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INTERDISCIPLINARITY THROUGH MODELLING

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1. Introduction

Over the last few decades, research organizations such as the National Academy of Sciences (2005) have emphasized the importance of interdisciplinary research and education (see also Tuana 2013). Research policymakers often acknowledge that interdisciplinary research is challenging for numerous reasons, such as the organization and funding of research, political obstacles, the complexity of interdisciplinary research, and the difficulty of communication within a multidisciplinary team (see Jacobs and Frickel 2009 for a critical evaluation). However, hardly any attention has been paid to the epistemological, methodological, and conceptual barriers and cognitive constraints of working across disciplinary domains (MacLeod 2018). In the philosophy of science, Nancy Nersessian, Miles MacLeod, Uskali Maki, and Michiru Nagatsu have done pioneering work in studying the strategies (esp. modeling strategies) of researchers in interdisciplinary scientific practices.

Thus, while the philosophy of science initially focused on questions of the nature, ontology, and representational properties of models, analyses of research into complex problems include the cognitive, epistemological, methodological, and pragmatic aspects related to modelers and model-users. Analyzing the cognitive complexity of modeling complex problems thereby offers new insights into the nature of models and modeling practices. When focusing on the nature of the intellectual work researchers accomplish through building and using models, cognitive processes becomes an inherent part of these studies, introducing new notions, such as *model-based understanding*, *model-based reasoning*, *model-based explanation*, *modeling strategies*, *mental models*,[1] and *models as cognitive artifacts* (Nersessian 2009; 2022, see also Magnani and Bertolotti 2017; Mattila 2005; O'Malley and Soyer 2012; MacLeod 2018). By including cognitive processes in philosophical analyses of models and modeling practices, other notions that emerge are: *inferential reasoning*, *model-users* and *competent cognitive agents* (Suárez 2004; Giere 2010);[2] *epistemological responsibility* (Van Baalen and Boon 2015); *epistemology of models and modeling* (Boon and Van Baalen 2019); and *researchers having disciplinary perspectives* (Boon 2020b). Additionally, this turn of focus provides crucial insights for *education* in interdisciplinary research (e.g., Boon 2020a; Boon et al. 2022; Nersessian 2022; Van den Beemt et al. 2020) and modeling

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strategies in *science-based policy* (e.g., MacLeod 2018; MacLeod and Nagatsu 2018; Nagatsu and Ruzzene 2019; Nagatsu et al. 2020; Frisch 2013; Inkpen and DesRoches 2020). Furthermore, when the *epistemic usefulness* of models in practical applications such as science-based policy is taken into account, where models are considered *epistemic tools* (Boon and Knuuttila 2009; Knuutila and Boon 2011) for problem-analysis, forecasting, and scenario studies, still other features of modeling become prominent, which have implications for philosophical views on models, in particular regarding their representational characteristics. For example, Elliot and McKaughan (2014) argue that scientific representations should also be evaluated on their suitability for the practical and epistemic purposes of model users, which requires including non-epistemic values. Similarly, in the context of climate modeling, Parker (2020) proposes an adequacy-for-purpose view on models. Studying interdisciplinary research practices thus leads to new themes and research questions for the philosophy of science (see Mäki 2016).

The topic of this chapter – interdisciplinarity through modeling in research, science-based policy, and education – connects two subjects that are often treated separately within the philosophy of science: interdisciplinarity and models. Section 2 addresses the why, what, and how of interdisciplinary research, and the role of models and modeling therein. To this end, scholarly, policy-related, and philosophical literature on interdisciplinary research has been surveyed. Section 3 discusses accounts of models and modeling strategies and provides an outline of epistemological and methodological issues of interdisciplinary research practices. Use is made of both scientific literature on methodologies in interdisciplinary research and philosophy of science literature on the role of models in this. Section 4 concludes with a brief overview of issues to be addressed in a *philosophy for interdisciplinary modeling practices*.

2. Interdisciplinarity

2.1 Definition of interdisciplinary research

Interdisciplinarity is studied in scholarly domains ranging from science policy studies, governance studies, STS (science, technology, and society), science education, cognitive sciences, philosophy of science, and social epistemology. One of the scholarly aims is a correct *definition* (e.g., Klein 1990; Aboelela et al. 2007; Repko 2008; Newell and Gagnon 2013). Three characteristics are usually found in definitions of interdisciplinary research: (I) the *rationale* for interdisciplinary research is solving a problem, or addressing a topic that is *too broad or complex* to be dealt with adequately by a single discipline or profession (cf. Newell and Gagnon 2013); (II) the *epistemic purpose* of interdisciplinary research is (a) to advance *fundamental understanding* of a phenomenon, or (b) to develop knowledge and understanding for *solving* (*complex*) *problems*; and (III) the crucial role of *integration* of (a) *knowledge* (or, more broadly, epistemic resources such as data, concepts, laws, and theories), (b) *instruments* (including methods and technologies), or even (c) *disciplinary perspectives*.[3] An example is the oft-cited definition by *The National Academy of Science* (2005): “Interdisciplinary research (IDR) is a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice” (National Academy of Science et al. 2005, 2).

2.2 Interdisciplinarity in scientific research, higher education, and science-based policy

Research policy documents from leading organizations, institutes, and research councils emphasize the critical importance of interdisciplinary research (e.g., NSF, NRC, NAS, ESF, ERC,[4] GRC,[5] NWO, Van Noorden 2015). Three arguments are often made in favor of interdisciplinary research (Rylance 2015). First, the grand challenges facing society – energy, water, climate, food, health – are not amenable to single-discipline investigation; they often require many types of expertise across the biological, physical, and social disciplines (see also Frodeman 2016; De Grandis and Efstathiou 2016; Nagatsu et al. 2020). Second, discoveries are said to be more likely on the boundaries between fields, where the latest techniques, perspectives, and insights can reorient or increase knowledge. Third encounters with others benefit single disciplines, extending their horizons. Moreover, the proliferation of disciplines in the twentieth century increasingly calls for bridging them and transcending the scope of single disciplines on complex problems, i.e., for interdisciplinary research (e.g., Allwood et al. 2020).

Similarly, higher education policy documents assume that interdisciplinarity is increasingly becoming the hallmark of contemporary knowledge production and professional life (Mansilla 2005).[6] Graduate students and their training programs are recognized as essential to increasing interdisciplinary research capacity (Borrego and Newswander 2010; Spelt et al. 2009; Tripp and Shortlidge 2019; Nersessian 2022). An example of this move towards interdisciplinary research and education is an AAAS vision report (2009)[7] on developments in biology research and education that are becoming increasingly interdisciplinary. However, scientific research into teaching and learning in interdisciplinary higher education, for example regarding necessary research and thinking skills, is still limited and exploratory (Spelt et al. 2009; Van den Beemt 2020; Boon et al. 2022).

Additionally, there is a strong interest in promoting and funding collaboration between scientific disciplines to support science-based policy. For example, between ecologists, economists, sociologists, civil engineers, and atmospheric scientists working on an integrated understanding of environmental problems in which social, economic, ecological, and climate systems are causally intertwined (MacLeod and Nagatsu 2018; see also Inkpen et al. 2020), or on assessment models that assist in climate policies (e.g., Frisch 2013; Goodwin 2015; Parker 2018). Similar examples are the interdisciplinary modeling of an ecosystem management approach to marine social-ecological systems (Starfield and Jarre 2011; see also Levontin et al. 2011; Niinimäki et al. 2012; Kelly et al. 2013; Strasser et al. 2014; Ni et al. 2020). Other examples of the importance of interdisciplinary research to policy and management are chronic disease management (e.g., Bardhan et al. 2020) and the policy and management of risk (e.g., Zinn and Taylor-Gooby 2006).[8]

2.3 Cognitive and epistemological challenges of interdisciplinary research

Interdisciplinarity scholars also propose models of the interdisciplinary research process (e.g., Klein 1990; Repko 2008; Menken and Keestra 2016; Repko and Szostak 2017) drawing on literature in cognitive science and social psychology. These authors assume *integration* (of the research question, theoretical frameworks, method, results, and conclusions) as a crucial aspect of interdisciplinary research. They recommend step-by-step research processes that closely resemble common models of research processes, with the addition that *finding or creating common ground* is recommended as a way to achieve *integration* *between disciplines*. This approach thus relies heavily on communication between the disciplines but disregards the fundamental cognitive and epistemological challenges of communication and integration between disciplines (cf. MacLeod 2018). Integration (or connecting, or fitting together) of epistemic resources and methodologies from different disciplines is challenging because they are embedded in a tightly-knit network of scientific concepts, theories, fundamental principles, epistemic and pragmatic values, as well as techniques, procedures, routines, and modeling strategies that form the discipline, to the effect that disciplines or their content cannot be put together in a straightforward manner (Boon 2020b; Nersessian 2022). Moreover, the mentioned scholarly studies do not assign an explicit role to models and modeling in achieving integration between disciplines, while modeling is standard practice in existing interdisciplinary research. So, despite scholarly studies to create strategies and plans for doing interdisciplinary research, there is still a lack of proper articulation and testing of interdisciplinary research approaches (cf. Nagatsu et al. 2020, 1810; see also Grüne-Yanoff 2016; Mäki 2016).

2.4 Interdisciplinary research in practice

Scientific disciplines are not closed silos but develop, among other things, through the transfer and implementation of aspects from other disciplines. Grüne-Yanoff and Mäki (2014) provide a systematic overview of types of exchanges between disciplines. Elaborate examples of such exchanges are described in the ethnographic studies conducted by Nersessian (2009; 2022), MacLeod (2016), MacLeod and Nersessian (2013; 2015; 2016; 2018), and MacLeod and Nagatsu (2016). Exchange includes elements such as: knowledge about specific phenomena; experimental methods to create and investigate phenomena; measurement equipment and techniques; scientific concepts (e.g., 'conservation principles,' 'operations,' 'mechanisms,' 'energy,' 'equilibrium,' 'dynamics,' 'threshold,' 'saturation,' 'buffer,' 'reversibility,' 'hysteresis,' 'evolution,' 'ecology,' 'ecosystem'); mathematical and statistical methods to find structure in data and establish meaningful, quantifiable phenomena or patterns in data; mathematical templates (Humphreys 2019); model templates (e.g., Knuuttila and Loettgers 2016; Houkes and Zwart 2019); computer simulation methods to estimate unknown parameters or to link different types of models and study the dynamics of a system; the combination of different types of (quantitative and qualitative) research methods into mixed methods that expand research designs; and modeling strategies (e.g., from engineering sciences to molecular or systems biology).[9] Section 3 explains that these types of (heterogeneous) elements (exchanged between disciplines) are built into scientific models (Boumans 1999; Boon and Knuuttila 2009; Knuutila and Boon 2011). Interdisciplinarity is thus achieved through modeling, whereby integration of the mentioned elements takes place in modeling (i.e., models as integrators) and the resulting models become epistemic tools. As a result of these dynamics between research practices, some of these aspects are no longer discipline-specific but are shared cross-disciplinarily and embedded in multiple disciplines.

New disciplines emerge when researchers collaborate on problems or systems that are considered to consist of *causally interacting sub-systems* investigated in distinct disciplines. The sub-systems and their interactions are often investigated in experimental models and represented and interconnected by means of conceptual models, mathematical models, computer simulations (Nersessian 2022), and diagrammatic models (Boon 2008). Traditional examples are specialized disciplines in the engineering, agricultural, and biomedical sciences (e.g., Nerssessian and Patton 2009; Nersessian 2009; 2022). More recent examples are nuclear physics, systems biology (Coveney and Fowler 2005; O'Malley and Soyer 2012; Green 2013; MacLeod and Nerssessian 2013; 2015; 2016; 2018), neurosciences (e.g., Fagan 2017), computer sciences, geo- and climate sciences (e.g., Parker 2018; MacLeod and Nagatsu 2018). Interdisciplinary research, therefore, does not always take place through *integration* in the sense of the aforementioned definition of interdisciplinary research (cf. Grüne-Yanoff 2016) but is often a matter of cross-fertilization through transfer and exchange between disciplines.

A major motivation for promoting interdisciplinary research is to contribute to problems or opportunities outside science, such as those addressed in so-called applied sciences (the engineering, agricultural and biomedical sciences), and more generally, "real-world" problems related to new industrial opportunities, complex policy issues in society, and the UNESCO's sustainability goals. In these application contexts, interdisciplinary research projects usually focus on developing technologies,[10] computer simulations, scenario designs, and other types of tools for epistemic purposes, such as measurement, diagnosis, exploration, forecasting, and scenario investigation.

The distinction between interdisciplinary research within academic disciplines focused on *true knowledge about (fundamental) aspects of the world* versus interdisciplinary research focused on *actionable epistemic tools that make it possible to address real-world problems* (e.g., in science-based policy contexts) implies different epistemic and pragmatic criteria for research quality (cf. Elliot and McKaughan 2014; Brister 2016; De Grandis and Efstathiou 2016; Parker 2020),[11,12] as well as epistemologies, methodologies, and modeling strategies to meet these various criteria.

3. Models and modeling in interdisciplinary research practices

3.1 Models as integrators

In research practices, models and modeling are standard practices to achieve integration. Boumans' (1999) study on business cycles in the seminal collection *Models as Mediators* (Morrison and Morgan 1999) shows that models are *constructed by integrating many heterogeneous "ingredients,"* such as analogies, metaphors, theoretical notions, mathematical concepts, mathematical techniques, stylized facts, empirical data and finally relevant policy views, whereby the correctness of the resulting scientific model is partly justified by the scientifically sound choices researchers make in the modeling process. This approach to modeling in scientific practices is also studied by ethnographic studies. For example, Nersessian and Patton (2009), have studied biomedical engineering laboratories and argue that mental, physical, and computer models function as hubs that enable the integration ("interlocking") of biological and engineering concepts, methods, and materials. These models, in turn, are mental and external representations that enable model-based inferences that support research and learning about the system (see also Nersessian 2022).

In this view, modeling thus plays a role in integration processes, with *models as integrators* of not only the "ingredients" mentioned by Boumans, but also, as will be illustrated below with examples from practice, of sub-models that represent sub-systems within interdisciplinary research.

3.2 How the construction of scientific models facilitates interdisciplinary research

This process towards philosophical accounts of models and modeling that includes the cognitive, epistemological, methodological, and pragmatic aspects related to modelers and model-users in research practices, is further elaborated by Boon and Knuuttila (2009; see also Knuuttila and Boon 2011), who propose considering *models as epistemic tools*. They thereby build on Knuuttila's (2005) notion of models as *epistemic artefacts*, which explicitly deviates from the idea that our understanding of modeling should be reduced to models representing some external target systems – for models are not only representative artefacts, but also productive artefacts in, for example, model-based reasoning about the target system. Boon (2020a) elaborates on how models are constructed, namely by determining the heterogeneous "ingredients" that are usually built into the model (cf. Boumans 1999). Boon (2020b) provides further epistemological substantiation for this account, which also emphasizes the choices that researchers have to make in the construction of a model. Researchers can be held accountable for these choices, which is captured by the concept of *epistemological responsibility* (cf. Van Baalen and Boon 2015). Additionally, scientific models are *justified* and tested in at least three ways that complement each other, namely: (i) by justifying the relevance, physical plausibility, and adequacy of aspects built into the model; (ii) by assessing whether the model meets relevant epistemic and pragmatic criteria; and (iii) by empirical or experimental testing against reality, e.g., by comparing *model-outcomes* and experimental results (cf. Boon 2020b).

But the construction of models is also determined by "the specificities of a discipline," each with its own concepts and specific modeling strategies, which makes interdisciplinary collaboration (including integration and transfer between disciplines) difficult (cf. MacLeod 2018). Boon and Van Baalen (2019) and Boon (2020b) analyse this problem of interdisciplinary research in terms of *disciplinary perspectives* and argue that these are not necessarily opaque. Instead, disciplinary perspectives should be made explicit and explained in interdisciplinary research projects. Based on Kuhn's notion of disciplinary matrices and the aforementioned epistemology of model construction, they develop a framework for analyzing disciplinary perspectives that can be used by individual researchers (recognizing that researchers may have slightly different perspectives even within a discipline), which facilitates interdisciplinary understanding and communication.

On a more fine-grained practical level, model construction in interdisciplinary research involves a broad spectrum of *modeling strategies*, which raise additional epistemological, methodological, and ethical issues, for example:

- How to connect models from different disciplines, for which researchers use the notion of *coupling* (e.g., Coveney and Fowler 2005; Kremling and Saez-Rodriguez 2007; MacLeod and Nersessian 2013; MacLeod and Nagatsu 2016).
- How to deal with connecting models of dynamic physically related systems at *different time – and length-scales* as in: systems biology (e.g., Coveney and Fowler 2005; Kremling and Saez-Rodriguez 2007; MacLeod and Nersessian 2015; 2016); integrated assessment of agricultural production systems (Antle and Stoorvogel 2006); or integrated environmental assessment and management (Kelly et al. 2013).
- How to connect models of different kinds in the natural and engineering sciences, such as mechanistic and mathematical models, for which *diagrammatic models* are proposed (cf. Boon 2008).

- How to connect models from the natural sciences (broadly interpreted as sciences that concern natural and physical processes) and social sciences, e.g., in climate modeling to support policy decisions, for which *integrated assessment models* are proposed (e.g., Frisch 2013; also see Strasser et al. 2014; Parker 2006; 2011).
- How to assess the *reliability* of (*complex multiscale*) models that result from interdisciplinary research as in climate models (e.g., Goodwin 2015; Parker 2006).
- How to deal with the *uncertainty* of (e.g., complex multiscale) models and their predictions that result from interdisciplinary research as in climate models (e.g., Parker 2011).
- How to achieve an integrated treatment of complex societal issues, e.g., by integrating stakeholders, models of dynamic processes, different scales, and societal considerations into *integrated environmental assessment models* for management decisions under uncertainty (cf. Kelly et al. 2013; see also Strasser et al. 2014; Inkpen et al. 2020).

3.3 Modeling strategies in interdisciplinary research practices

Practicing researchers have developed several modeling and integration strategies to address the issues mentioned. This is illustrated with a number of examples, ranging from modeling in systems biology to models that support the management of complex systems.

Kremling and Saez-Rodriguez (2007) propose an engineering approach to *systems biology*, for which they adopt a *modeling framework based on network theory*. Network theory considers all processes a connection of *components* and *coupling elements*. Components represent physical quantities like energy, mass, (bio)chemical substances, or momentum. That is, the time- and location-dependent amounts of these components in the physical system are (conceptually and mathematically) represented as time- and location-dependent variables in the model while coupling elements describe the physical fluxes of components. In other words, the physical amount of components flowing into or out of a location is (conceptually and mathematically) represented as changes in the time- and location-dependent variable values in the model. Additionally, components and coupling elements can be defined on different *hierarchical modeling levels*, which enable the aggregation of systems of components and coupling elements into a single component on a higher level.

Similarly, Coveney and Fowler (2005) explain, “from the perspective of a physicist,” the role of *multiscale models* in connecting models of systems at different time- and length-scales. Their case study also resides in systems biology. Their ultimate epistemic goal is to construct a *whole-organ heart model* (for example, to study the dynamics of the heart or circadian rhythms), by coupling models that represent processes at the molecular and cellular scale. Hence, (conceptual and mathematical) models of processes at the molecular biological level must be connected (i.e., integrated) with models of processes at the cellular level, in order to represent (conceptually and mathematically) interactions between dynamical systems that are physically related. One of the challenges they aim to solve by the coupled multiscale approach is to account for the role of feedback, i.e., to build into the model changes on the larger length-scale that affect behavior at the smaller length-scale.

Antle and Stoorvogel (2006) study vulnerable *agricultural* (or, agro-eco) *production systems*. They view these as complex and dynamic systems that result from interacting physical, biological, and human decision-making processes and many internal feedbacks. Their goal is a *computer simulation model* of the system describing the interacting bio-physical and economic decision-making subsystems on compatible spatial and temporal scales. Their modeling strategy is a *modular model-coupling* approach, in which models of subsystems are coupled by using a subset of (spatially and temporally varying) state variables from one subsystem as inputs into another subsystem. According to these authors, advantages to the modular approach are that the disciplines involved develop (modular) models of subsystems, which, when coupled, are kept in their original (perhaps simplified) form. This warrants the transparency of models and makes it easier for researchers to build and test the models. In a case study of a vulnerable agricultural system, they illustrate the importance of a *modular model-coupling* approach that includes the dynamics and spatial heterogeneity in the analysis of the agro-eco behavior of the production system. For example, the economic problem facing farmers is deciding which crop to grow. This is where the computer simulation of the agricultural system in their area can assist by showing the long-term impacts, such as soil depth falling below a critical threshold due to erosion, which can be prevented if farmers opt for crop rotation.

Ni et al. (2020) developed a hybrid model aimed at an *accurate and reliable forecasting model* for water resource planning and management. Their *hybrid model* is based on the *principle of modular modelling*, in which a complex problem is divided into more simple sub-models. The epistemic and pragmatic purpose of these types of models is accurate and reliable streamflow (low and high) forecasting to provide information for water resource management and timely warning of natural disasters, such as droughts and floods.

Levontin et al. (2011) use *Bayesian belief networks* (BBN) to integrate the findings of separate biological, economic, and sociological studies, to be used as a decision-support tool for the interdisciplinary evaluation of potential Baltic salmon management plans. Their epistemic and pragmatic aim is to evaluate the robustness of management decisions to different priorities and various sources of uncertainty. The BBN can thus be considered a model constructed as an epistemic tool to represent interactions and responses to policy decisions.

Kelly et al. (2013) present a comprehensive review of five common modeling approaches in environmental sciences that have the capacity to integrate knowledge – that is, modeling approaches that can accommodate multiple issues, values, scales (e.g., time- and length-scales) and uncertainty considerations, as well as facilitate stakeholder engagement. These modeling approaches are *systems dynamics*, *Bayesian networks*, *coupled component models*, *agent-based models,* and *knowledge-based models* (as in expert systems). Additionally, Kelly et al. use their analysis to develop a framework to help modelers and model-users select an appropriate modeling approach for their integrated environmental assessment and management applications and enable more effective learning in interdisciplinary settings.

Starfield and Jarre (2011) propose a set of recommendations for conducting interdisciplinary research – which in their case focuses on *interdisciplinary modeling for an ecosystem approach to management in marine social-ecological systems* – emphasizing that "Interdisciplinary work needs to be constrained by clear system objectives. The emphasis is on the word 'system' because it is a mistake to define objectives from the viewpoint of the disciplines themselves. …. It is essential to use a modeling paradigm that focuses on objectives and leads to a balanced contribution from each discipline" (Starfield and Jarre 2011, 217–218). They consider *frame-based modeling* suitable as a modeling paradigm for addressing long-term changes in social-ecological systems. Notably, the emphatic premise of letting the overarching epistemic and pragmatic goal take precedence (rather than the epistemic goals of the disciplines) may conflict with "the advantages of the *modular model-coupling* approach" recommended by Antle and Stoorvogel (2006).

Strasser et al. (2014) develop a *coupled component model* to facilitate an integrative assessment of the impact of climate change on snow conditions and skiing tourism in a typical Austrian ski resort. They use this as a case study for the design of *interface tools* to enable the integration between disciplinary sub-models. Importantly, their focus on interfaces to enable integration of quantitative and qualitative knowledge– that is, values, from relevant natural and social science disciplines-such as *variables* from climate and weather sciences, and *indicators* and *threshold values* from economy and ecology. These interface tools were jointly developed by scientists (in climate, snow hydrology, economy, and tourism) and the decision-makers responsible for the skiing industry and regional tourism development. The authors emphasize that "the joint model development and interface design are core elements of integration, and can be regarded as a mutual learning and negotiation process where understanding continuously develop" (Strasser et al. 2014, 186; see also Antle and Stoorvogel 2006, Kelly et al. 2013). Similarly, De Sandes-Guimarães et al. (2022) argue that for this type of problem, policymakers should take part in the interdisciplinary research project, thus making it a process of *knowledge coproduction* aimed at supporting policy decisions for complex problems (see also De Grandis and Efstathiou 2016).

3.4 Philosophical accounts of modeling practices in interdisciplinary research

These kinds of examples from interdisciplinary research practices are analyzed by philosophers of science to uncover epistemological, methodological, and ethical aspects of interdisciplinary scientific research (cf. Mäki 2016). The practice examples show that the same concepts are used to characterize the nature of a target-system across a wide range of scientific disciplines, such as: "complex systems," "dynamical systems," "sub-systems," "physically (or otherwise causally) related processes," "feedbacks," "processes at different time- and length-scales," and "variables." The same applies to the concepts used by researchers in different research areas to describe modeling strategies, such as "integration," "modularity," "model coupling," "coupled-component models," "multi-scale modeling," "hierarchical modeling," "hybrid modeling," "networks," "systems dynamics," and "interfaces between models." In the scientific literature, these concepts are used to explain interdisciplinary research strategies and methodologies.

Philosophical analyses of existing scientific research practices show that scientific researchers in a wide range of scientific disciplines generally follow the same strategy when developing *conceptual models* (cf. Boon 2020a; also see MacLeod and Nersessian 2013; Nersessian 2022). The similarity of research strategies enables integration between disciplines (Boon 2020b). An example is the way researchers develop an integrated model of a more complex system, by representing the system as (causal) interactions between relevant (often dynamic) processes or subsystems (typically represented in space-time diagrams, cf. Boon 2008). Usually, each of those subsystems is the subject of a separate scientific discipline. In this strategy, the relevant (discipline-specific) measurable and calculable *variables and parameters* are determined for each subsystem. Based on this, a *mathematical sub-model* can be constructed for each subsystem. Integration then takes place by constructing a mathematical model that connects the mathematical sub-models via the time- and space-dependent variables (also called state variables), namely as input and output variables between the sub-models. Finally, these mathematical models form the basis for the construction of *computer simulation models*.

These examples also show that models across a wide range of complex systems are usually aimed at a specific epistemic purpose, e.g., the closer study of the system in terms of its dynamic behavior, the effects of interventions, and the determination of unknown parameter values (e.g., through computer simulations), or as an aid in policy decisions using the model in scenario studies or forecasting (e.g. Kelly et al. 2013; Ni et al. 2020). Altogether, this implies that models created in the specific research contexts can be interpreted as *epistemic artifacts* and *tools* built for use by researchers and other stakeholders in understanding, handling, or intervening with complex systems (cf. Knuuttila 2005; see also Parker 2020; Nersessian 2022).

It is worth mentioning separately that some modeling strategies also aim at incorporating social, economic, and sustainability values (cf. Elliott and McKaughan 2014; Parker 2020) and mapping the vulnerability of the dynamic system in relation to them, which is built into the model, for example, via threshold values (e.g., Strasser et al. 2014). These practice examples, therefore, illustrate how models can simultaneously play a role in exploring the ethical implications of (postponing) interventions in or (lack of) decisions about a complex system.

In ethnographic studies, philosophers stay close to first aiming at a rich and detailed description of these practices and making explicit salient features. Ethnographic methods have thus been used (cf. Nersessian and MacLeod 2022; Nersessian and Patton 2009; MacLeod 2016; Nersessian 2009; 2022; MacLeod and Nersessian 2013; 2015; 2016; 2018; MacLeod and Nagatsu 2016) to make *modeling strategies* in concrete interdisciplinary research practices explicit and to analyze critically their epistemological approach, inventions, and quality (e.g., Mattila 2005; Parker 2006; 2011; Nersessian and Patton 2009; Grüne-Yanoff 2016; MacLeod 2018; MacLeod and Nagatsu 2016; 2018; Nagatsu et al. 2020; Inkpen and DesRoches 2020; Nersessian 2022). Some examples are:

Green's (2013) analysis of modeling practices by a case study on network modeling in systems biology, shows that engineering approaches are applied to the study of biological systems. Based on this case study, she argues that *the use of engineering principles* affords a conceptualization of biological functions in language from control- and graph theory, which can open a *new epistemic space for understanding biological function*.

MacLeod and Nagatsu's (2016) ethnographic study of the collaboration of economists and ecologists in the resource economy aims to analyze the role of *model-building frameworks and strategies* that can play a role in overcoming the inherent difficulties of interdisciplinary research. They distill various features of how models are put together and show how a *coupled-model framework* is used to coordinate and combine background models from ecology and economics.

Nersessian's (2022) book-long study analyses research on the epistemic practices of interdisciplinary research in laboratories of biomedical engineering (BME) and integrative systems biology (ISB). She argues that interdisciplinary modeling in BME uses *engineering design methods and principles* to *understand basic biological phenomena* in order to control disease processes or create interventions for specific medical disorders. ISB aims at an *integrative analysis* of the behavior of complex *(nonlinear) biological systems at all levels*, from intracellular interactions to ecosystem processes, to investigate *how higher-level functionality emerges* from myriad interactions at lower levels. To this end, ISB modeling practices *integrate* computation, applied mathematics, engineering concepts and methods, and biological experimentation (see also MacLeod and Nersessian 2016).

In addition to ethnographic studies that provide rich and detailed descriptions of interdisciplinary modeling practices, philosophers also aim at targeting epistemological and ethical aspects. Some examples are: Elliott and McKaughan (2014) on the role of *non-epistemic values*, Andersen and Wagenknecht (2013) on the role of *epistemic dependence and trust* in interdisciplinary research, Andersen (2016) on the tension between interdisciplinarity and *quality control*, and MacLeod and Nagatsu (2018) who propose *categorizing* four different integrative modeling strategies. Green (2013) argues that the use of *multiple representational means* is an essential part of the dynamic of knowledge generation because the diversity of constraints of different interlocking epistemic means creates a *potential for knowledge production*. Parker (2006) shows how *incompatible climate models* are used together in *multi-model ensembles* and explains why this practice is *reasonable*, given scientists' inability to identify a "best" model for predicting the future climate. Finally, Frisch (2013) argues that integrated assessment models used in climate policies involve highly conjectural (non-evidenced), simplified (unjustified), and intrinsically normative *assumptions*.

4. Philosophy for interdisciplinary modeling practices

The knowledge of epistemological and methodological challenges of interdisciplinary research and the role of modeling therein is far from complete. The presented overview highlights a number of aspects. First, representational accounts of models are problematized because the construction of models is enabled by the specificities of the scientific disciplines (i.e., the disciplinary perspective) so that discipline-specific theoretical, conceptual, instrumental, and strategic features determine the model content. This explains why crucial characteristics of interdisciplinary research, namely *transfer* and *integration* (e.g., of epistemic resources and methodologies), encounter epistemological, methodological, and conceptual barriers. It also means that models function as integrators (hubs) of heterogeneous aspects and, in interdisciplinary research, of sub-models. Another aspect arises from the advocacy of interdisciplinary research focused on epistemic utility, which implies that models are seen as epistemic tools that must meet epistemic and pragmatic criteria relevant to the intended epistemic purpose, and in the case of science-based policy also ethical criteria, e.g., model-based reasoning or computer simulations for the analysis, prediction, or scenario-study of complex target-systems. Researchers do cope with the mentioned epistemological, methodological, and cognitive issues and barriers, as illustrated by the aforementioned real-world examples of interdisciplinary modeling practices.

The *philosophy of scientific modeling* that targets interdisciplinary research practices, science-based policy, and higher education, should therefore study epistemologies and methodologies of modeling strategies aimed at understanding complex systems, including the critical roles of human cognition and responsibility therein (cf. Boon et al. 2022; Nersessian 2022, 283).

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Notes

1 The cognitive scientist, Barbara Tversky (2017) offers a concise explanation of mental models, in which models as representations are interpreted from cognitive sciences perspective: "representations are internalized perceptions. However, representations cannot be copies, they are highly processed. They are interpretations of the content that is the focus of thought. They may select some information from the world and ignore other information, they may rework the information selected, and they may add information, drawing on information already stored in the brain. In this sense, representations are models" (Tversky 2017, VI–VII).

2 Suárez (2004) proposes an inferential conception of representation, which entails the idea that "[the internal structure of the representation, e.g., a model] A allows competent and informed agents to [correctly] draw specific inferences regarding [the target] B" (Suárez 2004, 773).

3 For a more comprehensive review of aspects addressed in definitions of interdisciplinary science, see Tripp and Shortlidge (2019).

4 E.g., Speech by ERC President Prof. Jean-Pierre Bourguignon (2019).

5 Gleed and Marchant (2016) *Interdisciplinarity Survey Report for the Global Research Council 2016 Annual Meeting*. Also see: Global Research Council (n.d.) *Statement of Principles on Interdisciplinarity*.

6 For example: National Academy of Sciences et al. (2005). National Academy of Engineering (2005). National Science Foundation (2008). National Academies of Sciences et al. (2018, Chapter 3). Witchel (2022) and Psychological Society (2021). Craciun et al. (2023). Moser et al. (2022).

7 American Association for the Advancement of Science AAAS. (2009). *Vision and change in Undergraduate Biology Education: A Call to Action, Final Report*. Washington, DC. Retrieved January 3, 2023. This report is no longer available online; see Woodin et al. (2010).

8 Chronic disease management requires an integrated care approach to managing illness that includes screenings, check-ups, monitoring, and coordinating treatment, and patient education (cf. Bardhan et al. 2020). Policy and management of risk (e.g., by governments, insurance companies, and industries) requires interdisciplinary research that combines technical risk analysis (focusing on the controllability, safety, and reliability of technical systems and processes, and analysis of how failure can occur) or epidemiological and toxicological risk analysis (focusing on probability and seriousness of illness due to toxic compounds or medicines) with studies into public perception of risk (e.g., conceptualizing and studying social processes influencing risk perception) and risk communication (Zinn and Taylor-Gooby 2006).

9 These kinds of (heterogeneous) elements —that are exchanged between disciplines— are built-into models, as in models-as-integrators and models-as-epistemic-tools. More elaborate accounts of knowledge transfer between disciplines can be found in a special issue on this topic edited by Herfeld and Lisciandra (2019).

10 Van Baalen (2019) provides an example of interdisciplinary biomedical research to develop a diagnostic technology. She conducted an ethnographic study to analyse reasoning and decision-making processes within a multidisciplinary research team —consisting of a clinician, a radiologist (specialized in thorax imaging), a radiographer and an MRI engineer— who collaboratively developed a new clinical MRI imaging technique for the non-invasive diagnosis of respiratory diseases.

11 Recognizing different epistemic goals is also crucial to interdisciplinary research within academia (c.f. Green 2013). See also Parker (2020). Love and Brigand (2017) push for a shift in focus *from metaphysics to epistemology*. Philosophers should approach conceptual problems in science (such as the problem of biological individuality) by paying attention to the variety of *epistemic goals* underlying successful scientific practice.

12 Notable, pragmatic and epistemic criteria relevant to the research project at hand, should also guide the assessment of the quality of interdisciplinary work in educational settings (cf. Mansilla 2005).

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