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MAKING SENSE OF MODELING: BEYOND REPRESENTATION[1]

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1 Introduction

Scientific models have been freed, to some extent, from theories[2]. In this paper, I wish to free them, to some extent, from the world, just when they are paradoxically the closest to it, that is, when they are representational models and their target is a real system. This paper investigates a neglected way in which such models may be used: not to represent, even if they do represent, but to construct other models and generate new target systems. It is what I will call the generative constructive use of models. This use is philosophically important because it is what makes some models scientifically significant. Even though these models are successful representations, to make sense of their scientific significance, we need to go beyond their success as representation. I will distinguish this use from other uses and, in particular, from two other ways in which models can be used to construct models.

As we will see in **Section 2**, the role of use and users has become a common issue in philosophical studies on models. Use and users are invoked to account for the

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[2] 'To some extent' in the sense that if models are not contained in or derived from theories (Cartwright 1995, Morgan & Morisson 1999, Suárez & Cartwright 2008), that does not mean that theories have no role to play in the construction of models. Theories provide structural resources and constraints (Morrison 2007) as well as a narrative that characterizes the entities of the domain of application of the theory (Morgan 2001; Peschard 2007)

representational status of models or to account for the epistemic function and epistemological status of models. It is the epistemic function that is primarily addressed in this paper. Other studies have discussed what I will call the constructive use of models, that is, the use of models to construct models. But these studies are generally concerned with models that are not representational or models whose representational content is not taken seriously, like the fictional model of silogen used in the construction of simulation models (Winsberg 2006), or the chemical formulas used as paper-tool models in the construction of models of chemical reactions (Klein 1999). By contrast, I will discuss models that are taken seriously as representations and nevertheless are not used to represent, but to construct other models.

The generative use applies to representational models with a real target system. **Section 3** will clarify the notion of representational model by contrasting representational models with abstract models (Cartwright 1999; Giere 2008, 2010). As we will see, both representational and abstract models can be used to construct models. But in the generative use, the use of the model does not consist in producing a less abstract model, and the construction does not lead from theoretical principles to the world.[3] This use, illustrated in **section 4** with the construction of models of coupled wakes, leads rather from one representational model to another. In this sense, the construction takes place in a space of models and modeling activities. What the case study will also suggest is that it may be more appropriate, in this type of use, to think of what is used as being, not the model alone, but the model in coordination to its target. That is, it is the model-target unit that should be regarded as an epistemic tool in a space of modeling activities where new models and targets are produced.[4] The epistemic significance that accrues to a model

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[3] This is not to claim that the use of abstract models to construct more specific models always takes place along a line relating a theory to the world. For instance, Boumans (1999) shows how the construction of economic models might involve a diversity of theoretical models or principles. The use of template models (Humphreys 2004) would also be a counter-example to that claim.

[4] The use of models as epistemic tools in a sense that also redirects the attention away from representation has been discussed by Mieke Boon and Tarja Knuutila in relation to engineering science in Boon & Knuutila (2009) and in Knuutila (2006)

from its use will only then appear in a perspective large enough to include the models that are produced.

The last section of the paper, **section 5**, will contrast the generative constructive use with two other major forms of constructive use of representational models. One is the modification of a model to improve it, as in the construction of the London model (Suárez & Cartwright 2008, Cartwright et al. 1995), the other is the use of a model as an ingredient in the construction of a more complex model (Boumans 1999). With the benefit of the illustration given in the preceding section, these contrasts will reveal two characteristic features of a generative constructive use. Importantly, these two features characterize the target of the model as much as the model itself.

2 Role of use and users in accounts of modeling

Appeal to use and users has become commonplace in the literature on scientific modeling. In this section, I will distinguish two motivations for this appeal with two distinct roles that use and users play in accounts of modeling. The first motivation is a concern with representations in general and what one may call their ontological status. Use and users are here introduced to account for what makes something a representation, a model. The second motivation is a concern with the epistemological autonomy of models, autonomy from theories, revealed by attending to the different epistemic functions of models (Morgan & Morrison 1999). In this perspective on use and users, it is the different ways in which models may be manipulated that is examined.

2.1 Constitution of models

Use and users play a crucial role in many accounts of the representational function of models: in the inferential account developed by Mauricio Suárez (2004, 2010a), the intentional account recently proposed by Ronald Giere (2010) (see also Mäki 2011) or the empiricist structuralist account by Bas van Fraassen (2008), and the list is certainly not exhaustive.

In these accounts, use and users form the link between a source and a target that enables the source to function as a representation of the target[5]. For instance, in Suárez' inferential conception, a necessary condition for something, a source, to function as a representation of a given target is that it would enable "an informed and competent user" to draw inferences from the source to the target[6]. In Giere's account, the user is required to specify which similarities between the source and the target are intended (Giere 2010) whereas van Fraassen stresses that "there is no representation except in the sense that some things are used, made or taken to represent something as thus and so" (2008, 23). To these views, one may add the stipulative account defended, for instance by Paul Teller (2001) (see also (Cohen & Callender 2006)) in which something becomes a representation in virtue of an act of stipulation.

The use that is considered in these accounts is one that makes something into a representation, into a model of a given target. It has a constitutive function (Cohen & Callender 2006). But if this use has a constitutive function, then it cannot yet be a use of the model as such. Rather it is the use of something, not yet a model, to represent a target, that makes this something into a model of the target. Could this something be anything? This is what the stipulative account claims: according to this account, all that is required for something to become a representation is a user stipulating that it will be so. It is doubtful however that this can be a satisfactory account as far as scientific representation/models are concerned[7]. The reason is that it separates the justification of the use of the source from the selection itself and leaves the selection of the source deprived of any normative guidance. This is at odds with analyses of the process of model production revealing that this process already incorporates elements that have some justificatory power[8]. As we will see in the last section of the paper, if seen from the

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[5] By contrast, for instance, with Steven French's (2003) view that something may be a representation in and by itself.

[6] Another necessary condition is the existence of a representational force directed from the source towards the target.

[7] See, for instance, Frigg (2010) for a compelling criticism of this account.

[8] Insightful in this respect is Boumans (1999) showing justification built-in through the incorporation of empirical data or Winsberg (2010) explaining how reliability of simulation models is built-in through the reliance on trusted principles and techniques.

standpoint of the models *produced*, a study of the use of models to produce models, the constructive use of models, might contribute some insight into the way in which justification can be built-in during the construction of the model. From this standpoint, studies of the constructive use of models then prove relevant to constitutive concerns.

In so far, however, as one focuses on the models *used* to construct models, the role of use and users should be clearly distinguished from the role they receive in a perspective concerned with constitution. The reason is that in the former case, what is used is already a model of a given target. What I will do now, then, is to situate the constructive use of models within the perspective concerned with manipulation of models.

2.2 Manipulation of models and constructive use

The attention to use (and users) in the literature on scientific modeling has produced a wealth of studies of the different ways models can be manipulated so as to produce knowledge. The idea of models as mediators between theories and the world invites a first distinction between four very general types of use[9]: 1) directed towards the target: the model is used to draw inferences about the target; 2) directed towards the theory: the model is used to provide insight about the theory (insight about the theory also comes, in an indirect way, from the use directed towards the target; 3) directed towards itself; 4) directed towards other models.

The use of models that will be discussed and illustrated is one that is not primarily directed at the theory or at their target. It is a use directed at the construction of other models. As we will see later, this use does not exclude use of the model to learn about its target; the point is rather that this latter use does not exhaust the ways in which the model can be used and, as mentioned before, may not be sufficient to account for the scientific significance of the model.

I will use for discussion and illustration a model of a wake, in fluid dynamics. But the basic idea may be introduced with a better-known model, namely, the famous HKB

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[9] This distinction will be useful in the context of this paper but is not claimed to cover all types of uses.

model (Haken, Kelso and Bunz 1985), a dynamical model of the coordinated, wagging, movement of the index fingers of both hands. This model is successful in predicting, for instance, that if the subject begins in the anti-phase wagging mode then a spontaneous switch to symmetrical, in-phase movement[10] will occur when the speed of movement is increased, and it predicts the value of the shifting. This predictive capacity of the model is however far from giving an idea of how and why scientists have been using this model and how and why this model has become such a reference in cognitive science. For what it does not show is that the model was a starting point for the construction of models in a variety of studies: from studies of the effects of different factors on coordination to studies of the underlying neural dynamics of coordinated actions, to modeling of social interactions[11]. What becomes visible, from this larger perspective, is the productive and transformative effect of the model on the development of a whole scientific domain of investigation, here the domain of coordination dynamics.

There are different ways in which models can be used to construct other models beside the one that I will focus on. Some can be quite easily distinguished from the generative constructive use. That is the case with (what I will call) the top-down use and the fictional use of models.

The *top-down use* consists in producing representational models through the progressive specification of more abstract models. I will come back to it in the next section. By contrast, in the generative use that I will discuss, the model that is used is already representational. In the *fictional use*, the model that is used in the construction of models does not have a real target (Winsberg 2006, 2009) or whether it has one is irrelevant (Suárez 2010b)[12]. This is not the case in the generative use because there both

[10] The anti-phase mode corresponds to the fingers moving towards and away from the midline at the same time, whereas in the in-phase mode the fingers move in the same direction at the same time.

[11] For an indicative account of the plurality of uses of this model see Jirsa & Kelso (2004) and Chemero (2009).

[12] It is not to say that the representational content of the fictional model or fictional assumption is irrelevant but rather to say that the use of the fictional model or assumption does not rely on the existence of what is represented or the truth of the assumption.

the model and its target are involved in the construction of a new model with a new target. For instance, in the case study that will be discussed, a model of a single wake is used to construct a model of coupled wakes, whose target is generated by putting side-by-side several single wakes. In the HKB model, a new model was constructed by adding a new parameter corresponding to the relative position of the hands (Fuchs & Jirsa 2000) and predictions were made about the evolution of the corresponding target, that would be generated by adding this dimension to the original experimental set-up.

The generative constructive use is then distinguishable as a use of models that are representational and that are not fictional. The reason why this form of constructive use has not received much attention is, I suspect, the mesmerizing effect of the relation between the model and its target, what it represents. It is as if, once the model represents a real system, there is no need to look further for accounting for its epistemic value, as if "scientific representations have cognitive value *because* they aim to provide us with specific information regarding their target" (Suárez 2004, 772, it. added). Yet, it is doubtful that just any target will be of equal epistemic[13] interest. Being capable of representing adequately its target may be a necessary condition for the cognitive value of a model, but by itself it does not enable us to understand what makes some of them scientifically remarkable, significant[14].

There are two other forms of constructive use of models that seem to share many of the features that I just attributed to the generative constructive use. One of these uses consists in modifying a model in order to produce a better model. Another one is the use of a model as a module in a more complex model. The discussion of the differences between such uses and the generative constructive use is postponed until the case study has been presented so as to be in a better position for finer distinctions.

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[13] I will use 'cognitive value' and 'epistemic value' to refer to the value that accrues to models from their capacity to generate knowledge.

[14] As Joseph Rouse writes, "Science as an ongoing practice of inquiry discounts truths that are trivial, marginal, anomalous, arcane, or otherwise 'uninteresting', in order to focus resources and attention upon others that are taken to be significantly revealing" (Rouse, 2002, 157)

Before that, the next section will explicate what it is for a model to be representational.

3. Representational Models

According to Giere (2008, 2010), Newton's laws, that he calls the Principles of Mechanics, as well as the Principles of Thermodynamics or the Principles of Relativity, can be seen as characterizing models of a highly general, abstract type[15]. At the other end of what Giere sees as a hierarchical structure of models lie representational models that are fully specified, with all the terms in the model being ascribed a specific value, and representing a point in a state space. We go from one extreme to the other through models of different degrees of generality that are obtained through successive operations of specification. For instance, starting with the Principle of Mechanics, a first level of specification consists in the specification of the force function, for instance F = -kx; another one would be to specify the value for k, and then the value for x.

The category of representational models does not seem limited, however, for Giere, to the most specified models, even though what he calls 'abstract models' do not qualify as such. Where then, in the hierarchy of models, do we start finding representational models? Considering the models generated by the Principles of Mechanics, representational models appears right after the specification of the force function. But why there? What characterizes a model as representational?

Giere seems to think of representational models as models that can be made fully specified and can be used to represent actual systems in experimental situations, in contrast with abstract models that "cannot by themselves be used to make any direct claims about the world" (2010, 270). But how does that differentiate between a principled model, with the force function not yet specified, and the model of a harmonic oscillator for which F is specified as F = -kx but the value of k is not? Neither can, after all, be used to make direct claims about a specific system. And, on the other hand, one may argue that both types of model actually have a representational content in that they both define a class of abstract objects, one simply larger than the other. The Principles of

[15] As we will see, they are abstract not only in the sense that they are abstract entities but in the sense that they are not fully specified (Giere 2010, 125).

Mechanics can be seen as providing a representation of a class of systems in the sense that they formulate some basic structural constraints that will have to be satisfied by the behavior of these systems. As Margaret Morrison writes, “we use models to represent physical phenomena in more or less abstract ways. […] While the model may be highly abstract, it nevertheless refers to basic concrete features of a physical system and in that sense functions in a representational capacity” (Morrison 2009, 216).

Yet, I think that there is some value in making the sort of distinction that Giere makes between abstract and representational models, even if the terms may be misleading. This value appears more clearly through Nancy Cartwright’s distinction between abstract and concrete models. According to Cartwright, what is needed in order to be able to use the principled models of the theory (to use Giere’s term) are what she calls interpretive models and bridge principles (Cartwright 1999, 189). Bridge principles relate abstract concepts like force to more concrete descriptions, provided by the interpretive models, of the situation in which we want to apply the model. The principled models can only be used in situations to which one of these interpretive models applies. In classical mechanics, they are the models that specify different possible forms of the force function. But what makes the description of the model concrete is not that all the mathematical variables have been assigned a value; it is that it is possible to assign them a value. In what sense is it possible in a way that was not possible before? Could we not have, very early on, assigned a value to the force function? The difference between F, on the one hand, and, say, -kx, on the other hand, is that we cannot empirically specify the value of F without specifying first the value of other quantities, like k and x.

A concrete model is a model all of whose variables are fully expressed as physical basic quantities with no further dependence on other terms not made visible in the model. And this may well be what Giere has in mind with the idea of representational models as models that *can be* made fully specified and that can be connected, coordinated, to specific systems. But to call such models representational is misleading for it is not simply that they have some representational content, it is also that they have the sort of representational content that enables to qualify as concrete model, in the sense just indicated. One may then rather call them ‘concrete representational models’, and this is what will be meant hereafter by ‘representational models’.

4. Construction

4.1 Scientific background and motivation

The representational model that will be used to illustrate a case of generative constructive use of model is a model of the wake that develops behind a cylinder.

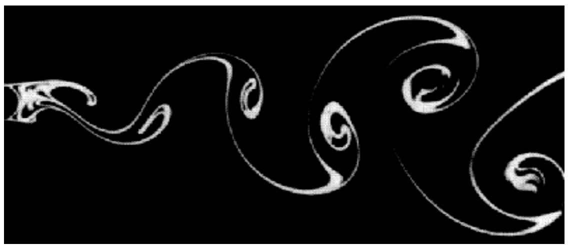

Figure 1: Wake behind a cylinder (on the left). The wake is formed by the vortices emitted on each side of the cylinder and carried away with the flow (from left to right)

The motion of the flow behind a cylinder (which is an idealization of the flow behind an island, a rock, a pole, the pylons of a bridge, etc.) is one of the typical configurations that one will find described in textbooks and discussed in colloquia. The configuration is an open fluid system with a cylinder whose axis is perpendicular to the direction of the flow and generally regarded as infinite. The wake behind a cylinder is formed by vortices that are emitted alternatively on each side of the cylinder and are carried away with the downstream flow.

The model to be considered here is actually directed at a specific type of configuration, where the cylinder is not infinite but, on the contrary, of very short aspect ratio (the ratio of the length to the diameter: L/D). This condition dramatically restricts the range of application of the model, as well, it seems, as its practical and theoretical relevance. That the model enables true but rather trivial (at the time they were made) and marginal inferences is not sufficient to make it scientifically worthwhile, worth the trouble. But its scientific, epistemic value is actually far from being exhausted by its representational qualities. It also stems from its use in relation with other models and their experimental targets: on the one hand, some models that had produced intriguing results and motivated its construction, and on the other hand, models that came later, constructed by using it as a basis. Before saying more about the constructive use of the model, I will give some elements of the background that motivated its own construction.

In contrast with other typical flow configurations, like the parallel flow between two planes, the flow in a cylinder or a jet, or the flow between two concentric cylinders, the wake is still regarded in many ways as a challenge. The reason is that, in addition to being an open system, this configuration adds the complication of the obstacle, with the loss of symmetry that this implies. This is also what makes possible its phenomenal prodigality: as the Reynolds number is increased beyond its critical value, the flow undergoes a series of bifurcations, as different forms of behavior become successively unstable, from laminar to fully turbulent state. It is not surprising then that the wake has become a popular experimental instrument to investigate the growth of different types of instability or scenarios of transition towards chaotic behavior.

It was only in the 80s, however, that scientists became able to characterize precisely the first and simplest bifurcation, that leads from a laminar flow around the cylinder to the periodic shedding of vortices. The critical moment was the formulation of a mathematical model of the growth of a perturbation in the vicinity of the critical value of the control parameter (Mathis et al. 1984). The model is known as the Stuart-Landau model (SL model):

$$dA/dt = (a_r + i a_i)\, A - (l_r + i l_i)\, |A|^2 A$$

This equation describes the evolution of the amplitude of a perturbation with the first term on the right representing the linear growth of the amplitude, and the second term representing the non-linear effects that progressively compensate the linear effects until a stable state is reached. From the model, one can derive, for the stabilized state, the value of the frequency of shedding of the vortices as a function of the Reynolds number, the control parameter.

Unfortunately, after a controversy of a few decades and conflicting experimental results, it was agreed that the frequency does not generally evolve with the Reynolds number as predicted by this model[16]. The reason of the discrepancy, it was suggested, is

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[16] Decisive for ending the controversy was the thoroughgoing experimental study of Chas Williamson (1989).

that the model is based on the presupposition that there is no dynamics along the axis of the cylinder. That is, it presupposes that the state of the flow is, at any moment, the same everywhere on the axis. Instead, there are some three-dimensional effects that propagate from the ends of the cylinder, even for very large cylinder aspect ratio (L/D). Because such a three-dimensional dynamics is suspected to play a crucial role regarding instabilities and chaotic behavior, it was seen as critical to be able to account for its development.

In order to account for these effects a new model was proposed with an additional term (Albarède and Provansal, 1995):

$$dA/dt = (a_r + i a_i) A - (l_r + i l_i) |A|^2 A + (\mu_r + \mu_i) dA/dz$$

This model is generally referred as the Ginzburg-Landau model (GL model) of the wake. When it was proposed, this model could give promising qualitative results but little quantitative predictions. In addition, as it could not be derived from Navier-Stokes equations, it was regarded by some as lacking theoretical justification and, finally, the physical interpretation of the term that was added was unclear. The uncertainty regarding its theoretical justification made a clarification of its physical content even more pressing. One way to interpret the new term is as a term of continuous coupling of oscillators along the axis. But how can the effect supposed to be represented be investigated? The investigation of the effect of a parameter normally proceeds through the controlled manipulation of this parameter. But how to vary the coupling parameter in this case? How to clarify the effect it has on the development of three-dimensional instabilities in the wake? How to assess its physical relevance?

These are some of the questions that motivated the process of model construction that will be presented[17]. The project was to construct what will look like a physical model of the mechanism of continuous coupling posited as explanation of the 3D dynamics observed along a long cylinder. Or maybe, more accurately, it was to construct a mechanistic model of the postulated continuous coupling: a model representing parts of

[17] For scientific publication of the case study see: (Legal et al. 1996) (Peschard and Legal 1996, 1999).

the system under study and aiming to account of the global evolution of the system in terms of the functioning of the parts[18]. The parts, here, would be individual fluid oscillators, placed next to one another so as to form a row, and the mechanism would be the discrete, variable coupling of these oscillators, measured by the distance between the oscillators. The spatial dimension along the row would serve as analog of the dimension along the axis of a long cylinder. And a theoretical model of this discrete physical system/model would make possible a systematic investigation of the effect of the coupling parameter and hopefully shed some light on the case of a continuous form of the coupling. As we will see later, it is actually not clear that we should speak of the discrete row as a mechanistic model of the long cylinder. The reason is that there are no individual, separable, oscillators along the cylinder that would be what the elements of the row represent. But let's focus for now on the construction of the row and its model.

4.2 Basis for construction

The first step was to construct the unit of the row and a model for it. The oscillator that would serve as a unit would be the wake created behind a cylinder. But this wake would have to be free of 3D dynamics since the idea is to generate this dynamics via the coupling of the oscillators. It had to be a 2D wake. An implication of the explanation of the 3D effects behind the long cylinder was that they could be avoided if the cylinder had a very small aspect ratio (L/D). And with no 3D effects, the original Stuart-Landau model should 'work'[19]. To use this model in such a configuration was then a preliminary test of this explanation. For the model to qualify as 'working', it has to enable successful inferences about its intended target (Suárez 2004, 2010). But in and by itself, what is then learnt is of little epistemic interest if any, especially compared to the multiple costs of realizing the experimental set-up. What makes it epistemically valuable points in two other directions. First, it is a contribution to a better identification of the condition in which the 3D effects do or do not occur and thereby to a better

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[18] For recent discussion of mechanistic approach in science see (Machamer et al. 2000).

[19] Obviously, what it means that the model 'works' depends on the precision needed in the predictions. In this case it was deemed sufficient to only keep the first non-linear term of the development.

understanding of the GL model. It is a use of models comparable to the use directed at the exploration of a theoretical framework (Bokulich 2003; Hartman 1999), but with the difference that it is not a theoretical framework that is illuminated but another representational model. Another important feature of this exploratory use of the model can be highlighted by a contrast with Morrison's example of Maxwell's use of a model of the ether to develop his theory, which model represented "a mechanical system of rotating vortices…[w]hile no one thought that the ether consisted of vortices" (Morrison 1999: 211). In the generative constructive use of models, the model used is representational in the sense explained in section 3 of being concrete, and therefore non-fictional. It is important because it is not actually the model alone that provides information about the GL model, but the model and its target taken together, as a whole: it is the fact that this model works in this specific configuration that is informative, rather than what the model says about this configuration.

The second source of epistemic significance points towards the future and again concerns the model and its target taken as a whole rather than the model alone. Once the model has been coordinated to its target by specifying and realizing the appropriate experimental conditions and determining the values of the quantities that, in the model, characterize these conditions, the model and its target can serve as basis for the construction of a discrete system of coupled wakes together with its own model.

Hans-Jörg Rheinberger writes that "sufficiently stabilized epistemic things turn into the technical repertoire of the experimental arrangement" (1997, 29). What was object of investigation becomes an object of manipulation, an instrument in a new experimental investigation. This is what would happen to the 2D wake that would serve as a unit for the construction of a system of coupled wakes.

But in addition, at the same time, the model of the 2D wake would become an object of manipulation and instrument for the construction of a new model, model of a system of coupled wakes. What forms an instrument for further investigation, what is built upon, is not the model or its experimental target alone, but the entity formed by the model coordinated to its target.

4.3 Construction

The next step was to construct an experimental set-up with two coupled wakes and once this new target was stabilized and coordinated to a model of two coupled wakes, to extend the experimental set-up to a row of wakes and build on the previous model to construct a model of the row. The intermediate step with two wakes was designed, on the one hand, to specify the coupling term in the model and, on the other hand, to explore and characterize, in the light of the prediction of the model, the state space of the target system.

Once again, it should be clear that the generative constructive use of models is not exclusive of other uses. In particular, the generation of inferences is an integral part of the process of construction. It is critical, in particular, in order to coordinate the model with its target, via the specification of the values of the coupling parameter. But the inferences themselves provide information about the state space described by the model rather than about the intended target system. Information about the target system needs to be obtained experimentally and confronted to the products of the inferences to determine the relevant values of the parameter.

It is true that once the relevant values of the parameter have been determined, and the model is thereby coordinated to the intended target system, two coupled wakes, it can function autonomously as a source of inferences about this target. The question is whether it is this capacity of the model that accounts for its epistemic value. This kind of capacity could be of great value to an engineer or someone interested in determining the state of target system in some particular conditions. But that is not what motivates the construction of the model here. Nor is it what motivates the construction of a model like the HKB model. Once the model functions as 'an answering machine', giving the state of the target system as an answer for a given set of initial conditions, it functions, according to Rheinberger, as a 'technical product'. And if it is true that "the realm of the technical is a prerequisite of scientific research… scientist are, first and foremost, bricoleurs (tinkerers)[20], not engineers" (1997, 32). The technical object is a prerequisite but, at least as far as experimental science is concerned, it is not necessarily the aim. This is why it

[20] Emphasis of the tinkering aspect of scientific activity can also be found in Pickering (1995), Rouse (1996), Galison (1997).

may be difficult to grasp the scientific significance of a model by merely focusing on the model and how it relates to its target. Because what we see then is the model as a technical object. Taken in coordination to its target, however, it also generates new questions and points towards its own transformation, extension, modification and that of its target. The question here is: what happens if instead of two wakes, there is a row of wakes?

On the basis of the model of two coupled wakes, the model of a row of coupled wakes took the following form:

$$d_t A_n(t) = \sigma A_n(t) - l|A_n(t)|^2 A_n(t) + g\,[A_{n+1}(t) + A_{n-1}(t) - 2A_n(t)]$$

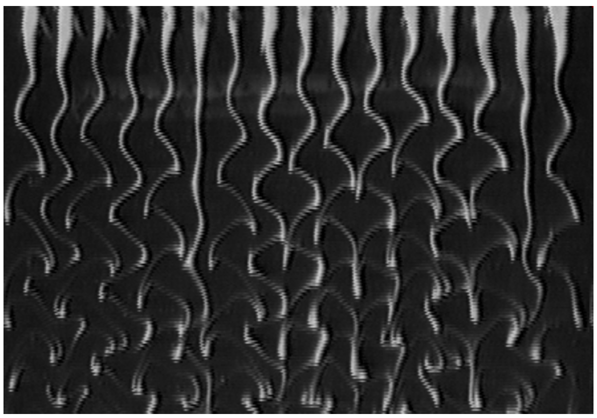

Figure 3: View from above of a row of wakes behind cylinders placed side-by-side in the direction perpendicular to the direction of the flow. The cylinders are on top of the photo. The fluid is flowing downwards.

The model represents the evolution of a system formed by a row of wakes coupled to the nearest neighbors. Because of the small aspect ratio of the cylinders, there is no dynamics along the axis of each cylinder. Each wake is a simple oscillator that can be represented by the SL model.

However the formation of the row of wake introduces a spatial dimension that is supposed to be an analog to the span-wise dimension (along the axis) of a long cylinder. The row of 2D wakes seems to function as a physical, discrete model for the process of continuous coupling of oscillators along the axis of a long cylinder.

As all models, it embodies approximation and idealization. One major idealization is, of course, in the discretization. Whereas the postulated mechanism in the long cylinder is a continuous row of coupled oscillators, the physical model is a discrete row of coupled oscillators (wakes). But the discretization is also, precisely, what makes possible the investigation of the coupling mechanism and its effects since it makes the coupling parameter a controllable parameter of the system. With the discrete row of wakes, the coupling is easily manipulated by modifying the distance between the cylinders.

Of course, as previously, the new experimental set-up needs to be coordinated to the discrete mathematical model. The coordination makes it possible, on the one hand, to distinguish and identify the different possible evolutions of the physical system, on the basis of the analysis of the model[21], and on the other hand, to specify the range of values of the coupling parameter for these different domains. Once the coordination is realized, it should be possible, by increasing the coupling between the wakes to see how it affects the dynamics of the system as a whole and, in particular, whether it generates the 3D effects observed in the case of a long cylinder.

Contrary to the previous models, this model of the rows was not used as a basis to construct a further system. In addition, systems of coupled oscillators are in themselves object of scientific importance simply because of their pervasive and still perplexing realizations in physics, biology, chemistry, ecology, or neurophysiology[22]. But here also, focusing solely on the relation between the model and its target misses a dimension of use of this model. It misses the function of the model-target unit, the discrete model in coordination with the discrete target, in the investigation of the dynamics that develops behind an infinite cylinder.

In particular, this function raises philosophically interesting questions regarding the epistemic relation between the discrete model and the continuous system. I said earlier that the physical row of cylinders looks like a mechanistic model of the infinite cylinder. So the discrete mathematical model would be a mathematical model of a physical model of the infinite cylinder. But is the discrete mathematical model a mathematical model of the infinite cylinder? A positive answer would raise some

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[21] The analysis must be realized here via simulation.

[22] See for instance Strogatz (2003)

questions about the relation between the discrete model and the continuous mathematical model, given that the discrete mathematical model contains different amplitudes for each of the wakes in the row whereas the continuous model only contains a global amplitude. It seems that these two models could not be coordinated to the same system and so cannot be both models of the wake behind the long cylinder.

Both the discrete physical system and the discrete model could be seen as a simulacrum intended to represent the global dynamics without being expected to be a realistic representation of the elements of the system[23]. And indeed, the discrete models, both the mathematical and the physical, do reproduce some crucial features of the global dynamics of the wake behind an infinite cylinder. But to take these discrete models in isolation is not the right way to understand how they are used. Instead, it is the discrete model in coordination with its discrete target, as forming a model-target unit, that contributes to clarifying the dynamics behind an infinite cylinder. In coordination with its target, the model can be used as a basis to develop more precisely the continuous model (GL model) of the wake behind the infinite cylinder. On this view, the discrete mathematical model does not function as a simulacrum. It is a discrete model of a discrete system with each element of the physical system being represented in the mathematical model and it is not regarded as a model of the continuous system[24]. This is not the place to discuss further these two perspectives on the use of this model. What is important is that the issue underscores the need, in order to understand how the model is used, for a perspective that goes beyond the way in which a model relates to its target.

As I said earlier, there are two other forms of constructive use of models that share several of the features that I attributed to the generative constructive use. In the light of the case study that was just presented, it is now possible to identify two central features that distinguish the generative constructive use. This is the task of the next section.

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[23] See Cartwright (1983) for the idea of models as simulacra.

[24] These two perspectives on the use of the discrete mathematical model to learn about the continuous physical system may reflect two different requirements on the epistemic function of the model: accuracy and correctness (Boumans 2005).

5. Generative constructive use

The construction of a model can be analyzed from two complementary standpoints: the elements that go into the construction, the final product of the construction. I have until now focused on the former, discussing specifically models as instrument of construction rather than product of construction. It is clear however that with respect to the models constructed, the discussion echoes previous works showing models to be the result of a construction rather than a derivation from theories. For instance, the construction of the GL model drew on results from disciplines other than fluids mechanics and the determination of the form of the coupling term in the model of two wakes drew on experimental studies made with electro-dynamical oscillators. In addition, the interpretation of the dynamics of the wakes involved the theory of dynamical system and techniques in non-linear analysis of stability in addition to theoretical principles in fluid dynamics.

But works focusing on the model as a product can, in turn, themselves be relevant to the discussion of models as elements of construction. I will consider two such studies and use them to highlight two distinctive features of the generative constructive use of models.

The first study is the detailed analysis of the construction of the London model of superconductivity by Suárez & Cartwright (2008). The authors offer an argument against the idea of models being contained within or derived from a theory by showing that some crucial elements of the construction were not provided by the theory. From the standpoint of the model used in the construction, what we need to focus on, however, is the model that is used as a starting point. Like the models that enter in the generative constructive use, this model is not fictional and is not abstract (in the sense distinguished from concrete representational in section 3). It has a target to which it can be coordinated. The coordination, in fact, reveals some failures of the model, that motivate the construction of a new model: it could not account for what is known as the Meissner effect, characterizing superconducting material. The use of this model is similar to the generative constructive use in that the transformation of the model results in a new model, which is as representational as the original one, the London brother' model. The difference between this constructive use and the generative constructive use is not to be found in the examination of the model alone and what is 'done' to the model. What we need to examine is the model in coordination to its target and how this unit transformed the space of modeling activities. But in this case it was not the model-target unit that is used to produce the new model, the London model. The reason is that the initial coordination was not deemed successful in the first place. The use of the original model in this example does not produce or aim to produce a new model coordinated to a *new* target; it aims to produce a new, better, model for the *same* target, a new model that will replace the original one. The use of the original model to produce a new model is not a case where this use makes the model that is used epistemically, scientifically significant. It rather makes it insignificant since it is a case where the model 'used' simply disappears from the scientific stage. This is not the case with the generative constructive use. Here, the construction does not aim at a model that will replace the model used in the construction because the model used and the model produced have *different targets*.

The second type of use that I want to compare to the generative constructive use is offered by Boumans (1999) who gives a striking illustration of the diversity of the elements that may go into the construction of a model: theoretical principles, mathematical techniques, metaphor, analogies and empirical data that need to be accounted for by the model under construction.

Whereas Suárez and Cartwright were particularly concerned with the relation between theory and models, the two main points Boumans makes in addition are that 1) there is no general recipe for the construction of models and 2) when the model is constructed so as to account for empirical data, some empirical justification is built-in through the process of construction itself, hence blurring the distinction between procedure of discovery and procedure of justification. Similarly in the case study presented above some justification was built-in in the construction of the discrete model of coupled wakes. That was done by using models of single wakes and a representation of the coupling that were already justified. But what is of special interest for our purpose, in

Boumans' study, is that among the different ingredients of the construction, one finds models. Models used in the construction function as modules in a more complex model.[25]

For instance, in Michal Kalecki's model, Boumans distinguishes four equations describing the relations between different quantities characterizing the economic system. Each of these equations can be seen as describing a sub-process of the macrodynamics so that the model of the economic system as a whole is obtained by coupling several models representing sub-processes, like the relation between the volume of investment orders and the volume of existing industrial equipment. It is clear that these sub-models are used in the construction of a model and that the models used and the model constructed do not have the same target. In addition, even though the sub-models have their own representational content, it seems that an essential part of their epistemic significance comes from their constructive use. But here are what I see as two crucial differences between this use and the generative constructive use. In the use of models as modules, the success of the construction does not necessarily depend on how well coordinated to its target the model used in the construction is. The modules may even be regarded as black boxes: they have to produce the result that is appropriate for an appropriate functioning of the model constructed, which in turn depends on the intended function of this model.

In addition, even though, like in the generative constructive use, the module and the complex model it is part of have different targets, the module and its target, taken as a unit, does not seem to have the autonomy found in the generative constructive use. This autonomy was visible in the way in which the target of the original model suggested a new target, whether through its own extension or transformation, like in the case of the wake, or by analogy, like in the case of the HKB model used for linguistic coupling. The coordination between the original target and its model then suggests a parallel procedure of extension, transformation or analogy for the construction of a model of the new target. By contrast, a model used as module is one of the diverse ingredients that go into the

[25] Such a case of construction also finds a nice illustration also in the recent technique of construction of models of climate system by coupling models of the different elements of the system (Küppers and Lenhard 2006).

construction of the new model; the model is recruited in the construction but does not seem to serve as a *basis* for the construction. Similarly, the target of the original model becomes an element of the target of the constructed model but this is the result of an analysis of the complex system into parts rather than the result of a transformation or extension of the original target.

6. Conclusion

Models can be used to construct other models. It is the constructive use of models. This paper focused, more specifically, on one form of constructive use: the generative constructive use. Models used this way are representational and their target system is a real system. In coordination to their target, they form the basis for the construction of new representational models and the generation of new target systems. As such, even though the models are representational, they are not used to represent. Rather, they are used in the development of new forms of investigation through the development of new models and targets and play a crucial role in the transformation of a domain of investigation. This role was illustrated, briefly, with the HKB model in coordination dynamics and, in greater detail, with the model of a wake in fluid dynamics.

This way of using representational models has not received the attention it deserves in philosophical literature on scientific modeling, by contrast to the constructive use of fictional or of abstract models. The suspected reason for this lack of attention is an excessive concern, regarding representational models, for representation, and exclusive focus on the relation between the model and its target. Constructive use of models can only be apprehended from a larger perspective that includes the models they are used to produce. And the reason why an account is philosophically important is that this use makes an essential contribution to the scientific significance of these models.

The generative constructive use was distinguished from two other forms of constructive use of representational models and two distinctive features were identified. First, the target of the model constructed is different from that of the model that is used. In addition, the target of the new model is the result of an extension or transformation of the original target. These two features account for the generative character of this constructive use: generative of new targets of new models. Finally they show that the relevant unit of use is not so much the model alone as the model in coordination with its target, which is another way of saying that the use of the model is not to represent, is not directed at its target, but directed at other models in coordination with their own targets.

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