1, g^a_2, ..., g^a_m\}$, where $TTF(f_j) = g^a_j$, there is an isomorphism between $\mathcal{DR}$ and $\mathcal{A}$, i.e. for every ϵ_q (denoting $f_{r_1} \circ f_{r_2} \circ ... \circ f_{r_u} = f_{s_1} \circ f_{s_2} \circ ... \circ f_{s_v}$), a token ϵ^a_p exists. In other words, $TTF(f_{r_1}) \circ TTF(f_{r_2}) \circ ... \circ TTF(f_{r_u}) = TTF(f_{s_1}) \circ TTF(f_{s_2}) \circ ... \circ TTF(f_{s_v})$ (or equivalently $g^a_{r_1} \circ g^a_{r_2} \circ ... \circ g^a_{r_u} = g^a_{s_1} \circ g^a_{s_2} \circ ... \circ g^a_{s_v}$).

Some qualifications regarding the characterization of engineering modeling need to be added. First, for ease of presentation and want of space, we have only considered a fairly straightforward example having only the three parts and carrying out an extremely simple function. Of course, artifacts produced by engineers nowadays are much more sophisticated, having many parts and complex functions. But the olog framework provides us with the possibility of representing sophisticated artifacts and their design representations through a recursive procedure.[13] For instance, the TV remote control discussed above might be represented within another olog in which different parts, e.g. several buttons, LED, integrated circuits, have their own functions. No matter how much an artifact is sophisticated, the salient point is that we can structurally represent it in a recursive manner within the olog framework.

[13] The olog language has been used in materials design studies. For example, see Giesa et al. (2012), Wong et al. (2012), and Cranford and Buehler (2012).

Secondly, the aim of philosophical accounts of scientific representation is to answer the constitution question of scientific modeling and not to persuade scientists to represent the world via their theoretical machinery. In a similar vein, the above characterization aims to answer the constitution question of engineering modeling, not to convince engineers to use it practically in design processes. Furthermore, the olog framework is merely a category-theoretic and thus a structuralist *tool* to show that the two sorts of modeling are structurally similar; the point we do not know pre-theoretically.

The third qualification concerns the intentional aspects of engineering modeling. Like scientific modeling, *choosing* maps between a target (an artifact) and a model (a design representation), on which structural representation is grounded, has a substantial role in engineering modeling. Concerning the artifact discussed above, for instance, the question is why we conceive of a specific key on the remote control as a token of the type of power key. Probably because the key has a specific symbol. Or why do we think of a remote control whose mute button switches off the TV as an artifact that malfunctions? Indeed, both cases involve the intentional aspects. To be more precise, there should be someone *to interpret* the specific keys as the tokens of the types of power and mute keys. The same holds true for the function types, e.g. the way of interpreting the function "`has as remote control`".

So in sum, engineering modeling is a relation having a hybrid nature: its representational status, like scientific modeling, is grounded in both structural and intentional aspects. Having said that, our intuition suggests that they are, after all, distinct conceptions.[14] If so, what might differentiate them? The next part would address this issue, proposing a new demarcation criterion.

4 The Mark of Scientific/Engineering Modeling

As I have already mentioned in the introduction, although the relationship between pure and applied sciences has been extensively explored by philosophers of science and science studies practitioners, the relation between science and engineering modeling has been rarely discussed. An exception is Poznic's (2016) proposal according to which engineering models, like scientific counterparts, are in modeling relation but with a different direction of fit. More precisely, while the direction of fit in engineering modeling is from a target (i.e. an artifact under construction) to a model (i.e. a design plan), in scientific modeling is from a scientific model to a target (i.e. a selected part of the world). As such, it is the direction of fit that distinguishes scientific from engineering modeling. In this section, I will consider some engineering models whose direction of fit is from the model to the world, and some scientific models whose direction of fit is from the world to the model. Therefore, the criterion developed by Poznic is both too strong and too weak, identifying some scientific models as engineering and vice versa. I will conclude this section by introducing a new mark of engineering/scientific modeling.

[14] Of course, there are some minor differences between the two kinds of modeling as reconstructed above. For instance, while the structures involved in scientific modeling are set-theoretic, the structures employed in engineering modeling are category-theoretic. These slight differences, however, are not substantial enough to fundamentally differentiate the two kinds of modeling. For in both cases the source and target of modeling are structures, the relation between them is structural, and intentional aspects matter for such relation. More importantly, The Elementary Theory of the Category of Sets (ECST) provides us with a machinery to derive set-theoretic notions from category-theoretic ones (Lawvere 1964).

4.1 The Semantic Demarcation

Before delving into the argument, let us first see how the direction of fit of a representation, of any kind, is determined. Next I will briefly outline Poznic's suggestion which addresses the demarcation problem. To determine the direction of fit of a typical representation relation, suppose that *A* is a representation or model of *B*. Following Anscombe's (1957, 56) instruction on how to find out the direction of fit, as Poznic (2016, 365) has noted, the direction of fit is *A*-to-*B* iff the agent to be able to make correct claims about *B* via *A* adjusts *A*, not *B*, and it is *B*-to-*A* iff she adjusts *B*, not *A*. For instance, consider a design plan (as a model) of an aircraft (as a target). If the aircraft does not operate according to the desired results, aeronautical engineers will re-built the aircraft such that it will deliver the desired results. However, if the standard model of fundamental particles fails to predict or explain adequately, physicists will change the model, not the world.

To provide a unifying framework within which both kinds of modeling are characterized, Poznic (2016) discusses a case study from bioengineering, i.e. the so-called "organs-on-chips", in which science and engineering are closely intertwined. An organ-on-a-chip is a concrete model intended to represent a human organ. The aim of producing these models, consisted of different biochemical, biophysical and other highly integrated subsystems, is two-fold. On the one hand, scientists by studying them, which replicate the key aspects of human physiology, try to predict and understand, for example, how a human organ reacts to drugs (Zhang et al. 2018) or how cancer cells behave (Sontheimer-Phelps et al. 2019). On the other hand, they are produced for practical ends, e.g. reducing pharmaceutical R&D costs (Franzen et al. 2019) or in the hope of someday replacing damaged organs (Ashammakhi et al. 2019). As such, they have a dual-nature: in the former they are dealt with as scientific representations and in the latter as technical artifacts. Poznic to account for their dual nature deploys the conception of the direction of fit. To see how his account explains it, we should first consider the third essential element, i.e. the design plan of the model. He argues, and rightly so, that an organ-on-chip model is in two modeling relations: the relation with its design plan and the relation with a human organ. While the first is a design relation (or engineering one), "because the chip is adjusted to this design plan during the construction of the chip" (Poznic 2016, 366), the second is a scientific representation relation. The reason is that "the vehicle [i.e. the organ-on-chip model] has to be adjusted in order to represent the target [the human organ] well enough" (Poznic 2016, 366).

Now the question is whether the criterion developed by Poznic can draw a reasonably precise boundary between the two sorts of modeling. In the following, I will argue that his suggestion misidentifies some cases of scientific and engineering modeling. They include, for instance, the redesigning process of Concorde in aeronautical engineering and the representing the Higgs boson in high energy physics. In opposing the semantic criterion of Poznic, I will show that the direction of fit in the former is from the design representation to the world and from the world to the scientific representation in the latter.

4.2 Redesigned but Never Built

Technical designing is not a linear process beginning with a design model and ending with a technical artifact. Facing an existing technical artifact, engineers assess its strengths and weaknesses regarding the expectations of users, policy-makers, industries and other stakeholders. They then initiate a *redesign* process to produce a new modified artifact. Such a process, which is called by Walter Vincenti as "normal design", contrasts with "radical design" in which the concerned artifact does not exist from the first (Vincenti et al. 1990). Thus understood, "to a large extent, technical designing remains a process of *re*designing" (Vermaas et al. 2011, 26). Although craftsmen to meet functional requirements have often dealt with the redesign process or normal design, due to emerging ethical, societal, environmental and in general value-related problems arising from new technologies, the process has become increasingly more important nowadays. The literature on technology assessment (Grunwald 2009; 2011; 2015; 2018) and design for values (van de Poel 2009; Van den Hoven et al. 2015) in science and technology studies and also in design research has provided some resources to link values and the design processes. In what follows, I will review the case of Concorde from a reverse engineering point of view to show that the direction of fit, in many phases of engineering, is from the artifact to its design plan, since it is the latter, before everything else, that undergoes a change.

Four months after Concorde began to operate commercially on 21 January 1976, Jacques Mitterrand, Chairman and Managing Director of Aeŕospatiale, the joint Concorde manufacturer, wrote a letter to the French and British governments, suggesting that a modified version of Concorde could be produced (Bale and Sharp 2013, 119). Indeed, to overcome the problems of its predecessor, the Concorde manufacturers had prepared themselves two years earlier in 1974 to design and produce a new model of Concorde, the so-called *Concorde B* (Ramsden 1974). One of the major problems of the supersonic aircraft, which had social and economic considerable impacts (Drake and Purvis 2001), was producing the sonic boom and sideline noise during take-off. These difficulties, among others such as its pollution issue, were so severe that many nations canceled their orders, remaining France and Britain as the only buyers of the aircraft (Bale and Sharp 2013, 35). So the manufactures decided to produce Concorde B equipped with a new engine, i.e. the Olympus Mk 622, proposed to have some modifications compared to its predecessor:

> The proposed Olympus Mk 622 has a *higher mass flow* thanks to a *slightly bigger compressor* ... and a *slower jet velocity*. Mass flow is about 8 percent *higher* and thrust between 7 and 8 percent above *the existing* Mk 610 take-off rating. (Ramsden 1974, 463, emphases added)

In fact, the engineers had decided to *redesign* the existing Concorde, or, in other words, to adjust the design plans at hand[15] in such a way that it could satisfy the social expectations (e.g. reducing the noise). Thus understood, it was the design representation, not the artifact, that underwent revision. But this contradicts the semantic criterion.

In spite of this disagreement, someone might hold that the final subject of adjustment, even in this case, was the artifact (i.e. the existing Concorde), not its design plan. The crucial point, however, is that neither Mk 622 nor Concorde B was never built, meaning that the only things had been produced by adjustment were (re)design representations. In fact, "Britain and France doomed the needle-nosed $3 billion project with a joint decision not to finance development of a second generation model" because, besides the rising cost of fuel, there were "some unsold first-generation Concordes—to build a second one would be a bit stupid", as said the British Department of Industry spokesman Geoffrey Pallet (Smale 1979, p. 13A).

It is a common practice in engineering: existing technical artifacts are assessed, and then their (re)design representations are produced to meet different values the stakeholders

15 Emphases added in the above quotation illustrate this point.

pursue, from technical (e.g. more efficiency) to societal (e.g. more sustainability). The production does not begin from the first, but by changing the design representations in question. To do so, reverse engineering is an effective and a conventional method. According to Otto and Wood's (1998; 2001) model of it, which is based on the functionalist account of design discussed earlier, the methodology has three phases: reverse engineering, modeling and analysis, and redesign. In the first step, the functions and subfunctions of the artifact, regarding costumer needs and its physical properties, are studied and extracted. The second phase "entails the development and execution of design models, analysis strategies, model calibration, and experimentation" (Otto and Wood 1998, 227). Finally, in the third step the process of redesign begins, based on the results of the two earlier phases. According to the model, there are two kinds of redesigning. While in *parametric redesign*, it is predicted that by imposing minor adaptive changes the to-be-built artifact would likely realize the values, in *original redesign* the conflict of values is so deep that an entirely new artifact is in need of production. By accounting for the case of Concorde within Otto and Wood's view, we would see that changing MK 610 model to design MK 621 was a kind of parametric redesign, since it was anticipated that Concorde B with an Olympus MK 622 would have a much lesser noise. However, halting the development of Concorde together with initiating other projects were towards reaching an original redesign, because the conflict of economic values with other goals was so serious that no Concorde could resolve them. Putting aside the details of the methodology, what matters here is that the production of reverse engineering, which seems to be an essential part of engineering sciences, is a (re) design model. Whether it leads to a technical artifact or not is a completely different matter, depending on contextual factors.

Now let me sum up this subsection. According to the semantic demarcation suggested by Poznic (2016), while the direction of fit of engineering modeling is from the target to the model, in scientific modeling it is in reverse. Here I have tried to show that in reverse engineering or redesign process the direction of fit is from the model to its related artifact. This is because, to satisfy the wants of stakeholders, the design representation firstly would be adjusted, maybe with no possibility of changing the artifact. Therefore, the semantic criterion identifies reverse engineering as a scientific practice, that is not true. I should note that I am not here trying to show that there is *no* engineering model whose direction of fit is from the target to the model, but arguing for a weaker claim: in *some* engineering practices, e.g. reverse engineering, it is in the opposite direction of what the semantic criterion suggests.

4.3 Generated to be Represented

This idea that scientific modeling is not linear (from a model to the world) but roundabout is not new, and some philosophers have already pointed it out (Cartwright 1983; Hacking 1983; Cartwright 1999; Knuuttila 2011). Knuuttila, for instance, holds that "in scientific practice the fitting of experimental data with models is often a bi-directional process in which the model and data are tailored to fit each other" (Knuuttila 2011, 269). In a similar vein, Gelfert argues that "the traditional picture of modeling as a *unidirectional* activity—either leading from theory to phenomena, via simplifications and idealizations, or the other way round, by aggregating empirical data into a format that can be subsumed under theory—is inadequate; instead, modeling is a complex process of integration and exploration" (Gelfert 2016, 94, emphasis added), accounting for the role of suitability of target in exploratory modeling. In this subsection, I will focus on a way of modeling in which target systems are not only adjusted or explored but also are generated. Representing the Higgs particle detected at the LHC at CERN using the standard model is a prime example of this type.[16] Drawing on this example, I will show that the direction fit of scientific models is not *always* from the model to the target.

The standard model, one of the most outstanding achievements of theoretical and experimental physics, has been developed over the past fifty years[17] to explain, make predictions and unify what happens in the realm of the material world. Standing on quantum field theory and special relativity as its theoretical pillars, it predicts the probability of creation and annihilation of the elementary particles.[18] The world supposed to be represented by the model has the two categories of fermions and bosons. The fermion family includes, roughly speaking, the grains of matter like electrons and quarks. The boson family is made up of the carriers of interactions between fermions, such as photons and gluons. In the early years of the 1960s, the question how some bosons acquire mass had puzzled particle physicists until in 1964 that the three groups of physicists (Englert-Brout, Higgs and Kibble-Guralnik-Hagen) independently suggested a mechanism, the so-called "Higgs mechanism", through which conferring mass was explained. It was in 1967 that Steven Weinberg and Abdus Salam used this mechanism to account for how some carriers of the electroweak force, i.e. Z and W bosons, acquire their mass (Weinberg 2004). This mechanism proceeds on a field, named the "Higgs field", which leads the fundamental particles to be massive. However, was the field just a theoretical apparatus or a real entity? According to the conventional interpretation of quantum field theory, every field is associated with a sort of particles being understood as its excitation. So detecting the particle associated with the Higgs field, the so-called "Higgs boson", had been offering a strong support for the standard model. However, it was very unlikely that the Higgs boson would be found in normal circumstances, since our cooled universe did not have enough energy to excite the field and thus produce the Higgs boson. Therefore, the energy needed to be artificially produced in accelerators. After several efforts to detect the Higgs boson in accelerators like the Tevatron at Fermilab and LEP at CERN (Wu 2014), CERN on July 4, 2012 announced that the particles seem to be Higgs bosons have been detected in ATLAS and CMS detectors at the LHC at CERN (ATLAS Collaboration et al. 2012; Taylor 2012).

The story couched in the terminology used in the literature on scientific representation would be as follows. From 1967 to 2012, particle physicists had been having a good model of the material world which was not *fully* representational, because some part of its target, i.e. the Higss boson, had not yet been detected. Physicists tried to detect it in the Tevatron at Fermilab and LEP at CERN, but only its range mass was derived. Given that, did the physicists change the standard model or adjust the whole target system (i.e. create a suitable experimental environment in which the Higgs boson can be generated)? Indeed, they did the latter, meaning that they created a more powerful particle accelerator (i.e. the LHC), concentrating larger amounts of energy into a very small point of space to generate the Higgs boson. Put differently, it was the target, not the model, that underwent a change. Of course, it does not mean the standard model is not subject to revision

[16] The constructive nature of target systems in high energy physics has already been discussed in the science studies literature (Galison et al. 1997; Pickering 1999).

[17] For a very brief history, see Weinberg (2004).

[18] Modern books on quantum field theory usually discuss the standard model (Schwartz 2014; Peskin 2018). For a more introductory book, see Goldberg (2017). The detection of the Higgs at the LHC has been narrated by Gagnon (2016).

or even replacement. Accounting for neutrino oscillation, embedding gravity in a quantum field theoretic frame and subsuming tetraquarks under the model turn out to be challenging jobs of the standard model. In spite of them, several phenomena are designed and adjusted again and again in high energy physics labs to be finally represented by the model. But this is once more in contradiction with the semantic criterion of demarcation. Once again, I should remark that I am not arguing that the direction fit of scientific modeling is *always* from the world to the model, just saying that in *some* situations which are not negligible at all in scientific practice (e.g. representing the Higgs boson), it is in the reverse direction.

4.4 An Axiological Demarcation

Regarding the problems facing the semantic criterion, I will provide an axiological alternative to delimit the boundary between the two kinds of modeling. According to the conceptual framework suggested by Korsgaard (1983), there are two sorts of distinctions in goodness: finally versus instrumentally and extrinsically versus intrinsically valuable things. Within her view, *A* is finally valued iff it is valuable as an end (or for its own sake). It is instrumentally valued iff it is valuable as a means (or for the sake of something else). Also, *A* is intrinsically valued iff its goodness depends only on the intrinsic properties of *A*. It is extrinsically valued iff its goodness depends—at least to some extent—on the relational properties of *A*. Deploying the first distinction, someone may submit that *while scientific models are finally valuable, engineering models are instrumentally valuable*. But before going there, it will help to clarify what kinds of aims scientists and engineers pursue. Following the analyses that emphasize on the substantial roles of design in applied sciences and of knowledge in pure sciences (Simon 1968; Niiniluoto 1993; Kroes 2002), and particularly according to the functionalist account of pure-applied distinction (Yaghmaie 2017), while pure scientists produce science representations (i.e. scientific models) to achieve cognitive goals, engineers produce design representations (i.e. engineering models) to attain pragmatic ends.[19] In the previous sections, however, it was shown that both kinds of models are cognitively similar. It means that both scientists and engineers produce models to reach, before everything else, cognitive aims. But the crucial point is that they do so for different wills. While a scientist produces a model for its own sake (i.e. representing the reality that is the feature of the model), an engineer produces a model not for its own sake but for the sake of something else (i.e. solving practical problems). It is true that engineers, like scientists, produce models to pursue cognitive aims. But, after all, the final end in engineering sciences is not achieving them, but solving practical problems. To sum up, *while being representational for an engineering model is a means, for a scientific model it is an end.*

Now I should consider some possible objections to the criterion proposed above. First, someone might complain that even scientific models are not valuable for their own sake, since there should be the world and an agent using them which in virtue of their grounding roles the models are representational. To drop the objection, it could be said, following Korsgaard, that a thing, e.g. a luxurious instrument, may be finally but extrinsically valuable:

[19] This does not mean that pure and applied scientists produce *just*, respectively, science and design representation. These given productions are merely final ones.

> A mink coat can be valued the way we value things for their own sakes... Yet it is also odd to say it is valued simply for its own sake. ... To say that the coat in intrinsically or unconditionally valuable is absurd: *its value is dependent upon an enormously complicated set of conditions, physiological, economic, and symbolic.* (Korsgaard 1983, 185, emphasis added)

The goodness of a scientific model, like a luxurious instrument, does not depend merely on its intrinsic properties. It is also grounded in model's relations to other things, particularly to agent's actions and the world supposed to be represented. More precisely, a successful scientific model (e.g. the standard model) does not have any goodness in a possible world in which no physical object exists. This is because there is no one to use it and no target to be represented. But this does not imply that its representational value in the actual world is a means for something else. Being representational for a scientific model is a value for its own sake. In a similar vein, engineering models are instrumentally but extrinsically valuable—for there should be an agent to use and a problem to be solved with it.

With regard to the second objection, someone may argue that it is quite conceivable that a scientific model is used as a means, and an engineering model is taken as an end. Therefore, the axiological criterion, like Poznic's (2016), is also both too strong and too weak. For instance, consider a nanoscale computational model scientists have developed to understand and predict the properties of a nanomaterial. Yet despite its being as a scientific representation, someone might treat it as a means to produce a technical artifact. In a similar vein, consider the nanostructures which do no exist in nature and are human-made. Although these sorts of objects seem to be technical artifacts, in many cases scientists produce them to understand and predict their properties and not to solve a practical problem. Thus understood, the axiological features of models cannot properly identify them.

To answer the objection, we should once again consider the second dichotomy in Korsgaard's framework, i.e. extrinsic versus intrinsic goodness. According to her theory of value, as we have noted, the value of a luxurious thing depends on its extrinsic properties. But this implies that its final goodness may change to instrumental goodness by varying the context. For instance, imagine a wealthy alone traveler caught in a blizzard. She wears her only jacket, i.e. a mink coat, to protect herself against freezing. In this situation, the mink coat is valuable due to its instrumentality, not for its own sake. Or, as an artwork that is usually taken to be finally good but becomes valuable as an instrument, consider the ivy vine's leaf painted by Behrman, a character in *The Last Leaf* by O'Henry, which saves the life of his neighbor who got infected by pneumonia, giving her the desire to live. Furthermore, many things having instrumental value become finally valuable in some context. Duchamp's Fountain is a prime example of this kind. Therefore, to determine the kind of goodness a thing extrinsically has, we should fix the context, saying that A is instrumentally (finally), extrinsically valuable *with regard to the context C*.

The same analysis holds true for scientific/engineering models. Whether a model is instrumentally or finally valuable and consequently is an engineering or a scientific model depends on the context of use and interpretation. Thus it makes no sense to assert, regardless of the context, that M is a scientific (an engineering) model, for it has a final (an instrumental) value. To determine its nature, we should say M is a scientific (an engineering) model *for the context C*, because it is valuable for its own sake (for the sake of something else) in the context. Thus understood, the nanoscale computational model when used to represent the nanoworld is finally good, while the same model is a means if applicable to producing a nanostructure. In a similar vein, human-made nanostructres are engineering models only if engineers use them, for instance, as drugs in nanomedicine. They are also may be scientific models just in case scientists treat them as the representations of the nanoworld.[20]

Regarding this objection and its response, it might be said, then, that we cannot strictly characterize the demarcation between scientific and engineering modeling by using only non-contextual necessary-sufficient conditions, and finally it is the context that would determine the characterization of a model. This, however, renders the proposed account, in some sense, either circular or non-informative.[21] To assuage this concern, it should be pointed out that the axiological criterion together with the meaning of representation in science and engineering given here has a greater explanatory power than a circular or non-informative characterization. Indeed, *it explains why the model M can have a dual-nature, being recognized as a scientific model within the context C and as an engineering model within the context C'*. Furthermore, it explains the question in terms of certain theoretical concepts (i.e. final vs. instrumental and intrinsic vs. extrinsic goodness) within a specific theoretical framework (i.e. Korsgaard's account). So in sum, the proposal suggested here theoretically accounts for not only that the context matters but that how it matters.

And now the last remark. In response to the analysis, someone might hold that a similar strategy gets around the problem of Poznic's proposal, meaning that reversing the direction of fit *genuinely* changes the characterization of the concerned model. I do not think so. Neither an exploratory modeling with the target-to-model direction of fit is an engineering practice, nor a redesigning with the model-to-target direction of fit is a scientific activity. Therefore, a similar strategy does not save the semantic criterion. The major problem of Poznic's proposal is attributing a *fixed* direction of fit to each kind of modeling; the parameter that changes, but does not change, at least in the cases discussed above, the nature of modeling.

5 Conclusions

Scientists and engineers seemingly pursue different goals. While science is primarily concerned with modeling the world for its own sake, engineering involves models as tools for solving practical problems. I have argued here that engineers, like scientists, construct models to further, before everything else, cognitive aims. More importantly, they achieve them *in virtue of* the structural relations held between models (design representations) and targets (to-be-built artifacts). If this is correct, engineering and scientific modeling are both cognitively and representationally alike. It has been finally argued that what differentiate them are not their epistemic or semantic, but their axiological aspects. Indeed, while the goodness of scientific modeling is final and extrinsic, engineering modeling is an instrumentally and extrinsically valuable activity.

[20] Here it is taken for granted that there is a (though not clear-cut) distinction between science and engineering modeling. But there are many science and technology studies practitioners who deny any distinction between science and engineering (or between basic and applied science), advancing hybrid concepts such as technoscience (for more on this, see Channell 2017). For them, contextual (e.g. social, historical and political) factors have a key role in determining the meaning of the terms associated with these concepts (Latour 1987; Nordmann et al. 2011; Pielke 2012). There have recently been some attempts to reconcile these two approaches (e.g. Kant and Kerr 2019). The question whether the account proposed here would also do such a thing is interesting, but is beyond the scope of this article.

[21] I thank two anonymous referees for pointing out this worry to me.

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References

Anscombe, G. (1957). *Intention*. Oxford: Basil Blackwell.

Ashammakhi, N., Elkhammas, E., & Hasan, A. (2019). Translating advances in organ-on-a-chip technology for supporting organs. *Journal of Biomedical Materials Research Part B: Applied Biomaterials*, *107*(6), 2006–2018.

ATLAS Collaboration et al. (2012). *Latest results from atlas higgs search*. Press statement, ATLAS Updates.

Awodey, S. (2010). *Category theory*. Oxford: Oxford University Press.

Bale, B., & Sharp, D. (2013). *Concorde: Supersonic speedbird*. Horncastle: Mortons Media Group Ltd.

Bartels, A. (2006). Defending the structural concept of representation. *THEORIA. Revista de Teoría, Historia y Fundamentos de la Ciencia*, *21*(1), 7–19.

Boesch, B. (2019). Resolving and understanding differences between agent-based accounts of scientific representation. *Journal for General Philosophy of Science*, *50*, 195–213.

Boon, M. (2006). How science is applied in technology. *International Studies in the Philosophy of Science*, *20*(01), 27–47.

Boon, M., & Knuuttila, T. (2009). Models as epistemic tools in engineering sciences. In A. Meijers (Ed.), *Philosophy of technology and engineering sciences, handbook of the philosophy of science* (pp. 693–726). Amsterdam: North-Holland.

Bueno, O. (2017). Overcoming Newman's objection. In *EPSA15 selected papers* (pp. 3–12). Springer.

Bueno, O., & Colyvan, M. (2011). An inferential conception of the application of mathematics. *Noûs*, *45*(2), 345–374.

Bueno, O., & French, S. (2011). How theories represent. *The British Journal for the Philosophy of Science*, *62*(4), 857–894.

Bunge, M. (1966). Technology as applied science. *Technology and Culture*, *7*(3), 329–347.

Callender, C., & Cohen, J. (2006). There is no special problem about scientific representation. *Theoria. Revista de Teoría, Historia y Fundamentos de la Ciencia*, *21*(1), 67–85.

Cartwright, N. (1983). *How the laws of physics lie*., Clarendon paperbacks Oxford: Oxford University Press.

Cartwright, N. (1999). *The dappled world: A study of the boundaries of science*. Cambridge: Cambridge University Press.

Chakravartty, A. (2010). Informational versus functional theories of scientific representation. *Synthese*, *172*(2), 197.

Channell, D. F. (2017). *A history of technoscience: Erasing the boundaries between science and technology*. New York: Taylor & Francis.

Cranford, S. W., & Buehler, M. J. (2012). Universality-diversity paradigm: Music, materiomics, and category theory. In *Biomateriomics* (pp. 109–169). Springer.

Drake, F., & Purvis, M. (2001). The effect of supersonic transports on the global environment: A debate revisited. *Science, Technology, & Human Values*, *26*(4), 501–528.

Fletcher, S. C. (2018). On representational capacities, with an application to general relativity. *Foundations of Physics*, *50*, 228–249.

Franzen, N., van Harten, W. H., Retèl, V. P., Loskill, P., van den Eijnden-van Raaij, A., & Ijzerman, M. J. (2019). Impact of organ-on-a-chip technology on pharmaceutical R&D costs. *Drug Discovery Today*, *24*, 1720–1724.

French, S. (2003). A model-theoretic account of representation (or, i don't know much about art but i know it involves isomorphism). *Philosophy of Science*, *70*(5), 1472–1483.

Frigg, R., & Nguyen, J. (2017). Models and representation. In L. Magnani & T. Bertolotti (Eds.), *Springer handbook of model-based science* (pp. 49–102). Cham: Springer International Publishing.

Frigg, R., & Nguyen, J. (2018). Scientific representation. In E. N. Zalta (Ed.), *The Stanford encyclopedia of philosophy* (Winter 2018 ed.). Stanford: Metaphysics Research Lab, Stanford University.

Frigg, R., & Nguyen, J. (2019). Mirrors without warnings. *Synthese*. https://doi.org/10.1007/s11229-019-02222-9.

Gagnon, P. (2016). *Who cares about particle physics? Making sense of the Higgs boson, the Large Hadron Collider and CERN*. Oxford: Oxford University Press.
Galison, P., et al. (1997). *Image and logic: A material culture of microphysics*. Chicago: University of Chicago Press.
Galle, P. (1999). Design as intentional action: A conceptual analysis. *Design Studies*, *20*(1), 57–81.
Gelfert, A. (2016). *How to do science with models: A philosophical primer*. Berlin: Springer.
Gero, J. S., & Kannengiesser, U. (2004). The situated function-behaviour-structure framework. *Design Studies*, *25*(4), 373–391.
Giere, R. N. (2004). How models are used to represent reality. *Philosophy of Science*, *71*(5), 742–752.
Giere, R. N. (2010a). An agent-based conception of models and scientific representation. *Synthese*, *172*(2), 269.
Giere, R. N. (2010b). *Scientific perspectivism*. Chicago: University of Chicago Press.
Giesa, T., Spivak, D. I., & Buehler, M. J. (2012). Category theory based solution for the building block replacement problem in materials design. *Advanced Engineering Materials*, *14*(9), 810–817.
Goldberg, D. (2017). *The standard model in a nutshell*. Princeton: Princeton University Press.
Grunwald, A. (2009). Technology assessment: Concepts and methods. In A. Meijers (Ed.), *Philosophy of technology and engineering sciences* (pp. 1103–1146)., Handbook of the philosophy of science Amsterdam: North-Holland.
Grunwald, A. (2011). Responsible innovation: Bringing together technology assessment, applied ethics, and sts research. *Enterprise and Work Innovation Studies*, *31*, 10–9.
Grunwald, A. (2015). Technology assessment and design for values. In J. van den Hoven, P. E. Vermaas, & I. van de Poel (Eds.), *Handbook of ethics, values, and technological design: Sources, theory, values and application domains* (pp. 67–86). Dordrecht: Springer.
Grunwald, A. (2018). *Technology assessment in practice and theory*. London: Routledge.
Hacking, I. (1983). *Representing and intervening: Introductory topics in the philosophy of natural science*. Cambridge: Cambridge University Press.
Hatchuel, A., & Weil, B. (2009). Ck design theory: An advanced formulation. *Research in Engineering Design*, *19*(4), 181.
Houkes, W., & Vermaas, P. E. (2010). *Technical functions: On the use and design of artefacts* (Vol. 1). Berlin: Springer.
Hughes, R. I. (1997). Models and representation. *Philosophy of Science*, *64*, S325–S336.
Kagan, S. (1998). Rethinking intrinsic value. *The Journal of Ethics*, *2*(4), 277–297.
Kant, V., & Kerr, E. (2019). Taking stock of engineering epistemology: Multidisciplinary perspectives. *Philosophy & Technology*, *32*(4), 685–726.
Knuuttila, T. (2011). Modelling and representing: An artefactual approach to model-based representation. *Studies in History and Philosophy of Science Part A*, *42*(2), 262–271.
Korsgaard, C. M. (1983). Two distinctions in goodness. *The Philosophical Review*, *92*(2), 169–195.
Kroes, P. (2002). Design methodology and the nature of technical artefacts. *Design Studies*, *23*(3), 287–302.
Latour, B. (1987). *Science in action: How to follow scientists and engineers through society*. Cambridge: Harvard University Press.
Lawvere, F. W. (1964). An elementary theory of the category of sets. *Proceedings of the National academy of Sciences of the United States of America*, *52*(6), 1506.
Niiniluoto, I. (1993). The aim and structure of applied research. *Erkenntnis*, *38*(1), 1–21.
Nordmann, A., Radder, H., & Schiemann, G. (2011). Science after the end of science? An introduction to the epochal break thesis. In A. Nordmann, H. Radder, & G. Schiemann (Eds.), *Science transformed?* (pp. 1–15). Pittsburgh: University of Pittsburgh Press.
O'Neill, J. (1992). The varieties of intrinsic value. *The Monist*, *75*(2), 119–137.
Otto, K., & Wood, K. (2001). *Product design: Techniques in reverse engineering and new product development*. Upper Saddle River: Prentice Hall.
Otto, K. N., & Wood, K. L. (1998). Product evolution: A reverse engineering and redesign methodology. *Research in Engineering Design*, *10*(4), 226–243.
Peskin, M. E. (2018). *An introduction to quantum field theory*. Boca Raton: CRC Press.
Pickering, A. (1999). *Constructing quarks: A sociological history of particle physics*., Physics, history and sociology of science Chicago: University of Chicago Press.
Pielke, R. (2012). Basic research as a political symbol. *Minerva*, *50*(3), 339–361.
Poznic, M. (2016). Modeling organs with organs on chips: Scientific representation and engineering design as modeling relations. *Philosophy & Technology*, *29*(4), 357–371.
Ramsden, J. M. (1974, April 11). Up to date with Rolls-Royce Bristol. *FLIGHT International*, 463–466.
Roll-Hansen, N. (2017). A historical perspective on the distinction between basic and applied science. *Journal for General Philosophy of Science*, *48*(4), 535–551.

Schwartz, M. D. (2014). *Quantum field theory and the standard model*. Cambridge: Cambridge University Press.
Simon, H. (1968). *The sciences of the artificial*. Cambridge: The MIT Press.
Smale, A. (1979, September 22). Fuel costs kill second generation of concordes. *Sarasota Herald-Tribune*, 13A. https://news.google.com/newspapers?id=Q-0cAAAAIBAJ&pg=6914,3256355.
Sontheimer-Phelps, A., Hassell, B. A., & Ingber, D. E. (2019). Modelling cancer in microfluidic human organs-on-chips. *Nature Reviews Cancer*, *19*, 65–81. https://doi.org/10.1038/s41568-018-0104-6.
Spivak, D. I., & Kent, R. E. (2012). Ologs: A categorical framework for knowledge representation. *PLoS ONE*, *7*(1), e24274.
Stone, R. B., & Wood, K. L. (2000). Development of a functional basis for design. *Journal of Mechanical Design*, *122*(4), 359–370.
Suárez, M. (2003). Scientific representation: Against similarity and isomorphism. *International Studies in the Philosophy of Science*, *17*(3), 225–244.
Suárez, M. (2004). An inferential conception of scientific representation. *Philosophy of Science*, *71*(5), 767–779.
Suárez, M. (2010). Scientific representation. *Philosophy Compass*, *5*(1), 91–101.
Suárez, M. (2015). Deflationary representation, inference, and practice. *Studies in History and Philosophy of Science Part A*, *49*, 36–47.
Taylor, L. (2012). Observation of a new particle with a mass of 125 gev. CMS Public Website, CERN.
Ubbink, J. (1960). Model, description and knowledge. *Synthese*, *12*(2), 302.
van de Poel, I. (2009). Values in engineering design. In A. Meijers (Ed.), *Philosophy of technology and engineering sciences* (pp. 973–1006)., Handbook of the philosophy of science Amsterdam: North-Holland.
Van den Hoven, J., Vermaas, P., & Van de Poel, I. (2015). *Handbook of ethics, values and technological design*. Berlin: Springer.
van Eck, D. (2016). *The philosophy of science and engineering design*. Berlin: Springer.
van Fraassen, B. (2010). *Scientific representation: Paradoxes of perspective*. Oxford: OUP.
Vermaas, P., Kroes, P., van de Poel, I., Franssen, M., & Houkes, W. (2011). A philosophy of technology: From technical artefacts to sociotechnical systems. *Synthesis Lectures on Engineers, Technology, and Society*, *6*(1), 1–134.
Vincenti, W. G., et al. (1990). *What engineers know and how they know it* (Vol. 141). Baltimore: Johns Hopkins University Press.
Weinberg, S. (2004). The making of the standard model. *The European Physical Journal C-Particles and Fields*, *34*(1), 5–13.
Wong, J. Y., McDonald, J., Taylor-Pinney, M., Spivak, D. I., Kaplan, D. L., & Buehler, M. J. (2012). Materials by design: Merging proteins and music. *Nano Today*, *7*(6), 488–495.
Wu, S. L. (2014). Brief history for the search and discovery of the higgs particlea personal perspective. *International Journal of Modern Physics A*, *29*(27), 1430062.
Yaghmaie, A. (2017). How to characterise pure and applied science. *International Studies in the Philosophy of Science*, *31*(2), 133–149.
Zhang, B., Korolj, A., Lai, B. F. L., & Radisic, M. (2018). Advances in organ-on-a-chip engineering. *Nature Reviews Materials*, *3*(8), 257.