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ORIGINAL RESEARCH

Non-Representational Models and Objectual Understanding

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Abstract
This paper argues that investigations into how to best make something often provide researchers with an objectual understanding of their target phenomena. This argument starts with an extended investigation into the non-representational uses of models. In particular, we identify a special sort of "design model" whose aim is to guide the production of phenomena. Clarifying how these design models are evaluated shows that they are evaluated in different ways than representational models. Once the character of design models has been fixed, we argue that grasping design models can provide objectual understanding of phenomena. This argument proceeds through a critical engagement with Dellsén's (2020) position that a grasp of a good representational model of dependencies provides objectual understanding of a phenomenon. We agree with Dellsén that this is one way to achieve understanding, but maintain that grasping a good design model is another way to achieve understanding. The paper concludes by considering some important objections to our proposal and also by noting some of the broader questions about understanding and knowledge in both science and engineering.

Keywords Understanding · Non-Representational Models · Dependency Models · Engineering · Design

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1 Introduction

What sort of epistemic achievements do researchers acquire through their investigations into how to best make something? This is the leading question of the present paper. We will consider different cases that involve representational and non-representational models. Our focus is on the latter kind of models and we highlight one concrete problem in engineering: how to best produce methane that may be used in existing natural gas networks? This case of biological methanation and other examples will be analyzed in light of recent discussions of scientific understanding. Our overall conclusion is that non-representational models can afford objectual understanding of the very same target phenomena that is provided by the grasp of representational models. This conclusion is obtained in two steps. First, there is an important use of models as what we call "design models" that guide the production of phenomena. Second, when such a design model is sufficiently good in relevant respects, an agent who grasps that model acquires an understanding of the phenomenon in question.

Our discussion starts with an extended examination of the contrast between representational models and non-representational models. We show that models are evaluated in at least two different ways. Some models are evaluated as representations. For such uses, the main questions are how accurate or comprehensive such a model is as a representation of some actual or possible target system. Other models are evaluated as designs. For these uses, the main question is how well the model specifies how a product should be built. This contrast is illustrated using a number of examples from the sciences and from engineering. We also clarify how our proposal relates to other recent discussions in the literature, especially the claim that models are best thought of as tools or artifacts.

Once the non-representational character of these design models is clear, we turn to our claim that grasping design models can provide objectual understanding of phenomena. Our argument for this claim is developed by engaging with Finnur Dellsén's (2020) argument that a grasp of a good representational model of dependencies provides objectual understanding of a phenomenon. At the heart of our argument is the contention that there is no good reason to maintain that only models of dependencies afford understanding. This means that accounts of understanding based solely on representational models should be amended in order to make sense of the understanding tied to design models. As the goodness of a design model is determined by different criteria than the goodness of a representational model, existing accounts of understanding with the help of models should be extended. The goodness of a model influences the degree of understanding a subject can obtain, and this has repercussions for the engineer's or other researcher's understanding that is based on grasping design models.[1]

[1] The notion of design model is not meant to necessarily match how this term is used within engineering or design research. It does, however, line up with some other recent discussions in the philosophy of engineering (e.g., Eckert & Hillerbrand, 2018, 2022; Poznic, 2021), and can also be traced back to Per Galle's discussion of "design representations" (Galle, 1999). However, we make a distinction between models used as representations and models used as designs that Galle seems to conflate when he argues

We will proceed as follows. First, we will make the case that non-representational models may improve epistemic states about certain phenomena in Sect. 2. After that, Sect. 3 clarifies why we focus on the epistemic achievement of understanding, and we propose a particular interpretation of grasping that is directed at models. In Sect. 4, we discuss objections to our account and the role of the integration of design and representational models for the researchers' understanding. Finally, Sect. 5 concludes the paper.

2 Non-Representational Models

2.1 Uses of Models

In line with many recent discussions of model-based science, we assume here that models have an epistemic function: modeling is a distinctive sort of activity that involves the use of models to improve one's epistemic state. In the philosophy of science, it is common to distinguish between a specification of a model and the model system. Model specifications are often linguistic, but diagrammatic or mathematical specifications are also widely employed. Whatever their character, the assumption is that different specifications, e.g., in different languages, can generate the very same model system. These model systems are sometimes identified with hypothetical concrete scenarios or abstract interpreted structures. We are not here worried about the ontology of these model systems and will also not take a stand on whether or not models themselves are best identified with model specifications or model systems.[2] Our core assumption is that, whatever models are, different models may be evaluated in different ways, and that the very same model can be evaluated differently in different contexts. When models are evaluated in these different ways, we have different kinds of modeling activities, and so, in this sense, different kinds of models. The issue of the identification of models will be discussed in Sect. 3.1. as part of our interpretation of grasping.

One type of model that we will consider is a model of a chemical reaction. The Sabatier reaction takes as inputs carbon dioxide and hydrogen gas and outputs methane and water. One model of this reaction relates the number of molecules involved so that a balance of elements is achieved[3]:

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$, $\Delta H = -165.0\ \text{kJ mol}^{-1}$.

One common way of using this model of the Sabatier reaction is as a representational model. To say that a model is a representational model is just to say that the model is evaluated based on how well it corresponds to the target phenomenon, e.g.,

that there are design representations. See Sect. 2.1. for our analysis of the distinction between representational and design models.

[2] So, we do not take a stand on whether modeling is indirect, because it is mediated by model systems, or direct, because model specifications are immediately related to real-world systems (cf. Weisberg, 2007, 2013; Toon, 2012; Knuuttila & Loettgers, 2017).

[3] ΔH is a quantity provided in terms of the energy absorbed or released by the reaction per mole, where a mole is a standard way of counting molecules (1 mol is 6.022×10^{23} molecules). The negative value for ΔH indicates that the Sabatier reaction is exothermic, i.e., it releases energy in the form of heat.

the salient mechanisms. Each such model has a specification, which is sometimes called the vehicle of the modeling activity. As a representation, the model also has a target, e.g., the phenomenon of interest. The relation between a vehicle and a target can be called a modeling relation. We assume that modeling relations are constituted by agents who deploy vehicles with the aim of achieving a given relation to some target.

When the model of the Sabatier reaction is used as a representational model, it can be evaluated in ways that are typical for representations. For example, we can consider how accurate the model is. The model indicates that four moles of hydrogen gas are involved for every mole of methane that is produced by the reaction. If this claim is correct, then the model is accurate in this respect. Another dimension of evaluation for a representational model is how comprehensive it is. Are there features of the phenomenon, i.e., the Sabatier reaction, that are missing from the model? Our model fails to specify the rate of the reaction in this or that circumstance. A more detailed model that indicated this rate would thus be more comprehensive. In line with recent work by Parker (2020), we do not think that there are any absolute or fixed ways of evaluating representational models. A given representational model may turn out to be adequate for a given representational purpose even if it fails to be comprehensive or fully accurate.

Many philosophers have argued that some models are not representational models. This means that they are not evaluated in terms of their representational relation to some target. The evaluation of representational models in terms of accuracy or comprehensiveness has a distinctive direction of fit, a vehicle-to-target direction of fit. This becomes clear when a model is intended to be accurate in some respect, and yet found to be inaccurate in that respect. In this sort of situation, the model user would revise the vehicle (the model specification) so that the vehicle was in better agreement with its intended target. This is the key indication that a model is being used as a representational model according to our terminology. For example, if our model specification for the above model of the Sabatier reaction had indicated that only three hydrogen gas molecules were involved in the production of one methane molecule, and this inaccuracy was uncovered, the model would be specified in a new way to correct this inaccuracy. When a representational model is deemed adequate for its representational purpose, it may be used to learn about how its target phenomenon is (in salient respects).

To argue that not all models are representational, we have to find cases where models are evaluated in a different way. As Goodwin (2009) has emphasized, models of chemical reactions like the Sabatier reaction can be evaluated in terms of how well they guide the synthesis of the product molecules. If practitioners want to manufacture methane on a large scale, for example, then what Goodwin calls a "synthetic plan" for methane can be presented as a kind of step-by-step procedure for creating methane:

> The design of a synthetic plan is a technological problem in the sense that the potential solutions consist of courses of action, rather than, say, low-level phenomenological laws that describe a class of phenomena. The goal is to sketch

> a rule or policy, consisting of a sequence of structurally characterized chemical reactions, which will reliably produce the target molecule. (2009, p. 278)

For a target molecule as simple as methane, our model of the Sabatier reaction can serve as just such a synthetic plan. The model, treated as such a plan, instructs us to assemble carbon dioxide and hydrogen in the required ratios in order to produce a given quantity of methane and water. When a model that is evaluated in this action-guiding way is deployed, we claim that the use exhibits a non-representational target-to-vehicle direction of it. Suppose, for example, that an agent following the plan provided only three moles of hydrogen gas for every mole of carbon dioxide. If this deviation from the plan was recognized, the agent following the plan would not change their model specification to fit this situation, but instead change the situation by supplying the missing mole of hydrogen gas. This shows that when the model is being used as an action-guiding plan, it is no longer being evaluated in representational terms.

We maintain that the use of models as plans in the sense identified by Goodwin in chemistry is widespread throughout the sciences and especially prominent in engineering. In other contexts, the term “synthesis” is too narrow to capture the aim of the non-representational model. We will call models that are used as action-guiding plans for the construction of some product “design models.” Design models are not evaluated in terms of how well they represent the phenomena; instead, these design models are evaluated based on how well they specify how some states of affairs *should be*. An acceptable design model indicates how to best make something. As a result, design models involve modeling relations with a target-to-vehicle direction of fit.[4]

The difference in directions of fit can be clarified with a mundane example of a customer’s shopping list. The list may be used with the intention to buy what is on the list or as a record of what has been bought (cf. Anscombe, 1957). A customer who uses a shopping list to guide their purchases may collect various items in a basket according to their list. This customer acts with the intention to buy what is listed. Before going to the cash point, the shopper may check whether the items on the list correspond to the items in the basket. If something were missing, the shopper would add the missing item to the basket (and not alter the list) to realize their intention. Imagine a supermarket detective spying on the customer and recording the items the customer collects in their basket on a further list. The detective’s list is used to record or represent what the customer has collected. If there were mistakes in the detective’s list, then the detective would have to adjust the list (and not the items in the basket) so that the list would be an accurate representation. The customer’s list has a relation to the items with a target-to-vehicle direction of fit, just as how a design model is related to its target. The relation of the detective’s list to the items involves a vehicle-to-target direction of fit. This is the direction used when modeling with the help of a representational model. In both cases we have lists that are referring to items in the

[4] The validity of a model and especially the notion of internal validity may be used in additional considerations of how to characterize the distinction between the two kinds of models. Representational models may be assessed as validated or not. Design models seem to be not proper candidates for validation, at least at first glance. We do not have the space to follow up on this topic, here, but thank an anonymous reviewer for pointing this question out to us.

basket, but only one of the lists is used to represent whereas the other list is used to guide the purchase. The detective's list can be compared to a representational model whereas the shopping list can be compared to a design model (cf. Poznic, 2016, 2021).

Design models are central to many disciplines such as civil engineering, aeronautical engineering, or architecture. Consider an architect's model of a building that has not yet been built. The model may be used to guide the construction of an actual building. If this occurs, the model will be used as a design model that specifies how that building is to be built. At that stage, the model is not evaluated by considering how something is and how it is represented by the model, but it is rather evaluated based on how well it fosters the construction of the planned building that should conform to the design model. Of course, after the building has been built, the very same model may then be used as a representational model of the building. In such a case one may indeed adjust the model to the building for representational purposes. This could occur if the building was renovated and a new entrance was added, for example. In such a case, the model specification would be changed to ensure that the model remained an accurate representation of the actual building. This simple case illustrates how a model may be used and evaluated in different ways and different contexts.

2.2 The Case of Biological Methanation

A more involved case study that we draw on in this article is the engineering investigation into how best to implement the new technology of biological methanation to convert available carbon dioxide to methane suitable for use in existing natural gas energy infrastructure. The case concerns the building of a biological methanation plant. Biological methanation exploits naturally occurring microorganisms that consume hydrogen and carbon dioxide and produce methane. At the heart of this technology is the already mentioned Sabatier reaction that can be further analyzed into several chemical reactions as partial reactions.

A biological methanation plant is built to exploit the Sabatier reaction to produce methane as part of a system of sustainable energy production. The biology of the microorganisms – called "methanogens" – deployed in the plant is one aspect of the process. Researchers distinguish three types of methanogens (Lyu et al., 2018, p. R729). Additionally, the chemical reactions are facilitated by enzymes with their own complex chemical properties. Lyu et al. analyze three "Enzymatic Pathways of Methanogenesis" (ibid.).

Methanogens produce methane through the so-called CO_2 reducing pathway that requires only that hydrogen and carbon dioxide gas be provided to the microorganisms. One particular species of methanogens is commonly employed in the study of biological methanation. A recent survey article considers several issues that are relevant to evaluating proposed designs for a biological methanation plant (Rusmanis et al., 2019). The technology is at an early stage of development, but Davis Rusmanis et al. note that one "full-scale methanation plant" has been constructed, the Electrochaea Gmbh plant in Copenhagen, Denmark (2019, p. 627). The methanogens are held in a reactor that is supplied with the inputs necessary for efficient methanation.

First, raw biogas is provided that comes as a mixture of around 60% methane and 40% carbon dioxide. This biogas can be harvested from various sources, including “livestock manures and slurries” (ibid., p. 605). As this raw biogas is already being captured, the biological methanation plant aims primarily to efficiently convert the carbon dioxide that is present within the biogas to methane so that the resulting gas is rich enough in methane to be injected into existing natural gas networks. The aim here is for 95% or more of the gas produced to be methane. The second required input is hydrogen gas. This is provided by an electrolyzer that uses electricity to extract hydrogen gas from water.

The basic engineering problem is how to efficiently obtain this enriched methane gas using the methanogens. Practitioners have investigated various plant architectures that combine or separate the crucial stages of the process. For our purposes, the central element of this research is the presentation of various plans for the production of such a plant. These plans have the same action-guiding character that an architectural blueprint would have. Practitioners describe these plans as a kind of model: “a theoretic model and approach for a full-scale sequential ex-situ methanation unit” (Voelklein et al., 2019, p. 1069). In addition, the engineers take these models to provide epistemic benefits: “[t]his study provides insights into biological methanation strategies” (2019, p. 1071). By investigating how this process works at a small-scale, the best way to implement it at a larger-scale can be identified. This, in turn, informs a design model for a biological methanation plant that the engineers can endorse.

For a model of a chemical reaction, a model of a building or a model of a biological methanation plant, we have shown how the very same model can be evaluated in at least two different ways. A representational model is assessed in terms of how well it represents its intended target. A design model is assessed in terms of how well it guides the construction of its intended target. Representational models are intended to be accurate or comprehensive representations of an already existing target, in salient respects. So, if a representational model is found to be inaccurate or incomplete in a relevant way, it is corrected or supplemented to better match its existing target. Design models are intended to guide the construction of its intended target. So, if the process of construction deviates from the plan laid out in the model, then the elements of the production process are adjusted to fit the plan laid out in the model.

2.3 Representationalism and Artifactualism

In this subsection we briefly relate our analysis of models to two other positions in the modeling literature. The first position that we consider is the view that models are a kind of tool. This “artifactualist” approach to models is perhaps most familiar in the form developed by Tarja Knuuttila, who argues in favor of “approaching models as epistemic artifacts” (2021, 2). Another position that we consider is the “representationalist” position that all models are representations. For the representationalist, all that is distinctive of models is that they aim to represent an actual or merely possible system. Representationalists may want to criticize the present proposal by saying that design models are also representational, because they represent possible objects or systems.

Our discussion so far is broadly in line with artifactualist criticisms of the representationalist position that all models are ultimately employed for representational purposes (Currie, 2017; Knuuttila, 2021; de Oliveira, 2022). For example, Adrian Currie (2017) discusses the process of selecting a pump for a given site using what he calls preliminary models and procedural models, neither of which is used to represent an actual or possible target system. The function of a preliminary model is just to aid in the construction of other models. Our notion of a design model is closest to what Currie calls a procedural model. According to Currie, "Here, we simply care about its output … We simply need to know that following this procedure will provide the result we need", i.e., select "the optimal pump design" (2017, pp. 772–773). More generally, Currie argues that models are best thought of as tools. Each model can be assigned some function. Functions include generating new models, representing target systems or selecting some optimal design. As the functions vary, different sorts of evaluations become appropriate, just as with ordinary tools like a sewing needle.

We are happy to endorse Currie's point that models vary in their function. The only potential point of disagreement is that we insist that some design models work differently than the procedural models that Currie discusses. Some design models are evaluated in more demanding ways than simply by considering the output of some construction process. These additional dimensions of evaluation go along with a cognitive achievement when a design model is identified. These cognitive achievements are especially clear in the design of new sorts of technologies or other kinds of technological innovation. In Currie's case, the choice of the optimal pump may be handed off to a computer, once various modeling choices are made. In the case of biological methanation, the situation is more complex, and this goes along with a more nuanced evaluation of the design model.

Knuuttila, writing with various co-authors, has perhaps gone further than Currie in emphasizing the epistemic achievements that are facilitated by non-representational models, including models that are prominent in engineering. For example, Knuuttila and Mieke Boon (2011) consider the epistemic benefits of Carnot's model of a heat engine. In this case,

> The characteristic step-by-step construction of a scientific *model* is not due to the attempt to represent in more detail the different aspects of some real target system, but it rather reflects how the theoretical principles and theoretical conceptions develop as the model gets more sophisticated and how the model in each consecutive phase enables its further construction. (Knuuttila & Boon, 2011, p. 319).

The resulting "theoretical understanding" of heat engines quite generally need not proceed through the representational modeling of any actual target system.

As with Currie, we are happy to endorse Knuuttila's conclusion that non-representational models can afford theoretical understanding. However, what makes our design models different from the non-representational models that Knuuttila often discusses is that design models are used to guide the production of some technology such as a biological methanation plant. As we will discuss in Sect. 3, we maintain that design models can contribute to an engineer's understanding of some phenomenon, such as the phenomenon of biological methanation. This contribution does not involve the mediation of "theoretical principles and theoretical conceptions" that Knuuttila and Boon emphasize in the Carnot model case.

It might seem preferable to insist that all models are evaluated in representational terms and to handle engineering cases by supposing that the representations are targeted at possibilities, e.g., what could be realized. On this representationalist approach, the epistemic achievement of an engineer simply consists in the clearer appreciation of both how things actually are and how things could be as a result of this or that change in the natural world. However, we maintain that this interpretation of these models does not fit with the way that design models are evaluated and used. A design model is used to determine whether or not an object counts as an instance of that proposed design. If there is a lack of fit, the object is modified, and not the design model or proposed design. If the design model was a representation of a possible object, then it could not be used in this way. For, as a representation, its function is to accurately represent, and if it represents a possible object then it trivially represents it accurately, at least if the object is genuinely possible.

One could try to supplement the representational approach to avoid this sort of worry. For example, a representationalist could make the additional assumption that the design model functions to compare the features of the possible object with some actual object. But for this comparison to lead to a change in the actual object, there must be some additional intention or purpose at work, such as the intention to create an actual object that matches this possible object in all relevant respects. Our proposal identifies the design model with an intention from the beginning. On either our approach or the supplemented representational approach to the design model, there must be some intention with the right direction of fit in order for the use of the design model to make sense. We suggest that it is better to allow models that are directly evaluated in terms of these intentions rather than posit the complications of this supplemented representational approach.

Our position thus fits with what Guilherme Sanches de Oliveira has recently called "hybrid artifactualism": "here we find approaches that understand models as tools while also employing representational concepts and categories" (2022, p. 36) for some practices.[5] Our proposal is that the very same model can be used by one agent as a representational model and by another agent as a design model. This versatility does not require that we assign models to some special ontological category, just as it is not necessary to pin down the category that includes all and only tools. When a model is used and evaluated based on its accuracy in representing some actual or possible target system, then the model is being used as a representational model. When a model is used and evaluated based on the product it specifies, then it is being used as a design model. A blueprint for a building can first function as a design model that specifies how a building is to be built. Its use as a design model is shown by the way that practitioners alter the building to fit what the blueprint specifies. That same blue-

[5] Knuuttila's (2021) position could be interpreted as such a hybrid artifactualist position, as well. According to her point of view, internal representations can be included in an "artefactual approach" that "analyzes scientific models as purposefully designed human-made or human-altered objects that are used in view of particular questions or aims in the context of specific scientific practices" (2021, p. 2).

print can then function as a representational model that represents various features of the building. This use as a representational model would be shown by the way that practitioners update the blueprint to reflect how a part of the building such as a new entrance had been added.[6]

3 Objectual Understanding with Design Models

Now that the notion of design model and its distinctive direction of fit is clear, we can turn to our characterization of the epistemic achievements that design models can contribute to. We claim that grasping a design model can afford an understanding of the target phenomenon. This sort of objectual understanding is also available through the use of a representational model. So, on our analysis, there is one special sort of epistemic state, objectual understanding, that can be achieved through the use of a representational model, a design model, or some combination of models of both types.

3.1 Grasping Models

One way to support this position is to show how the arguments deployed in discussions of scientific understanding with representational models have compelling parallels when transferred to the understanding provided by design models. To start, we consider the important discussion of understanding in Dellsén (2020). He proposed that understanding in science is based on grasping models. However, in this very paper, it is left open how grasping is to be interpreted. Dellsén just says that he is not focusing "on the psychological aspects of understanding" (2020, p. 1267, fn. 8). In another publication, Dellsén (2017) is more explicit about this question and discusses belief and acceptance as potential interpretations for this "psychological state." Still, he doesn't take a stand on the issue (2017, p. 248, fn. 16).

Apart from the interpretation of grasping as a psychological or cognitive state, there is a second way of interpreting grasping to be found in the literature. Grasping is also related to abilities (cf. Hills, 2016; Elgin, 2017). Some accounts combine these two aspects of grasping and require one "mental state component" and an additional component that requires "having certain abilities" (Fleisher, 2022, p. 11). We argue that grasping should be conceptualized as incorporating at least three components. First, grasping a model requires the identification of the model. This identification involves both the identification of the model qua its content and the use of the model as a particular kind of model. The model has to be identified in terms of its content. Spelled out in structural terms: What is the domain of the model? Which entities belong to it? Which relations between these entities are defined? Potentially, also some functions have to be identified. Additionally, models can be identified qua being used as a particular kind of model. The use of the model can be a representational one, the model can also be used as a design model, and maybe also some other usages of

[6] De Oliveira (2022) considers a "radical artifactualism" that avoids the category of representational models altogether. We cannot engage with this proposal here.

models might be conceivable. Second, the grasping incorporates an evaluation. In the following we'll discuss this component in more detail in contrast to Dellsén's (2020) account. There two criteria for evaluation are analyzed, but they are not interpreted as belonging to an evaluation that is a component of grasping. Third, the ability to apply a model to new cases is an important feature of design models. In the context of constructive tasks, such an ability is a necessary competence of researchers like designing engineers, synthetic chemists, etc. For representational models, this is important, as well. Alison Hills's (2016) account of cognitive control is a proposal that is in line with our interpretation of grasping. Here we would just like to make the same point as regards Dellsén's account. The discussed component of the ability has to be expanded to cover cases such as non-representational models.

3.2 Dellsén's Account of DMA

According to Dellsén's account of objectual understanding, one can understand the respective target by grasping a so-called dependency model of the target. Dependency models are a kind of representational model. Like other representational models, dependency models are evaluated in at least two ways: accuracy and comprehensiveness. Accuracy concerns the correctness of how the model characterizes the target's dependencies. Comprehensiveness considers how many of the model's genuine dependencies are to be found in the target. Dellsén argues that a good representational model of dependencies is apt to provide objectual understanding of its target when an agent grasps that model. His key assumption is that when a model does well with respect to the standards tied to the type of model that it is, then that model can afford understanding. This argument can be broken down into two steps: First, "[T]o have understanding of phenomenon P, it is not enough to grasp any old dependency model of P. Rather, the model must in some sense be a 'good' representation of the relevant dependence relations" (Dellsén, 2020, p. 1267). Second, the criteria with which representational models are primarily evaluated are accuracy and comprehensiveness. If dependency models are apt to afford understanding when good, and their goodness consists in their accuracy and comprehensiveness, then an accurate and comprehensive dependency model provides understanding of its target. The conclusion of this argument is contained in Dellsén's (DMA) proposal:

> DMA: *S* understands a phenomenon, *P*, if and only if *S* grasps a sufficiently accurate and comprehensive dependency model of *P* (or its contextually relevant parts); *S*'s degree of understanding of *P* is proportional to the accuracy and comprehensiveness of that dependency model of *P* (or its contextually relevant parts). (Dellsén, 2020, p. 1268)

We are happy to accept the "if" direction of (DMA): if an agent grasps a good representational model, then that agent understands the target phenomena. However, we question the argument for the "only if" direction of (DMA). Everything that Dellsen says is consistent with good models of other kinds also affording understanding of the very same phenomenon.

3.3 Evaluating Design Models

To see how this might work, consider a design model such as the design models of a biological methanation plant mentioned in Sect. 2.2. As design models, these models are evaluated in at least three ways tied to how they guide the production of the artifacts in question. These three ways are tied to (i) usability, (ii) operational implementation, and (iii) the optimality of the product specified. As with Dellsén's two criteria for representational models, there are interesting potential tradeoffs between (i), (ii), and (iii). We do not aim to provide a complete account of how these tradeoffs might work. Instead, our proposal is that when a design model satisfies each of the three requirements to a contextually specified threshold, an agent who grasps such a model will have a sufficient understanding of the phenomenon in question. Our argument for this conclusion runs parallel to Dellsen's argument: just as representational models are evaluated in terms of accuracy and comprehensiveness, we will show how design models are evaluated in terms of usability, operational implementation, and optimality of the product specified. In the representational case, a good representational model affords understanding of its target. We claim that the same point holds in the design case: grasping a good design model also affords understanding of its target. Our argument involves two steps. First, we need to clarify how design models are evaluated (in the following paragraphs). Second, we explain why grasping a good design model in this sense affords objectual understanding (in Sect. 3.4.).

To start, a good design model must be usable by the agent. That is, the character of the model must be cognitively accessible to the agent so that it is feasible for them to deploy that model when building the specific product. The point is easily illustrated for a shopping list. For the list to be usable, the items must be presented in a clear and transparent way. Similarly, the information provided by the design models should be readily available to the agent that deploys these models. There are interesting questions here about training and expertise. A design model may only be usable by an agent with the right kind of education and experience. Still, for such a model, one dimension in which it will be evaluated is this kind of usability.

It is not clear how well the requirement of usability can be used to distinguish design modeling and representational modeling. One might argue that representational models are also evaluated in the very same way as design models with respect to their clarity and transparency. We do not take a stand on this issue here. It is sufficient for our purposes that the other two requirements are not applied when a model is used to represent.

There is a second kind of evaluation of design models that we call operational implementation. A given design model is to be used to build a product of some kind. This means that the model should make it clear how to go about building that product. Ideally, there might be some kind of step-by-step specification of the order in which the thing can be built, as with a cooking recipe or some Lego instructions. A shopping list could score quite low on operational implementation even if it scored well on usability. This would occur if the items on the list were legible, but the list did not make it clear where in the market the various items were located. So, an agent could complain about the list that it was not easy to deploy it to actually obtain the items listed. Similarly, a usable design model might not provide much indication of how to actually build the specified product. This is the case for some design models of a biological methanation plant that are mentioned in the cited engineering literature of our case in Sect. 2.2. They do not indicate how to actually build either kind of biological methanation plant. Presumably a great deal of additional work would be needed to go from either design model to something that a contractor could deploy in the construction of such a plant.[7]

The third kind of evaluation of a design model is focused on the product specified. In our case, the product specified is a way of implementing and controlling the phenomenon of biological methanation. A user of such a design model aims to build the best version of an implementation of biological methanation within an energy plant in the sense that it best achieves the goals of that technology, e.g., storing energy while reducing CO_2 emissions at a feasible cost. So, a design model will be good in this sense to the extent that it actually specifies a good version of implemented biological methanation. Clearly, a design model that scores well on usability and operational implementation may not specify a biological methanation plant that is good in this sense. A wide range of scores seem possible in this dimension. For example, the product specified may be optimal for agents with certain goals, but far from optimal for agents with other goals. So, as with the other two kinds of evaluations, there is a great deal of contextual variation in how this sort of evaluation is to be carried out.

3.4 Our Proposal of UD

Taking these three requirements for the evaluation of design models for granted, let us now consider the connections to understanding with design models. If objectual understanding is available by the grasp of a good representational model, then, we maintain, objectual understanding is also available by the grasp of a good design model. That is, the "if and only if" of (DMA) should be replaced by an "if", and an additional sufficient condition on understanding (UD) should be given in terms of design models:

> UD: *S* understands a target, *T*, if *S* grasps a sufficiently good design model of *T*; *S*'s degree of understanding of *T* is proportional to the goodness of that design model of *T*.

In UD, the goodness of the design model is based on the three kinds of goodness summarized above: (i) usability, (ii) operational implementation, and (iii) optimality of the product specified. For the engineers working with design models, it is not enough that their models are good in the same way that representational models are

[7] In fact, our picture is, of course, highly idealized. There is not only one design model that is studied by engineers and is, then, used by contractors to produce the artifact under consideration. One could distinguish many different subtypes of models within design projects. For example, one plausible assumption is that there is a final model used for manufacturing the product that is reached at the end of a long procedure of going through iterating steps within the modeling process in designing the respective artifact. As Claudia Eckert and Rafaela Hillerbrand write, accordingly: "Only the final manufacturing models are complete instructions for producing the product, which have been developed through many other models" (2022, p. 10).

good, either in terms of accuracy or comprehensiveness. The three requirements on goodness are distributed over the goodness of the model and the goodness of the target in the following sense: for a given context, a threshold must be achieved for each criterion. Beyond that threshold, some good design models will score better than others, and this will correspond to an improved state of understanding for an engineer in that context who grasps such a model. There are then two ways to achieve objectual understanding of some phenomenon, at least: either via grasping a representational model of dependencies or via a design model.

Our argument for (UD) relies on the parallels between representational models of dependencies and design models. One objection is that only representational models of dependencies are apt to generate objectual understanding of phenomena. Dellsén endorses this claim and traces it back to the influential work of Kim, Greco, and Grimm: "the aspects of a phenomenon that matter for understanding are the dependence relations that the phenomenon, or its features, stands in towards other things" (2020, p. 1266). However, no reasons are given for this exclusive focus on dependence relations. One reason would be that representations of dependence relations are special because they provide opportunities for fruitful interventions on the phenomena that we encounter. This is a prominent element of James Woodward's (2003) analysis of causation, for example. Woodward's idea is that we employ a concept of causation, and distinguish causes from mere correlations, so that we can effectively manipulate the world around us. This emphasis on intervention or manipulation is also central to Peter Dear's historical analysis of what distinguishes modern science from earlier approaches to the natural world which are often referred to as "natural philosophy":

> "science" can be represented in modern culture in its guise as natural philosophy or in its guise as instrumentality, but not both at the same time. When a scientific statement is regarded as a piece of natural philosophy, it has the status of a description of the natural world. Something might perhaps be done with it, but as it stands, it is simply about how the world is. Conversely, when a scientific statement is regarded as an expression of instrumentality, it is an account of how to do something, an account that may also be said to have implications about how the world is. (Dear, 2008, p. 8)

Dear's emphasis on what he calls "instrumentality" can be used to make sense of the claim that grasping representational models of dependencies affords the distinctive epistemic state of understanding. But, as this passage makes clear, a focus on instrumentality would also allow for other types of models to afford understanding if a grasp of those models went along with "an account of how to do something." Design models, as we have introduced them, are precisely these sorts of accounts: a good design model indicates how to make something. So, if the reason that representational models of dependencies afford understanding is their tie to instrumentality, then design models should also be tied to the very same sort of epistemic state.

Another consideration in favor of (UD) is a kind of thought experiment inspired by Frank Jackson's (1986) knowledge argument: imagine an agent Larry who grasps a large number of good representational models of dependencies, but does not grasp any good design model or related action-oriented guide to producing the phenomenon in question. There is clearly a sense in which Larry understands the phenomenon. They have a theoretical appreciation of many of the phenomenon's inner workings and how it develops when it occurs naturally. But they are unable to artificially create this phenomenon as they lack any action-oriented guide that would indicate how to make it. Larry's understanding of the phenomenon could thus be compared to a scientist who has a good representation of the dependencies inherent in a baked cake, but who lacks any way to bake the cake. Suppose that Larry is introduced to a good design model for their phenomenon. In grasping this new type of model, Larry now acquires an action-oriented guide that indicates how to artificially produce the phenomenon. It seems clear that grasping this new model, a good design model, has improved their overall understanding of the phenomenon. Just like a person who learns to bake a cake (or a musician who learns how to play a new piece of music), Larry's understanding is improved.[8]

We are aware that by giving these two considerations in favor of (UD) some proponents of alternative views on understanding who focus on purely theoretical kinds of epistemic achievements may not be convinced. One may think that we are begging the question when we claim that design models afford understanding. Because some uses of design models do not necessarily increase the understanding of their users, our claim that other uses of such models do might be wrong. Such understanding afforded by design models might in fact be grounded in a previous understanding of the phenomenon in question with the help of another vehicle such as a representational model according to an alternative view. Thereby, we would beg the question when we claimed that the design model affords understanding.

What we did implicitly assume is an approach to understanding that does not treat theoretical and pragmatic understanding as two separate and independent cognitive states. As Bengson (2017) argues there is a case to be made for a unificationist view of understanding as a state that includes practical, action-guiding aspects as well as theoretical, representational aspects. We happily endorse such a view that understanding embraces theoretical as well as practical aspects. Given that understanding as a comprehensive epistemic state contains practical as well as theoretical aspects, the charge of begging the question does not apply to our account, so we argue.

There are two different ways to relate the grasping of models to the state of understanding that are consistent with the Jackson-style argument given above. For Dellsén, the understanding that an agent has of some phenomenon is reduced to their grasp of a number of good models of that phenomenon. The grasp of a single model in isolation can provide understanding, and the grasp of many models just involves the combination of many distinct states of understanding. This aggregative approach is consistent with our proposal of (UD). However, we also wish our proposal to be consistent with the more holistic approach championed by Elgin (2017) and refined by Christoph Baumberger and Georg Brun (2021). On a holistic approach, the state

[8] At this point, one may also want to inquire into the relation between the epistemic state of Larry and the cognitive achievement of maker's knowledge (cf. Currie, 2022). In Currie (2022), the connections between knowing how and maker's knowledge are studied in the context of production processes that are relevant for experimental archaeology. We come back to this example in Sect. 4.

of understanding consists in grasping not only the individual models in isolation, but also their relationships. As Elgin summarizes her position,

> [U]nderstanding is an epistemic commitment to a comprehensive, systematically linked body of information that is grounded in fact, is duly responsive to reasons or evidence, and enables nontrivial inference, argument, and perhaps action regarding the topic the information pertains to. (Elgin, 2017, p. 44, cited by Baumberger & Brun, 2021, p. 7939)

As the “perhaps action” clause indicates, Elgin is happy to allow that action-guiding information can enhance a state of understanding. So, she should be open to our proposal that an agent who comes to grasp a good design model will move to a superior state of understanding. For our purposes, the main difference with Dellsén is that Elgin would not grant understanding to an agent who grasped only a single model in isolation. The point remains that both approaches should be expanded to allow for the objectual understanding of phenomena through the grasp of a good design model.

4 Three Objections

In this section we consider three objections to our claim that grasping a good design model can afford understanding of a phenomenon such as biological methanation. The first objection is that the grasp of a good design model is redundant to the state of understanding. The second objection is that the notion of phenomena is unclear, and once it is clarified, there is no way for a representational model and a design model to share a target. The third objection is that understanding with design models is really just a kind of knowledge such as the knowledge how to produce something or what some call “maker’s knowledge.”

The redundancy objection can be developed in the following way: the design model is redundant because the grasp of a good representational model allows any agent who desires to produce the phenomenon to do so simply by forming the relevant intention. Conversely, if an agent grasps a good design model, then they must be in a position to grasp a correspondingly good representational model. There is thus no special role for design models in attaining understanding of phenomena.

Our response to this objection is that the grasp of a good design model is a distinctive epistemic achievement, and for this reason it is far from routine to move from a good representational model to a good design model. This epistemic achievement can be illustrated using our main case of the engineering investigation into how to best implement the naturally-occurring process of biological methanation. Prior to their investigations, the engineers did grasp (or may have grasped) a wide range of good representational models of biological methanation, including models that depicted how the chemical reactions occurred and how they were carried out by various types of methanogens. But this grasp of representational models did not by itself indicate how best to produce a biological methanation plant. This is why the engineers conducted their research that involved experimenting with different versions of this technology and considering how best to achieve a well-functioning plant. The results of this research include what one paper calls “insights into biological methanation strategies” that were previously unavailable (Voelklein et al., 2019, p. 1071). We conclude that much more is needed than the combination of good representational models and the intention to build a biological methanation plant. The state of understanding that incorporates good design models of biological methanation is a different, and improved, state of understanding. The design models are thus not redundant.[9]

While the grasp of a good design model is epistemically significant, we would also admit that engineers are well-advised to draw on any available good representational models of their target phenomena when they are devising their design models. One reason to aim for this sort of integration is that an engineer who is equipped with a good representational model is more likely to arrive at a good design model than an engineer who has a bad representational model. For example, an inaccurate representational model of the Sabatier reaction could undermine the engineering studies that are used to develop a new design model for a biological methanation plant. So, even though a collection of good representational models does not guarantee the enhanced state of understanding afforded by the grasp of a good design model, it does make this epistemic achievement more likely. This of course fits with the common sense point that an advanced understanding of scientific matters can make an engineering success more likely.

The second objection that we will consider questions what the object or target of this state of objectual understanding is supposed to be. Dellsén is clear that on his account of objectual understanding “the target phenomenon, P, need not be a single object; rather, it may be a complex system that is itself most naturally described as being composed of several interacting objects” (2020, p. 1263). We endorse this broad characterization of phenomena. In fact, we suggest that an even broader way of picking out phenomena is appropriate for accounts of understanding. On James Bogen and James Woodward’s (1988) influential proposal, a phenomenon is a repeatable type of event, state or process.[10] This leads us to distinguish between a token of some process and that type of process (e.g., the Sabatier reaction). We agree with Bogen and Woodward that a very common object of scientific investigation is the type. In these cases, tokens of some process are studied in order to gain some understanding of the type. This is also what we see in our biological methanation case. Tokens of the biological methanation process are investigated in nature and in the laboratory with the aim of gaining an understanding of that common type of process. The objects of objectual understanding can thus be identified with phenomena, provided that it is clear that both tokens and types of events, states, and processes are included.

[9] One must grant that additional arguments are needed to convince any opponent to our view. If one sees understanding mainly as a state of theoretical understanding only afforded by representational vehicles, then the understanding afforded by a design model may not be seen as adding to such a narrow state of theoretical understanding. This consideration is related to the remarks on the relation of our view to the ones by Bengson (2017) and Elgin (2017) we made in Sect. 3.4 .

[10] See, e.g., “Instances of each of the phenomena described …” and “We expect phenomena to have stable, repeatable characteristics which will be detectable by means of a variety of different procedures …” (1988, p. 317). This suggests that only types are properly called phenomena, and not their tokens. However, at least for debates about objectual understanding, it seems better to allow the object to be either the token or the type, e.g., this very Sabatier reaction occurring on Jan. 3, 2022 in this lab as well as the Sabatier reaction.

This refinement of what a phenomenon consists in could encourage the following objection: the phenomenon targeted by a representational model is always going to be distinct from the phenomenon targeted by a design model, and so there is no unified state of understanding that can be obtained by grasping either sort of model. In our case, for example, the representational models might be thought to be targeted at naturally-occurring processes of biological methanation, while the design models are targeted at artificially-occurring processes of biological methanation that the engineer aims to bring about. If these processes involve distinct phenomena and so distinct objects, then there is no unified state of objectual understanding.

Our response to this objection is that there is no plausible way to individuate phenomena along these lines. A working assumption of scientists and engineers in these sorts of cases is that the very same process is occurring both naturally and artificially. This is why it makes sense to study the process in nature and in the laboratory. We are willing, of course, to admit that there are cases where what could be superficially treated as a single phenomenon turns out to be really two phenomena. For example, there are important differences between the processes through which diamonds are naturally formed and the processes through which they are best manufactured.[11] As these differences are significant, it is necessary to distinguish between two states of understanding, namely understanding the process of natural-diamond formation and understanding the process of manufactured-diamond formation. Our point is only that this sort of natural/artificial contrast cannot be universally applied to divide up phenomena into distinct types. So, when some phenomenon is appropriately unified, e.g., as a single type of process, an understanding of that phenomenon can be obtained by grasping either a representational model or a design model (or both).

The third objection maintains that understanding phenomena with design models is best conceived as a kind of knowledge-how or what some call "maker's knowledge". If this knowing how to make something were distinct from the understanding of a phenomenon afforded by the grasp of a representational model of dependencies, then it would follow that grasping a design model does not afford understanding of phenomena. More generally, it might seem essential to our proposal to settle how the understanding of phenomena relates to various kinds of knowledge that have been discussed in the philosophy of science and engineering.

A brief, but suggestive, connection between maker's knowledge and understanding is made by Currie (2022). One example from this paper is the archaeologist S. Kuhn's investigations into flint tools. Kuhn aimed to estimate how often a recovered flint tool had been sharpened by prehistoric humans. Crucially, for our purposes, one element of Kuhn's estimation procedure involved experiments where new flint tools were fashioned and sharpened in line with how they may have been originally made. This "flintknapping" is an example of what Currie calls "experimental archaeology." Making new tools helped to clarify various questions about these tools, in part by creating the knowledge of how to make and maintain these tools. As Currie puts it,

> Making negative scars through flintknapping is a direct way of seeing why negative scarring, and particular fine-grained properties of scarring, signals not

[11] https://www.gia.edu/gia-news-research/difference-between-natural-laboratory-grown-diamonds.

> only core-like properties [i.e., the properties of the rock not removed in the course of making the tool], but a sense of the expertise of the knapper, why the piece was worked as it was, and so forth. (Currie, 2022, p. 348)

This maker's knowledge of how to make flint tools involves an "understanding of flintknapping processes" and thus affords or "well-positions" the archaeologist to address questions of scientific interest (ibid.).

In our terms, the archaeologist who makes flint tools is likely to have grasped a design model that guides their actions. It is this grasp of a design model that is at the core of the experimental archaeologist's activity of making a new flint tool. We completely agree with Currie here that when a scientist or engineer understands a phenomenon in this way, they are often well-positioned to know the answers to various scientific questions. It is not clear, though, when we should say that grasping a design model affords not only understanding of the phenomenon, but also knowledge of some of the propositions that characterize that phenomenon. Currie does not address this question in any definitive way. For our purposes, we can allow that some cases of objectual understanding of phenomena through design models do involve propositional knowledge, while other cases do not. For example, consider our central case where there are engineers who grasp a good design model of a biological methanation plant that has not yet been built. Prior to building the plant, our analysis claims that the engineers have objectual understanding of this phenomenon. But it is likely that they do not know some of the propositions that they would know were they to go ahead and build a plant conforming to this proposed design. If this is right, then objectual understanding is a distinct epistemic state from propositional knowledge, even if carrying out the design at the center of the state of understanding is capable of providing propositional knowledge.

More generally, there are interesting additional questions about the relationships between objectual understanding of phenomena through design models and various forms of knowledge related to those phenomena. Perhaps the most extensive discussion of a special sort of engineering knowledge is offered by Vincenti (1990) in the book *What engineers know and how they know it*. We plan to investigate these connections more systematically in future work, but must set them aside here due to space limitations.

5 Conclusion

We have argued that some of the epistemic achievements of researchers that are directed at making things can be analyzed in terms of understanding. Dellsén's recent proposal that objectual understanding consists in the grasp of models can help with this analysis once the proposal is expanded to allow for understanding through the grasp of design models. Much of our discussion has considered how to evaluate the goodness of design models. The different ways of evaluating representational and design models go along with their differences in direction of fit. It is perhaps also not surprising that the evaluation of these two kinds of models is a highly contextual affair. A model that is excellent for one purpose may be a poor model when used for some other purpose. More case studies and additional conceptual investigations are needed to map out how models are evaluated and how various criteria can be related.

Another topic for future research that we have not discussed here concerns what is sometimes considered to be the central problem for the philosophy of engineering: how should we compare the epistemic achievements of engineers to the epistemic achievements of scientists? This question animates Vincenti's 1990 book, which was noted at the end of the last section. This book is part of a larger debate about the epistemic achievements of engineers. Vincenti begins by rejecting the view that engineering is merely applied science, but a wide range of options remains for how to make sense of engineering or technological knowledge (cf. Houkes, 2009; Kant & Kerr, 2019; Houkes & Meijers, 2021). It may prove feasible to identify both what is distinctive about engineering, and what engineering has in common with science, using our contrast between representational and design models. One suggestion is that, while both the scientist and the engineer understand by grasping models, the engineer's expertise with design models renders their understanding both special and autonomous. On this picture, the common aim of understanding is consistent with significant differences in priorities and standards of evaluation. Only additional investigations can determine how fruitful such a framework might be for examining the ongoing interactions between science and engineering.

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