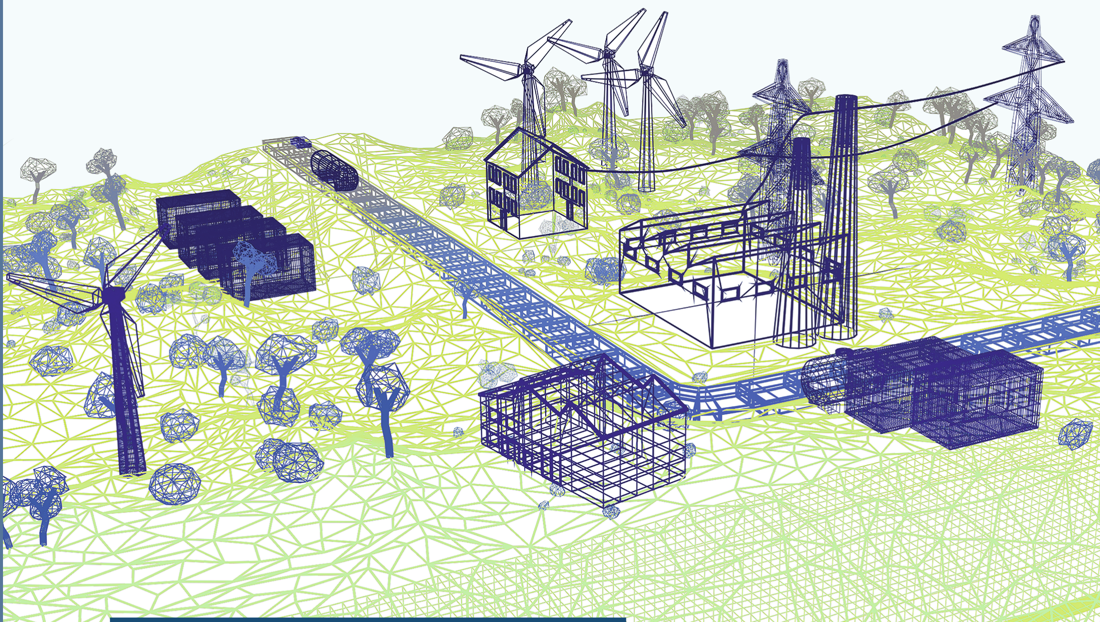
POETICS OF MODELLING



Modelling the Energy Transition

Cultures, Visions, Narratives

Edited by

Robert Matthias Erdbeer
Veit Hagenmeyer · Klaus Stierstorfer

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Poetics of Modelling

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This series offers an innovative approach to model research, pointing out two key deficiencies of representing science from a humanities point of view: in model theory the lack of a model aesthetics; in aesthetics the lack of a model theory. As models are among the basic tools of human orientation and identity, transparency both in performing and communicating modelling is of the utmost importance. Thus, in the comparative approach developed in this series, modelling will be conceived of as a cultural technique across technology, the sciences and the humanities, with a specific focus on technology assessment; literary studies will be crossed with energy technology, sociology with informatics, and philosophy of science with the arts. Informed by literary theory, the series seeks to set in motion interdisciplinary discussions on a transdisciplinary theory of models. Here, the term 'poetics' will exert its full potential—as a metacriticism of the targeted activities, representations and communications, and, no less important, of the undirected 'blind spots,' narratives and fabrications that the modelling actions perform. In doing so, poetic modelling provides a model hermeneutics, aiming to facilitate the understanding and communication of the modelling activity.

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Klaus Stierstorfer
Editors

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Contents

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Related publications:
Adeyemi, Kafayat O., Victor Eniola, Godwin Mong Kalu-Uka, Musa Zarmai, Muhammad Uthman, and Eli Bala. 2022. Forecasting Photovoltaic Energy Generation Using Multilayer Perceptron Neural Network. *International Journal Of Renewable Energy Research* 12(1): 1743–1753. https://www.ijrer.org/ijrer/index.php/ijrer/article/download/13306/pdf

Tobias Becker is a visual artist. He studied fine arts at the UdK in Berlin, at the Willem de Kooning Academy in Rotterdam and at the University of Illinois in Urbana-Champaign, Illinois, USA. In object and model construction media, painting, photography and cartography, he is concerned with the perception and construction of space and strategies of spatial location. After teaching at the TU Berlin, RWTH Aachen and HfG Karlsruhe, he received a professorship for design and design theory in the Department of Architecture at the University of Siegen in 2021.

Related publications:
Becker, Tobias, et al. (eds.). 2024. *Der konstruierende Blick: Fotografisches Entwerfen in der Architektur [Constructive Gazes—Making Architecture with Photography]*. Berlin: Schlaufen.

Becker, Tobias, and Thomas Schmitz. 2018. *This is not a Model—Zum künstlerischen Umgang mit dem Architekturmodell [Architectural Models in the Arts]*. Aachen: University of Aachen.

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Related publications:
Smolka, Mareike, and Stefan Böschen. 2023. Responsible innovation ecosystem governance: socio-technical integration research for systems-level capacity building. *Journal of Responsible Innovation* 10(1): 2207937. https://doi.org/10.1080/23299460.2023.2207937.

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Böschen, Stefan. 2016. *Hybride Wissensregime. Skizze einer soziologischen Feldtheorie [Hybrid Knowledge Regimes. Sketches of a Sociological Field Theory]*. Baden-Baden: Nomos.

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Related publications:
Cartwright, Nancy, Jeremy Hardie, Eleonora Montuschi, Matthew Soleiman, and Ann C. Thresher. 2022. *The Tangle of Science: Reliability Beyond Method, Rigour, and Objectivity*. Oxford: Oxford University Press.

James Dorson, Dr., is an Assistant Professor in the Department of Literature at the John F. Kennedy Institute for North American Studies, Freie Universität Berlin. He is the author of the monograph 'Counternarrative Possibilities: Virgin Land, Homeland, and Cormac McCarthy's Westerns' (Campus 2016) as well as several coedited volumes, including 'Fictions of Management: Efficiency and Control in American Literature and Culture' (Winter 2019) and the special issue 'Data Fiction: Naturalism, Narratives, and Numbers' (Studies in American Naturalism 2017). His most recent publication is titled 'Technovitalism and the Longue Durée of the Posthuman Economy,' published in Interconnections: Journal of Posthumanism (Spring 2023).

Related publications:
Dorson, James. 2023. Technovitalism and the Longue Durée of the Posthuman Economy. *Interconnections: Journal of Posthumanism* 2(1): 24–41.

Dorson, James. 2022. The Data of Life and the Life of Data: Epistemological and Aesthetic Liminality at the Fin de Siècle. In *Beyond Narrative: Exploring Narrative Liminality and Its Cultural Work*, eds. Sebastian M. Herrmann, Katja Kanzler, and Stefan Schubert, 41–56. Bielefeld: Transcript.

Øyvind Eide, Ph.D., is a Professor in Digital Humanities at the University of Cologne. He holds a Ph.D. in Digital Humanities from King's College London (2013). He worked in various positions at the University of Oslo from 1995 to 2013, doing research on digital humanities and cultural heritage informatics. From 2013 to 2015, he was a Lecturer and Research Associate at the University of Passau. He was the Chair of the European Association for Digital Humanities (EADH) from 2016 to 2019 and also actively engaged in several other international organisations including ICOM's International Committee for Documentation (CIDOC). His research interests are focused on transformative digital intermedia studies as a tool for critical engagement with media differences, especially the relationships between texts and maps as media of communication. He is also engaged in theoretical studies of modelling in the humanities and beyond.

Related publications:
Ciula, Arianna, Øyvind Eide, Cristina Marras, and Patrick Sahle. 2023. *Modelling Between Digital and Humanities: Thinking in Practice*. Cambridge: Open Book Publishers (forthcoming). https://www.openbookpublishers.com/books/10.11647/obp.0369.

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Victor Eniola holds a First Class Honours in Mechanical Engineering and obtained a M.Sc. degree with perfect Distinction in Renewable Energy. He has more than ten years of work experience in the energy sector and has worked as a Lecturer and Research Assistant at four universities. He is currently working for the Energy Commission of Nigeria where he is actively involved in cutting-edge research in renewable energy integration with PEM electrolysis and fuel cell modelling. He is a registered member of the International Association of Engineers (IAENG) and certified by the Council for the Regulation of Engineering in Nigeria (COREN).

Related publications:
Eniola, Victor, Tawat Suriwong, Chatchai Sirisamphanwong, Kasamsuk Ungchittrakool, and Olatubosun Fasipe. 2021. Validation of Genetic

Algorithm Optimized Hidden Markov Model for Short-term Photovoltaic Power Prediction. *International Journal of Renewable Energy Research* 11(2): 796–807.

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Robert Matthias Erdbeer, Dr., is an Associate Professor for German Literature and Literary Theory at the University of Münster, Germany. Together with Darin Tenev from Sofia University and Klaus Stierstorfer he introduced the research field of model theory to literary studies ('Poetik der Modelle,' 2015) and developed an 'aesthetics of modelling' in his work as research coordinator of the LMET networks 'Literary Modelling and Energy Transition' and 'Poetics of Modelling' at the University of Münster and the Karlsruhe Institute of Technology (Germany). He was the speaker of the Center for Philosophy of Science at the University of Münster and a Max Kade Distinguished Visiting Professor at the University of Illinois (USA), and received research grants from the Heinrich Hertz Foundation, from IFK Internationales Forschungszentrum Kulturwissenschaften in Vienna (Austria), CAS Centre for Advanced Study in Sofia (Bulgaria) and NEC New Europe College in Bucharest (Romania). His current research refers to the contact zone of science, technology and parascience with and within literary fiction, as well as to literary modelling and ludic art.

Related publications:

Erdbeer, Robert Matthias. 2022. Modell und Form [Model and Form]. In *Grundthemen der Literaturwissenschaft: Form [Key Concepts in Literary Studies: Form]*, eds. R. M. Erdbeer, Florian Klaeger, and Klaus Stierstorfer, 226–284. Berlin and Boston: de Gruyter.

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Gabriele Gramelsberger, Dr., is a Professor for Theory of Science and Technology at the RWTH Aachen University, Germany. Her research topic is the digitalisation of science, in particular the introduction of new research methods such as computer simulation and machine learning. She is Director of the Käte Hamburger Kolleg 'Cultures of Research', an international centre for advanced studies in the history, philosophy and sociology of science and technology, and a member of the North Rhine-Westphalian Academy of Sciences and Arts.

Related publications:
Senk, Johanna, Birgit Kriener, Mikael Djurfeldt, Nicole Voges, Han-Jia Jiang, Lisa Schüttler, Gabriele Gramelsberger, Markus Diesmann, Hans E. Plesser, and Sacha J. van Albada. 2022. *Connectivity Concepts in Neuronal Network Modeling*. *PLoS Computational Biology* 18(9): e1010086. https://doi.org/10.1371/journal.pcbi.1010086.

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Related publications:
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Related publications:
Weber, Moritz, Jona Enzinger, Hüseyin Kemal Çakmak, Uwe Kühnapfel, and Veit Hagenmeyer. 2023. PyAPI-RTS: A Python-API for RSCAD Modeling. *2023 Open Source Modelling and Simulation of Energy Systems* (OSMSES): 1-7. IEEE.

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Related publications:
Bersalli, Germán, Tim Tröndle, and Johan Lilliestam. 2023. Most industrialised countries have peaked carbon dioxide emissions during economic crises through strengthened structural change. *Communications Earth and Environment* 4: 44. https://www.nature.com/articles/s43247-023-00687-8.pdf.

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Related publications:
Pickering, Bry, Francesco Lombardi, and Stefan Pfenninger. 2022. Diversity of options to eliminate fossil fuels and reach carbon neutrality across the entire European energy system. *Joule* 6: 1253–1276. https://doi.org/10.1016/j.joule.2022.05.009

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Related publications:
Magnani, Lorenzo (ed.-in-chief). 2023. *Handbook of Abductive Cognition*. Cham: Springer.

Magnani, Lorenzo. 2022. *Discoverability. The Urgent Need of an Ecology of Human Creativity*. Cham: Springer.

Magnani, Lorenzo. 2022. *Eco-Cognitive Computationalism. Cognitive Domestication of Ignorant Entities*. Cham: Springer.

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Related publications:
Mueller, Stefanie. 2023. *The Corporation in the Nineteenth-Century American Imagination*. Edinburgh: Edinburgh UP.

Astrid Franke, Stefanie Mueller, and Katja Sarkowsky (eds.) 2022. *Reading the Social in American Studies*. London: Palgrave Macmillan.

Stefan Pfenninger, Dr., is an Associate Professor of Energy Systems Modelling at TU Delft. His research is on the global transition to a 100% clean and renewable energy system, and on identifying and resolving the technical, economic and policy barriers on the way to that goal. Together with his team he investigates three broad areas. First, understanding the variability of renewable energy at spatial scales ranging from individual buildings to entire continents, and at time scales ranging from minutes to decades. Second, designing the energy systems that can deal with and even thrive on this variability, with strategies from continent-spanning electricity grids to district heat networks. Third, trade-offs between sustainable energy and other issues, such as land use, material requirements and ecosystem impacts.

Related publications:
Pfenninger, Stefan, Lion Hirth, Ingmar Schlecht, Eva Schmid, Frauke Wiese, et al. 2018. Opening the black box of energy modelling: Strategies and lessons learned. *Energy Strategy Reviews* 19: 63–71. https://doi.org/10.1016/j.esr.2017.12.002.

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Related publications:
Rheinberger, Hans-Jörg. 2023. *Split and Splice. A Phenomenology of Experimentation*. Chicago: The University of Chicago Press.

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Rheinberger, Hans-Jörg. 1997. *Toward a History of Epistemic Things: Synthesizing Proteins in the Test Tube*. Stanford: Stanford University Press.

Benjamin Steininger, Dr., is a cultural theorist, historian of science and technology, and curator. He is a Postdoc Researcher at the Cluster of Excellence UniSysCat at TU Berlin and at the MPI for the History of Science, Berlin. His research topics are the role of industrial catalysis and fossil resources in modernity and in the Anthropocene. In 2016, together with Alexander Klose, he founded the research collective 'Beauty of Oil' (beauty-of-oil.org).

Related publications:
Steininger, Benjamin, Alexander Klose, and Andreas Beitin (eds.). 2021. *Oil. Beauty and Horror in the Petrol Age*. Köln: Verlag der Buchhandlung Walther König.

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Klaus Stierstorfer, Dr. (Oxford Univ.), is the Chair of British Studies at the University of Münster in Germany. He was the Speaker of the Münster CRC 1385 'Law and Literature,' of the LMET Research Network 'Literary Modelling and Energy Transition,' funded by the Volkswagen Foundation, and of the Marie Skłodovska Curie Initial Training Network 'Diasporic Constructions of Home and Belonging CoHaB' (Partner: Oxford, Northampton, SOAS, Stockholm, Mumbai). He initiated and directed the Graduate Training Group 'Literary Form. History and Culture of Aesthetic Modelling' at the University of Münster (2013–18), funded by the Germany Research Council (DFG), and received a DFG grant for his project '"Orbis Britannicus versus Orbis Europaeus?" Negotiations of National and European Identities in British and Irish Literature (2012–2015).' His research interests cover law and literature, diaspora studies, fundamentalism and literature, and literary modelling.

Related publications:
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Introduction: Energy Transition and its Narratives—A Challenge for Model Theory

Robert Matthias Erdbeer, Veit Hagenmeyer, and Klaus Stierstorfer

1 A Global Mission—Reviewing the Limits to Growth

Energy Transition is a global mission striving to correct a global failure: the effects of climate change. It operates within a zone of conflicts, of political uncertainty, societal dissent and ecological imbalance, struggling to establish a zone of consent. Fifty years from its initial set-up by the Club of Rome,[1] the wake-up call that seemed to have become an international consensus is in fact dissolving in an atmosphere of growing doubt, disorientation and disintegration of trust. The COVID-19 Crisis, Russia's War in Ukraine or the Taiwan Crisis cast a shadow not just on the safety of financial markets and supply-chains but on the ability and resolution

[1] Meadows et al. (1972), cf. Bardi and Pereira (2022).

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of decision makers, stakeholders and institutions to apply the necessary remedies. The crisis we encounter with regard to think tanks, central banks and research institutions has become a crisis of the ways they model their decisions. It is hard to avoid the conclusion: We are facing a crisis of modelling. This crisis, though, has not been caused by negligence, by lack of competence, by prejudice, misunderstanding or ill will, nor even by the bias that is always tied to certain interests, but by a rising level of complexity. Historically, this new complexity can be retraced to what has once been called the 'crisis of representation': to the disappearance of observables and to the rise of virtual realities with their specific spatio-temporality. The handling of this mixed ontology of real-world objects, digital technologies, societal entanglements and virtual scenarios, intent on rendering perceptible and manageable a reality that can no longer be expected to present and represent itself, has come to favour models over unreliable facts. Yet models are, by definition, temporary and provisional, they work as substitutes, as instruments and agents or as layouts and designs of possible solutions, and they need to be applied and tested in a virtual environment, a testing ground.[2] Mistaking models for the targets that they model is not doing justice to the models and the modellers. And yet the functional division between modelling assumptions, model sources, model objects, simulations, targets and—not least—interpretations is not easy to discern, not even for the experts themselves. In fact, to model something means to set up, realign and value all these modelling components. Ontologically speaking, modelling is in itself a mode of fabricating a reality and giving rise to facts.

Convincing as all this may sound from a more theoretical perspective, mixed ontologies in modelling remain a challenge when it comes to mediating and communicating models to the public at large. The crisis, therefore, can be reconfigured as a crisis of communicating modelling. As modelled facts are transient, negotiable and competitive, they entertain a rather difficult relation to our notion of scientific truth. If science is a game of truth, the art of modelling provides a game of options.

[2] The epistemic nature, function and applicability of models have been thoroughly discussed in model theory; see, e.g., Wartofsky (1979), Cartwright (1997), van Fraassen (2010), Morgan and Morrison (2010), Rheinberger (2010), Gonzalez (2014), and Magnani and Bertolotti (2017); a recent overview and critical discussion can be found in Roman Frigg's account on *Models and Theories. A Philosophical Inquiry* (Frigg 2023, chapter 14). For a transdisciplinary approach cf. Mahr (2011).

The remarkable alliance between what is true and what is possible accumulates—as Hans-Jörg Rheinberger has demonstrated in the present volume—even more opacity when models enter experimentation, altering the tried and tested road to generate reliable scientific data and facts. As Energy Transition is concerned, the models' layout and their public reputation may have dire consequences, as the models, policies and technological implementations necessary for a fundamental change of lifestyle are entirely dependent on the public's trust.

Today, the Energy Transition Project is not only one of the most daring technological endeavours, it is also a new master narrative. In targeting the narratives of Global Warming, Global Economic Growth and Demographic Change, this master narrative provides a rescue programme of gigantic dimensions. The temporal and spatial range of Energy Transition shows an almost mythical or evenchiliastic design. In this design, the whole and its totality demand a quest of every single individual; the *longue durée* of the transition plan compels immediacy. Thus, with regard to numerous apocalyptic energy scenarios the Energy Transition Project is regarded to be necessary, overdue and irrevocable. It seems to be an *apriori* of the great negotiations of society, and it affects the smallest units of our individual lives. It cannot—and it must not—fail.

Literary Modelling and Energy Transition (LMET) is a research project and alliance of the University of Münster and the Karlsruhe Institute of Technology (KIT). The project targets a transdisciplinary approach to modelling within the framework of the German Energy Transition Programme 'Energy System 2050'. It scrutinises the prevalent metanarrative that Energy Transition, as a discourse, has established in the contact zone of possible conflicts and crises, advanced technologies and daring possible futures. The narratives, however, that create and guide the Energy Transition discourse, have been constituted by a set of models which themselves are far from being narrative: by technical and computational models, by conventions of scientific style, by imaging procedures, by established practices and standards, by procedures of statistics and prognostics, and by routines of distributing research results. This border zone of narrative, aesthetic and scientific modelling has been the target of the LMET project and its book series *Poetics of Modelling*. 'Poetics' here refers to the specific ways and strategies of representing and communicating models: to their mode of being, rhetoric and narrativity, and to the preconditions of their validation. Hence, the current volume throws into relief the Energy Transition discourse with regard to five perspectives: theory, analysis and criticism, mediation and enhancement of the art of modelling—within and beyond the academy. It aims at reassessing both the state of Energy Transition and of Model Theory by offering a change of perspective. It looks into the role that models play within an atmosphere of mounting altercation in a stress field shared by technological, societal and ecological claims. In doing so, it adds a modelling perspective to the current review of the Club of Rome's assessment of the limits to growth.

2 Imbalances—Model Criticism and the Energy Imaginary

Models play a central part in the designs of Energy Transition and in the attempts and strategies to put them into practice. Thus, the art and craft of fabricating models is a driving force of technological development,[3] but also—and much harder to discern—of social and cultural change. Beyond its instrumental qualities of bringing things about or make them happen, modelling conveys both a creative agency and a conceptual power.[4] Everything related to an absence or a future; everything entangled in complexities beyond the reach of minds and senses; everything that needs to be controlled and ordered; everything that has to be evolved, enhanced or overcome by new conjectures—every object in the border zone of data and imagination needs modelling in the first place. By representing an existing item (object, matrix, archetype) or by conceiving of a future one, all models are supposed to bridge the gap between the facts that come in handy and the consequences that are out of hand. Though model theories are gaining insight into the intricacies of skills and concepts, they still tend to overlook (or underestimate) the techno-social underpinnings and aesthetic strategies of modelling. In this regard, the modelling of Energy Transition is confronted with imbalances—inside the experts' discourse when it comes to the 'blind spots' of modelling, but also with respect to what a model should accomplish and account for as a social agent or purveyor of scientific policies.

[3] Tarja Knuuttila has called this aspect "artefactual" (Knuuttila 2005), thus building on Bruno Latour's idea of the "*faitiche*" as a mixed epistemic entity of 'fact' and 'fetish' (Latour 1999). Models, as it were, acquire such in-between states.

[4] From a literary studies point of view, this problem has been addressed by the LMET project, see, e.g., Erdbeer et al. (2018) and Stierstorfer (2022).

Both as a technological endeavour and as a creative claim for social change, the modes of Energy Transition and its modelling are deeply rooted in what might be called the Energy Imaginary. As a type of modelling the Self, the Other and the World, it sets the scene for two familiar narratives: decline as overcome by progress and apocalypse as conquered by salvation. Thus, phenomena like Greta Thunberg's entry on the stage of a debate that is evolving rapidly into a battle between Good and Evil throws into relief the cultural dimensions of what once had been a specialists' approach to recondite effects of science and technology. Evoking images reminiscent of social combats or a children's crusade, movements like Extinction Rebellion, Last Generation or Fridays for Future have reached a level of emotional intensity and moral rigour unexpected by the well-established stakeholders in the political and economic fields. Accompanied at last by dire warnings from the academia and promises provided by the industry, these narratives have finally acquired the status of a twenty-first-century myth. They trigger an imaginary power building on scientific facts and rendered into popular representations in a wide variety of modes: in documentaries and round table discussions, talk shows, demonstrations, strikes, but also in environmental novels, movies and computer games. Here, models do not only show their instrumental or heuristic qualities but also their aesthetic impact that, in turn, is strengthening their functional impact as well.

The chapters in the present volume have their origins in contributions to the international LMET conference in Münster, Germany, in October 2021. They bring together experts' voices from a multitude of disciplines that are engaged with, shape and critically assess the most intriguing challenges of model theory and Energy Transition—in technology and economics, sociology and politics, as well as in cultural and literary studies, theory of science and philosophy. They represent a wide variety of disciplinary perspectives with a sharply focused, cross-disciplinary aim: to throw into relief the apparatus of the modelling procedure and its repercussions on the modelling of Energy Transition, one of the most daring challenges of our time. By giving insights into the specific narratives, transmedial representations, distribution concepts and communicative strategies of modelling, the present volume offers a deep probe of the entanglement of technical and social layers pertinent to

Energy Transition and technology assessment alike.[5] It covers the imbalances as well as the alliances between the social and the technical designs of modelling in four connected parts: by looking at what model theory can contribute to a new concept of TRANSPARENT MODELLING (I), by putting centre-stage the model applications of a new TECHNOLOGY IN PRACTICE (II), by portraying the SOCIETAL AND CULTURAL FUTURES (III) and by foregrounding the MODEL MEDIA devised in LITERATURE AND THE ARTS (IV). Thus, in addition to the question of direct representation raised in model theory, this volume aims at balancing the various imbalances of 'indirect representation' in cross-over modelling—by representing not so much through structures, 'vehicles' or 'cargoes', but through strategies like 'epistemic warfare', 'open modelling' or 'indicator politics'.

By viewing Energy Transition as a techno-social discourse with disruptive qualities, this volume tackles the precarious relations between Energy Transition models, cultural performances and social narratives. Thus, it will contribute to extricate the *Energy Imaginary* from a multitude of voices and representations, crossing boundaries between the sciences, humanities and arts. In doing so, this multi-disciplinary approach to modelling will follow up and build upon the challenges imagined by the Club of Rome.

3 Positions and Transgressions—Modelling the Energy Transition

Transparent Modelling: Revisiting Model Theory

The first part of the present volume, dedicated to TRANSPARENT MODELLING, envisages the epistemic force fields of contemporary model theory by casting light on the precarious and often covert points of intersection where societal and epistemic requirements meet. Thus, it deliberates the ways how modelling can be rendered transparent, to the modellers themselves and to the public at large. In a profound report on *Theories, Modelling, and Empirical Support* in science, Bas van Fraassen attributes the reasons for the rise of science scepticism to the gap between the confirmation of empirical statistical hypotheses and the empirical support for foundational scientific theories. By offering

[5] Grunwald et al. (2024).

a close revision of some of the key positions of philosophy of science, van Fraassen sets the scene for reassessing theoretical objects and the pitfalls of scientific methodologies like 'explanation', 'confirmation' or 'measurement', thus instigating a new strategy of Empirical Grounding in modelling. Investigating *Modelling in Experimentation*, Hans-Jörg Rheinberger elaborates the tension of reality and theory by pointing to the models' double function: Being both, configurations in the data space and objects of representation in the space of traces, models are not only subject to a change of media, they also foster an illusionary character that tends to hide itself and turn the models' beneficial 'precession' into an axiom or fetish. The ticklish interplay between the models' static and dynamic qualities and their effects on model theory has also fuelled the fundamental criticism launched by Lorenzo Magnani. In his article on *Model-Based Science as Epistemic Warfare. Scientific Models in a Static and Dynamic Perspective*, he refers to problems of abstraction, ideality and fiction in contemporary model theory. Distinguishing external models from internal ones, Magnani redefines the modelling technique of 'thinking through doing' as a case of 'manipulative abduction'. Models, he concludes, are neither fictions nor illusions, but they form an arsenal of tactical intermediate weapons. Given their directedness and operational bias: Is there any room for objectivity in models and the acts of modelling? This question is the topic of a thorough case study by Nancy Cartwright and Faron Ray. In *Modelling Objectively*, they point to two historical accounts of model failure, shedding light on problems of responsibility and ethical neglect as well as on the institutional entanglements and systems-level problems found in modelling. When used prescriptively or as a value to be found, the concept 'objectivity' can shape, the authors claim, the intellectual humility required to ensure the modellers' duty of care. Since all these preconditions and precautions to enhance transparency are linked to linguistic features, it will be of critical importance to observe how modelling is recognised within the science of language and literature. From this perspective, Darin Tenev points to problems of modality in literary modelling by offering a programmatic take on what he termed the *Basic Operations of Model Building in Literary Studies*. Tenev shows how a specific strategy of actualization, i.e. actualization of a potentiality inherent in a literary text, may generate not only a variety of readings and interpretations, but of generalizations, particularizations and naturalizations, too. By introducing the concept of a 'threshold of meaning,' Tenev opts for a 'repotenzialisation' of the literary work within the act of actualization, following the modal indices provided by the work. One may conclude that questions of modality, interpretation and self-reference belong to the essential concepts of the present context—empirical grounding, manipulative abduction, objectivity, collaborating—to achieve transparency in Energy Transition modelling.

Modelling the Energy Transition I: Technology in Practice

Whereas the theoretical revision of these key components of strategic modelling disclosed some of its preconditions and disturbances, the volume's second part dives into the more practical endeavours of contemporary ENERGY TRANSITION MODELLING. By giving the floor to the modellers, it offers insights into the procedures of their TECHNOLOGICAL PRACTICE, as well as into the judgements involved. Elaborating *On the Art of Electric Power System Modelling and Simulation for Integrated Transmission-Distribution Analysis*, Uwe Kühnapfel and Veit Hagenmeyer give an insiders' report of Europe's most distinguished simulation hub for Energy Transition, the EnergyLab at the Karlsruhe Institute of Technology (KIT). The paper demonstrates how grid stability, one of the vital issues in the modelling of Energy Transition, has to be accomplished by an art of careful balancing the data and devices with the modeller's implicit goals and 'experientiality'. The way how innovation can be triggered through a model transfer across disciplines can be derived from an innovative approach by Victor Eniola, Kafayat Adeyemi, Mohammed Adamu, Olatubosun Fasipe, Jimento Aikhuele, Musa Zarmai and Muhammad Uthman, members of the LMET network in Nigeria. In their case study on *Daily Streamflow Forecasting using an Enhanced LSTM Neural Network Model*, they apply a novel type of deep learning neural network to enhance the modelling of streamflow forecasting in water energy technology. The plea for open modelling implicit in the KIT laboratory and in the Neural Network Model has been dealt with from a socio-economical perspective in the programmatic contribution *Open Models are not Enough. Advancing Energy System Modelling towards Practical Usefulness*. In this article, the research group of Francesco Lombardi, Diana Süsser, Frauke Wiese, Johan Lilliestam and

Stefan Pfenninger develop a concise approach to strengthen the efficiency of model communication, advocating open-source-related strategies, a modular approach to model interoperability and, finally, a strategy of co-creation to involve all kinds of stakeholders, consumers and prosumers at every modelling stage.

Modelling the Energy Transition II: Societal and Cultural Futures

Building on this take on creativity as well as on the strategies to optimise the modelling procedure by enhancing social sensitivity, the third part of the present volume covers the SOCIETAL AND CULTURAL FUTURES pertinent to ENERGY TRANSITION MODELLING. It also captures problems of technology assessment with regard to how a technological procedure can assess the future and, in doing so, will have to revisit the past. Thus, in her contribution on the strategy of *Backcasting. Prototyping Future Ontologies by Backward Chaining Possible Futures*, Gabriele Gramelsberger emphasises a significant turn: the shift from forecasting to backcasting as an instructive method in environmental modelling. Caused by the rise of hybrid entities in science and technology, this shift affects the boundary conditions leading to alternative worlds. If modelling is the domain for prototyping different ontologies by designing computational environments for testing the trajectories of these ontologies, then backcasting will call for an instructive (rather than predictive) use of modelling. The question, how this epistemic shift in modelling might influence the politics of Energy Transition, is discussed in Stefan Böschen's far-reaching approach to *Indicator Politics. Modelling Societal Problems under Real-World Conditions*. Highlighting the institutional conditions of processing knowledge, Böschen tackles the relations of societal and epistemic problems by developing a theory of indicator politics. As tools for describing and analysing a problem methodically, such indicators are essentially normative. Applied to mobilize support for a selective description of problems in a partial way, they also function as expressions of a political will. From this perspective, Real-world labs may function as a playing field for indicator politics and their analysis, thus being an important part of an emergent 'civic epistemology.' As modelling the future has a history, the final contribution of this section opens up a vista on imagining post-fossil futures. In his article on *Understanding Petromodernity. Oil as a Medium between Geology, Technology, and Different*

Types of History, Benjamin Steininger unfolds the story of the non-renewable yet universally engaging 'medium oil'. By analysing the relation of geographies with energy-related disciplines, technologies and cultural techniques, in science politics as well as in popular culture, Steininger's account revives the Energy Imaginary of historical and present discourse, and the intricate technologies of their collective Selves.

The Energy Imaginary: Model Media in Literature and the Arts

Following the path of social modelling, its strategies and epistemic goals, IMAGINING THE ENERGY TRANSITION is the topic of the volume's final section. Dedicated to the energy trajectories, representations and inventions made in LITERATURE AND IN THE ARTS, the focus on the MEDIALITY OF MODELS shows how Energy Transition has already been developed as a global narrative, comprising model reasoning in theory and history of science, in technology and social theory. Emerging genres like resilience and climate fictions are a major part of this development, but also ways of implementing scale or miniature models in an entertainment setting, and, of course, the ways in which this topic is related by the visual arts. By introducing scaling as a central dimension of literary modelling, Stephanie Mueller's case study on Jenny Offill's *Weather* offers insights into one of the most intricate procedures of adopting, shaping and refashioning the climate change debate through literature. Moreover, from an interdisciplinary perspective on the art of modelling, her essay *Cycles, Spirals, and the Challenge of Scale: Literary Modelling in Climate Fiction* also aims at reconfiguring the type of worlds that literary and scientific models create. To illustrate how climate change and ecopolitics are being shaped in Energy Transition literature, James Dorson provides a profound reading of two types of fictional 'resilience stories.' In his take on *Literary Models of/for Resilience in Juliana Spahr's 'The Transformation' and Kim Stanley Robinson's 'The Ministry for the Future'*, Dorson shows how cli-fi models contribute to climate knowledge by means of 'embodied abstraction,' shaping and reshaping not just what we think, but how we think. His reading also offers insight into a substantial fictional critique of the resilience concept, understood both as a method for apprehending nonlinear and emergent processes and as a political design for a more sustainable future. Viewing models as a major type of media products, Øyvind Eide throws into relief the intermedial ability of literature, computer simulations and physical objects for *Modelling the Future with Miniature Worlds*. According to their individual affordances, the medial instantiations of these 'model worlds' develop a distinctive rhetoric creating stories about futures involved. Referring to the LMET exhibition setting, Eide claims that miniature worlds act as a hub where energy-related simulations, visualizations, textualizations and gamifications met and trigger the transfer of knowledge. As transmedial models, they offer 'modelling literacy.' Hence, as Tobias Becker put it in his essay on *Models in Art*: The model is the medium of our time. Arguing that models function as a tool for deciphering the present and making it practicable, the artist and curator of the LMET exhibition offers a broad overview on model types and strategies in art as well as on his own attempts to render visible the blind spots in the act of modelling. Here, Becker singles out three major areas of model fallacy in Energy Transition—'model amnesia', scaling and the horizon problem—and reconceptualises them as a problem of art.

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Transparent Modelling. Revisiting Model Theory

Theories, Modelling, and Empirical Support

Bas C. van Fraassen

What can account intellectually for science denial and science skepticism when it appears in a literate, well-informed public?

I submit: there is a gap between the familiar confirmation of statistical hypotheses and empirical support for advanced theories and modelling. Briefly: *confirmation and evidential support are not the same*. The failure to distinguish the two will quite naturally lead to skepticism about advanced scientific theories, no matter how much evidential support is presented. In this respect, there has been a failure in twentieth-century philosophy and in science education to this day.

The recourse must be, and can only be, had at a fundamental level in methodology, where understanding has deepened incrementally over the past century and a half. The hero of that story is, as we shall see, the German physicist-philosopher Hermann Weyl.

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1 Carl Gustav Hempel: from Positivism to Realism

The place to begin is the transition from logical positivism to scientific realism, at mid-century. The Center for Philosophy of Science at the University of Minnesota was its hotbed. My focus here will be the challenge posed for the newly emerging realism by Carl Hempel (whose own ideas were actually changing in the direction of scientific realism, while managing to impose his style of reasoning on the new movement).

What the scientific realists in Minnesota were offering as alternative to the logical positivist tradition was a conception of science as a pursuit of truth through theorizing, as aiming to reach true theories, not just theories that saved the phenomena. And they emphasized that to be true, it is not enough for a theory's consequences on the humanly observable and manipulable level to be true. Theories are not merely of instrumental value: if a theory says that there are humanly inaccessible processes going on, then that theory is true only if that is so—and truth matters.

However, we use science to predict and manipulate at that human level.

Accordingly, Hempel posed the question[1]: *isn't the only part of science that matters the scientific description of what we can observe*? What possible importance is there to the theoretical underpinnings, the description of the unobservable? Hempel posed this challenge in a form that could not be dismissed, and provoked a great deal of defensive response. What he called the Theoretician's Dilemma we now generally refer to as Hempel's Dilemma.

Theories, Models, and Quantities

The older, logical positivist view of science was not nearly as naïve as it has often been caricaturized. In popular writings, science depicts the world as having hidden depths: only a small part of nature is observable, but what happens there is just the surface of a mainly hidden structure. Observable things are made up of unobservable things.

That is not entirely inaccurate, but does scant justice to what advanced scientific theories are like. These are presented by means of equations, in mathematical language, and the terms in the equations do not refer to things: they refer to quantities.

[1] Hempel (1958).

These quantities form a characteristic algebra. A model of such a theory presents a representation of that algebra of quantities, in which all the quantities have specific values. Among these quantities, some are *directly measurable* and some are *theoretical*. Theoretical are the quantities whose values can be determined from results of direct measurements only by calculations based on the theory. (Of this, more later.)

The main figures in the logical positivist/empiricist movement were educated in physics, and one main inspiration was Einstein's 1905 paper introducing the special theory of relativity. In that paper, we see the scope of direct measurement limited, to what is determined by clocks and rods locally, and the quantities thus measurable are distinguished from all other quantities pertaining to the electrodynamics of moving bodies.

With the linguistic turn so dear to Logical Positivism, that distinction between directly measurable and theoretical quantities was discussed in terms of a distinction between predicates, between an 'observation vocabulary' and a 'theoretical vocabulary'. A scientific theory is written in a combination of these two vocabularies: *observation terms* denoting directly measurable quantities and *theoretical terms* denoting theoretical quantities, these two kinds being linked by equations supplied by the theory.

Hempel's Logical Point

What Hempel then pointed out was that, within the language so conceived, the empirical consequences of a theory form a theory as well. In applications and predictions based on the theory, the statements of importance are of the form:

given data $\mathbf{O_1}$, theory T implies $\mathbf{O_2}$

but that is equivalent to:

T implies (if $\mathbf{O_1}$ then $\mathbf{O_2}$)

and the consequent has no theoretical terms in it at all. These conditionals of form (if $\mathbf{O_1}$ then $\mathbf{O_2}$) are the empirical consequences of theory T. Taken all together they form the sub-theory T_E, and now Hempel is ready to pose his challenge:

What is the importance of T, given that T_E does all the work in application and prediction?

After all, if the point is to have applications and predictions at our human level, where we can tell whether it's all working, what more do we need? What is the value of theory? Here is how Hempel put it himself:

> The use of theoretical terms in science gives rise to a perplexing problem: why should science resort to the assumption of hypothetical entities when it is interested in establishing predictive and explanatory connections among observables?[2]
>
> The conclusion suggested [...] might be called the *paradox of theorizing*. It asserts that if the terms and the general principles of a scientific theory serve their purpose, i.e. if they establish definite connections among observable phenomena, then they can be dispensed with since any chain of laws and interpretative statements establishing such a connection should then be replaceable by a law which directly links observational antecedents to observational consequences.[3]

The question that Hempel labels '**a perplexing problem**' is not an innocent question. Since any evidence for the theory must consist in statements that belong to T_E, this question challenges the scientific realists' contention that it is the truth of the theory as a whole that matters.

And this sets us on course to a scrutiny of how evidential support is related to confirmation of the theory, how evidence relates to the question of how likely a theory is to be true, or its models are to be accurate representations of reality.

Three Reactions

The first two reactions to Hempel's challenge focused on features that Hempel was leaving out of account:

- **Practicality**. Theory T may be easy to use and understand while its empirical part T_E is clumsy, practically opaque.
- **Inductive value.** T may suggest *plausible* connections beyond its logical implications, which can lead to new empirical explorations.

[2] Hempel (1965, p. 179).

[3] Hempel (1965, p. 186).

Surely, these points are correct and important. So why was this not very satisfactory? Well, the emphasis on those specific features was not happy for the emerging scientific realists in Hempel's Minnesota cohort. These first two reactions list *instrumental* values, practical values. They assign theory a practical use, instrumental for obtaining the empirical results. They have nothing to do with truth of the theory as a whole, or as such, they concern aims that might be very well served by ingeniously designed fictions.

So, this was not satisfactory to the scientific realists who were rising to dominance in the field. But there was a third reaction[4]:

- **Explanatory value**. The description of the unobservable *explains* what is going on!

This became the dominant theme in the debates that followed. Note well that this reaction is apt only if explanation can be suitably connected with evidential support and confirmation.

2 Explanation

That putative connection is concisely expressed in the slogan 'it is because of the explanation that we believe the empirical predictions'. Induction is a notably feeble concept, and statistical methods can establish correlations in the phenomena so far, but cannot by themselves establish that these correlations are not spurious, fleeting, limited to the present. Nor do correlations on the observable level have any logical implications for what is not observable. So the confirmation of statistical hypotheses of matters on the observable level must be backed up somehow. The contention was that in practice, this is through the value we place on explanation.

Here, we may remember the recent story of the evidence for cold fusion. The publication of the initial empirical results was met with deep skepticism precisely because there was no explanation. This clearly mattered despite the official credo of the scientist that experimental results trump theory. The skepticism was therefore precisely about whether the

[4] This point does not show up very saliently in Hempel's own thinking about the Dilemma. I think this may be because Hempel's concept of explanation was exhausted by what he saw as the deductive and inductive uses of theory, with no special value added thereto.

data were to be trusted in the absence of any explanation coherent with currently accepted physics.

A more mainstream, and more telling, example is the story of the Balmer formula, an empirical equation for the hydrogen emission spectrum (Johann Balmer, 1885). In 1888, Johannes Rydberg extrapolated this to offer the Rydberg formula, a generalization of the Balmer formula to cover spectral lines for chemical elements, in general. But how could one have confidence in this as a theory when its basis was just a bare set of data? Then, in 1913, Bohr's model of the atom provided an explanation that implied the general validity, and established its bona fides in the eyes of the physics community. Or so the story goes.

Don't these examples sound natural, and convincing? And if they do, doesn't that mean that the explanatory theory is more believable, more likely to be true, than its mere empirical content taken by itself? A new slogan appeared: we believe the data because we believe the explanation!

Noticing that the explanatory theory T has considerably more content, which is logically stronger than its sub-theory T_E, we arrive at the putative epistemic principle:

> (*) The stronger, more informative, more explanatory theory is more *believable*, that is to say, judged more *likely to be true*, than its empirical content, and that is so precisely because it includes an explanation.

This idea has had remarkable staying power, reappearing especially as the idea that inference to the best explanation is the inference that drives science. But it encountered a great obstacle already in 1980.

Could that idea, labeled above as (*), possibly be correct?

Glymour's book *Theory and Evidence* (1980) is, or should be, a milestone in the history of philosophical reflection on confirmation and evidential support for theories. His critique of what were called, with astonishing optimism about their value, confirmation theories—the hypothetico-deductive method, Hempel's confirmation theory, Bayesian confirmation theory—is awesome.[5]

[5] So is his positive contribution, the 'bootstrap method', though its value was undoubtedly obscured by his attempts to present it in the sort of format, first-order logic, that Carnap and Hempel had installed as standard, as well as the impression that this was meant as new explication of confirmation. Glymour did also present it perspicuously for theories formulated by means of equations relating measurable quantities, and this should have been at the readers' focus.

Glymour restated Hempel's point as it applies if we take confirmation to consist in a raising of probabilities:

> Let us suppose that we can divide the consequences of a theory into sentences consisting of reports of actual or possible observations, and simple generalizations of such observations, on the one hand; and on the other hand, sentences that are theoretical. Then the collection of 'observational' consequences of the theory will always be at least as probable as the theory itself; generally, the theory will be less probable than its observational consequences. A theory is never any better established than is the collection of its observational consequences. Why, then, should we entertain theories at all?[6]

But this point, thus made, speaks immediately against (*). It is a matter of logic that the probability of (A&B) cannot be greater than that of A, and more generally that if one thing implies another it cannot be more likely to be true than the other. Thus theory T, no matter how explanatory, cannot be more likely to be true, or more confirmed, than its sub-theory T_E.[7]

A stronger, more informative theory *cannot* *be more probable!* Explanation of a phenomenon requires additional information, which must be non-trivial. So an explanatory theory about X must be *less likely to be true* than a mere description of X.

The story of the Balmer series and Bohr's model of the atom must give us pause here. But we can understand it if we distinguish between confirmation, in the standard sense of 'making more likely to be true' from other forms of support, reasons for acceptance, in which explanation may take its place with such practical considerations as simplicity and calculability. The question 'just what is the value of explanation?' was largely left aside. I will leave it now also, for we need to concentrate on just how confirmation and evidential support may actually be related.

[6] Glymour (1980, p. 83).

[7] Although Glymour presents this relying on the 'syntactic view' of theories as sets of sentences, in the way Hempel did, the point does not depend on that. However we think of theories, it is clear that they are bodies of putative information, that they can be true or false, and that one theory can imply another in the semantic sense that if the former is true so is the latter. And in that case, the former cannot be more probable than the latter.

3 Evidence and the Concept of Confirmation

We have here a puzzling conceptual situation. Following Hempel, it seemed to be generally accepted that the aim, or perhaps the main or central aim, of science is explanation. But science is also in pursuit of truth, not in pursuit of explanation to the extent of making the requirement of truth defeasible. If explanation itself tends to make a theory more likely to be true—if *explanatory* implies *confirmatory*—this tension is relieved. But Glymour's argument rejects this as a feasible option. For being explanatory requires more informative content, over and above what is predicted for the observable phenomena, and increase in content implies decrease in the likelihood of truth. In order to analyze this puzzle, we need to fix our terms very carefully. I will use the term 'confirm' solely with the meaning of *making more likely to be true*, with likelihood understood in terms of conditional probability. It is of crucial importance here not to smuggle in other meanings or connotations of the word 'confirm' or to assume that it is synonymous with such expressions as 'evidential support'. To be sure to avoid equivocation, therefore we must stick to this sense of the word:

> E *confirms* T if and only if the probability of T given E is greater than the probability of T taken by itself.

This reference to probability may be qualified as you wish. You may take it as objective probability relative to background knowledge, and thus take confirmation to be relative to that background. Or you may take it to be the probability that represents the prior opinion in the context of discussion (so that the concept of confirmation is to be understood as similarly contextual).

What about *evidential support*? Since that very concept is now in question, we can't give it such a quick and easy definition, and certainly cannot presume that it is explicable simply in terms of probability relations among propositions. We'll have to tread carefully here.

Using P to stand for 'the probability of' and '|' for 'conditional upon', the above definition is symbolized as:

> E *confirms* T exactly if $P(T|E) > P(T)$.

Then, Glymour's point emerges as the immediate consequence: if T* is logically stronger, more informative than T (relative to any background information, if relevant), then $P(T^*|E) < P(T|E)$. This follows from a general feature of probability theory. Hence, if E is the total evidence available, whatever it is, that evidence confirms the stronger theory less than the weaker theory.

And now the puzzle continues with a historical point, emphasized by Glymour, that in the history of science we see that often there is evidence for a stronger, extended theory which ***would not have been*** evidence for an earlier, weaker version.

4 How There Can Be More Evidence for a Stronger Theory

As Glymour points out, if explanatory hypotheses are added to a theory, new sorts of measurement results can count as relevant, can add evidential support for the extended theory, while it seems they could not count as doing so for the original part of the theory.

In the abstract, it is easy to see how that is possible: to design and experiment you need to have the guidance of a sufficiently informative theory, and to count or interpret its outcome as evidence for the theory that outcome has to be informatively linked to models of that theory.

When a theory, in its first stages, when first proposed, is still rather weak, it may not provide enough of that either to guide experimental design, or to interpret outcomes of given processes as fitting or not fitting its models.

- If the theory is as yet too weak to allow the design of an experiment, how can there be any evidence for it?
- If the theory is strengthened by adding postulates or hypotheses, and these allow the design of an experiment to test the whole, how can that be evidence for the original, weaker theory?

The first question could be answered by insisting that there can be features, such as explanatoriness, that count as evidence independent of any measurement data. That runs into the objections I have already displayed above.

The second question could be answered by insisting that the original theory can ride on the coat tails of its stronger descendant, and receive confirmation derivatively. In what follows, I propose to show, both by example and by logical argument, that this is not so.

We need clear examples of how it is possible to have evidence, for example from experimental outcomes, for a strengthened theory that is not, and could not have been, evidence for the original, weaker theory. Let us take a look at the historical episode which Glymour presents and has since been the focal subject for the discussion that was thus initiated.

Example: Growth of a Theory

How did the atomic theory evolve from the purely hypothetical to scientific acceptance? Here is the popular story:

Early in the nineteenth century, Dalton proposed the theory that matter is ultimately discrete, that it consists of atoms, and that these atoms combine into molecules in various ways to produce chemically distinct substances.[8] All during that century the evidence grew, so that the theory became more and more likely to be true. Finally, at the beginning of the twentieth century experiments by Jean Perrin in combination with theoretical work by Einstein add the results that showed that the theory was true and that atoms and molecules are real.

We could quickly quibble with that last part: Perrin was working with a theory that depicted atoms as very much like small billiard balls, and no one would really say today that this is true. But we can put the conclusion carefully and much more neutrally: the evidence grew, and finally became conclusive, that the theory that matter is discrete is true.

But there is a problem with this that is not a quibble at all: that the story is an *equivocation*, because the theory that Perrin addressed just was not at all the theory that was originally proposed. It was not just the evidence that grew during that century, it was the theory that both gained and lost much along the way. If we want to be really charitable to the story, we can ignore all the bits and parts that were pruned along the way, including much that Dalton held dear, and take the initial theory as just what was left of it a hundred years later. But then the point still remains that this residue of the initial version had been hugely augmented.

[8] Dalton (1808).

Could we now say: well, all the evidence for the later, augmented theory is also automatically evidence for that initial part—which was now made overwhelmingly probable because of evidence that had not yet been collected at the outset?

No, that would be a real distortion by misdirection as well. For it suggests that the new evidence could have been collected at the outset, or at least, that it consisted of data that would count as relevant for that initial core theory taken by itself. *That is not so*, because to get that evidence, experiments had to be designed that could only be designed with the guidance of the new additions. The newly relevant measurements were procedures that involved the new postulates to draw conclusions from the direct measurement results. So if we think of that minimal theory all by itself, just the theory that matter is discrete, none of those experimental results that came later were evidence for it.

This is a simple point, and it has striking illustration in the history of the atomic theory: not only what experiments can be designed that count as relevant, but even what operations count as measurement of relevant quantities, is dependent on the theory that is in play.

Dalton's Theory and Its Fortunes

Dalton takes as accepted:

- **law of definite proportions** of elements in compounds

and proposes a theory that implies this, plus:

- **law of equivalent proportions** (ratio of A:B reacting with C is independent of C)
- **law of multiple proportions** (ratio of A:B in compounds C and C' is a ratio of whole numbers).

For example, carbon monoxide and carbon dioxide are both compounds of carbon with oxygen, and a fixed mass of carbon will combine with oxygen to produce these two compounds in proportions 1 to 2. Dalton postulated that substances are either elements or compounds of elements, that the atoms of elements combine with each other to form the molecules of which compounds consist, and the mass of a molecule is the sum of the masses of the atoms in it. Dalton's theory deals with three quantities:

a. combining proportions
b. molecular structure (atomic or diatomic, etc.)
c. relative atomic weights

Within his theory, from any two the other can be determined. But, note well, *only the first is directly measurable*.

Dalton's postulate about the masses and numbers was fairly minimal. First, all atoms of a given element have the same mass. Second, when two elements combine, then in the simplest case only one sort of compound is produced, by one atom of one being joined with one atom of the other. For example, one atom of hydrogen and one atom of oxygen combine to form one molecule of water. When the combination of two elements can produce two different substances, then one of those is produced by the combination of one element of one with two of the other, and so forth. And the composition, hence mass, of molecules of the same such substance is the same for all. Thirdly, a sample of a substance contains a definite number of atoms or molecules, and its mass is the sum of their masses.

The immediate, significant question for scientific inquiry here is this: how can the masses of the atoms or molecules be determined on the basis of measurements?

If we assume that Dalton's postulates are correct, and then classify some substances in its terms, we can arrive at least at some proportions between the masses of atoms of various compounds. He took the mass of a hydrogen as unit, and on the basis of his rules, for example, an oxygen atom would then have mass 7 (see Chapter III of his *A New System of Chemical Philosophy*).

But what I listed as the second part of what he postulated, about how the compounds are produced, did not have any independent warrant: it was just the simplest to propose.

Enrichment of the Theory to Allow Design of Measurement Procedures

What happened, naturally, is that his rules were disputed but additions were made. Gay-Lussac's work on combining volumes of gases and

Avogadro's hypothesis about numbers of molecules in a given volume provide the earliest steps that have withstood the fortunes of history.

Dalton's controversy with Gay-Lussac is instructive here.[9] Gay-Lussac's law of combining volumes, for gases (at fixed temperature and pressure), is that gases chemically reacting together do so in volumes in a simple ratio to one another and to the volume of the product. For example, one volume of hydrogen combining with one volume of chlorine forms two volumes of hydrogen chloride gas.

It is easy to see the similarity of this law to the law of multiple proportions, but it did not fit well with Dalton's theory. Dalton himself gave the reason: the number of particles in the product would not be the sum of the numbers of particles in the two combined gases, for example because the latter's atoms would have combined to form molecules of the product. That argument appears to presuppose that the new molecules could individually take up more room than the atoms or molecules in the different combined gases, e.g., due to size.

Since the two laws are both empirical, it looks first as if Dalton's theory can be tested, by testing Gay-Lussac's law. But a few years later, in 1814, Dalton argued that actually, his theory could be kept neutral between the various hypotheses about the sizes of the molecules of different substances, and hence about the numbers of molecules in a given volume of a gas.[10] That dismisses his own initial argument, but it also makes it impossible to design an empirical test involving volume measurements.

As is well known, the first famous surviving addition was Avogadro's hypothesis 1811: equal volumes of *any* gases at the same temperature and pressure contain the same number of molecules. With this addition assumed, it becomes possible to determine atomic mass ratios for different elements. Another addition was proposed by Dulong and Petit (1819): all atoms have the same heat capacity. Then, it follows that specific heat, which can be measured, is inversely proportional to atomic mass.

These were just the first among many efforts to strengthen the theory—and to what end? We get the answer when we go to the end of the story, with Perrin's investigation.

[9] Gay-Lussac (1802) and Gay-Lussac (1809). Cf. Glymour (1980, pp. 233–234).

[10] Cf. Glymour (1980, p. 234).

Perrin Begins [11]

In his 1909 article, Jean Perrin presents a list of the surviving hypotheses that had been added so far, involving these theoretical parameters:

- Avogadro's N
- molecular mass
- mean molecular speed
- minimal electric charge
- mean free path
- molecular diameter

With these additions, the informativeness of the extended theory is vastly greater than that of the original. In fact, Perrin can show that the accepted equations at this point provide such a tight connection between the theoretical parameters that *if anyone can be empirically determined*, the values of all will be determined.

Then, Perrin does precisely what his predecessors did: to fill the remaining gap he proposes a new hypothesis: in section I-12 of this article, Perrin writes:

> Let us now consider a particle a little larger [...], in a word, *dust*. [...] Will it not comport itself simply as a very large molecule, in the sense that its mean energy has still the same value as that of an isolated molecule? This cannot be averred without hesitation [...].[12]

No, it is not obviously true, but it can be added to the theory to strengthen it further. And as we know, Perrin was successful. With this hypothesis assumed, he could design the relevant experiments, and the results were positive.

So the much strengthened theory allows for the design of tests and experiments, hence for gathering evidential support, from data that could not have done anything to support the initial weak theory.

What stands out here, and is crucially important, is that the measurement procedures count as measurements of the relevant theoretical quantities *relative to* the strengthened theory. They are not independent

[11] See further van Fraassen (2009).

[12] Perrin (1910, p. 20).

of that theory, and their results would have had no significance for, nor offer any evidential support to, the small part of that theory which was original.

So, in outline, what was the story? The pattern we can see in the development of the kinetic theory, which is quite typical, is this. Initially, there are theoretical quantities for which no measurement procedures can be designed. What follows then is:

a. addition of specific hypotheses,
b. with result: ***relative to the theory*** certain empirical procedures take on significance as measurements,
c. their outcomes place constraints on the values of the theoretical parameters,
d. eventually so strict as to determine those values precisely (under some realizable conditions, at least in principle),

and it becomes possible to amass evidential support, based on measurement outcomes, for the thus extended theory.

5 Challenge

So far we are seeing what looks like an important difference between confirmation and evidential support, when the evidence is from the outcomes of measurements of theoretical quantities. For what counts as such a measurement depends on the theory: it is a procedure that involves both direct measurements and calculations sanctioned by the theory. It is a *theory-mediated measurement*. So it appears that evidential support, gained after the theory has been extended, at the very least cannot be cited as confirmation of the un-extended theory.

But doesn't evidential support for the *extended* theory then make the *original* also more likely to be true?

To answer yes would be, in effect, to take the slogan that *A rising tide lifts all boats,* as an epistemic principle.[13] Could that be right?

No, it is not right. To show that I will first present a fictional, toy theory, to whet our imagination. Then, I will show how probability theory backs up its negative conclusion for the general case.

[13] This was US President Kennedy's claim of economic progress.

Does evidence for the larger theory make the smaller part more likely to be true as well?

A Toy Theory as Example

The toy theory, let's call it the Theory of Extra-Terrestriality, has just one postulate.

T1 = Invisible aliens are here.

By 'alien', I mean 'extra-terrestrial', and 'here' refers to the very city of Münster where the LMET conference took place. Since this theory provides no information about how we could detect such aliens, nor about what they are like except for being invisible, nor about how many there are, there is no way to design a test. There cannot be any empirical evidence for this theory. Since T1 is not testable in any way, we begin to strengthen it by adding new postulates:

T2 = Milk turns sour when invisible aliens pass by.

Our situation with respect to empirical evidence has not significantly improved. Milk turns sour under ordinary circumstances and may turn sour faster and more often under many conditions far more likely than any postulated to be of extra-terrestrial origin. So we must add more.

T3 = Invisible aliens are attracted by smell of cheese.

Now, we can design an experiment! We place many samples of milk all around in Münster, some accompanied with cheese and some not.

Imagine now that we obtain the result: a statistical analysis reveals a significant correlation between the presence of cheese and milk turning sour. That is a result predicted on the basis of the extended theory T = (T1 & T2 & T3), and the data confirm this extended theory.

Now do you believe that invisible aliens are here?

Theory T has evidential support. More than that: we must admit that it is now more likely to be true than we might have deemed it originally. But I think you may share the intuition that the probability of T1 has not increased at all. It is important to test our intuitions here, for of course the burning question is whether the confirmation of this empirical correlation also increases the probability of T1.

A moment's reflection:

- Something is confirmed: an empirical correlation.
- This correlation is explained by deduction from the theory.
- Each of the postulates was necessary to deduce the testable consequence.
- The *full* theory that aliens are here received evidential support.
- The *full* theory that aliens are here has received some confirmation.

Let's point out at once that even the full theory may have for us, prior to any experimental evidence, a very low probability. So even if its confirmation is considerable, say its probability multiplied by 100, our posterior probability for the full theory may still be only negligibly higher than zero. But that depends on what our prior probability was, which depends on the choice of T1 for our example, and is not relevant to the main question:

> Does confirmation of the full theory T = (T1 & T2 & T3) imply confirmation of T1?

What Does Probability Theory Show?

In this story, what was directly confirmed was something we can state with no reference to the theory: the empirical fact that there was a strong correlation between the presence of cheese and the souring of the milk.

There was no prior connection at all between the first hypothesis about extra-terrestrial aliens and any relation between souring milk and cheese. They are connected only via the new hypotheses, and the connection completes an explanation. Does this do anything to the probability of the first hypothesis, given that empirical fact?

We need to state the question in a more general form: if a conjunction is confirmed, by a test of its consequences, does this confirm both conjuncts? Well, it depends. Let the conjunction be (A&B): think of A as the hypothesis and B as the evidence gathered much later, after new hypotheses are added. And assume that prior to any additional hypotheses, A and B are independent of each other. That means that, relative to all our background information, P(A&B) = P(A)P(B), or equivalently, that P(A|B) = P(A).

In a diagram where the areas represent probabilities, that independence is shown by the dividing lines being straight horizontal and vertical[14] (Fig. 1).

Now suppose that a hypothesis H is added to A, to produce the more informative theory (A&H), which allows for the design of an experiment that yields that evidence B. This hypothesis H may be such that B is indeed relevant to the conjunction (A&H). The small rectangle in the revised picture represents H (Fig. 2).

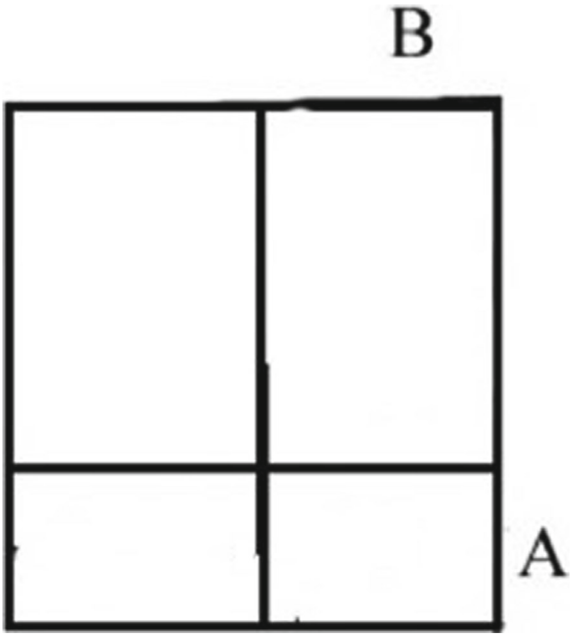

Fig. 1 A and evidence B statistically independent (© Bas van Fraassen)

[14] To see the reasoning done in numbers, we can set P(A) = 0.3, P(B) = (0.5), and P(A|B) = 0.3. Then in the second diagram, add that P(H) = 0.3 as well, P(H|B) = 2/3 and equally P(A&H|B) = 0.3.

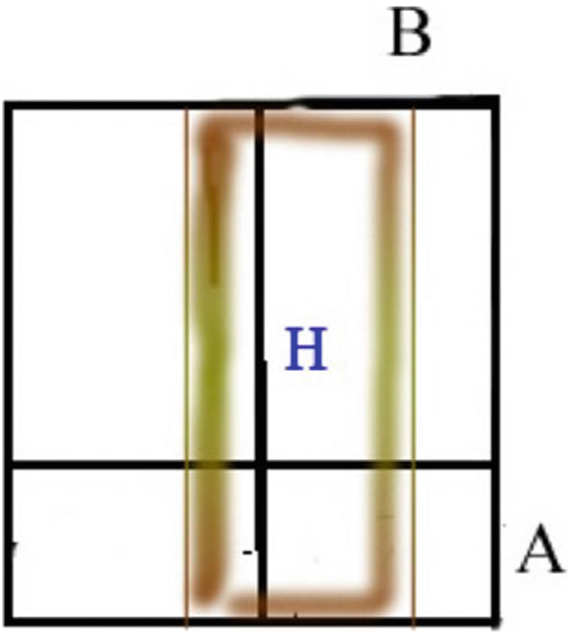

Fig. 2 Evidence B confirms (A&H), A and B remain statistically independent (© Bas van Fraassen)

Notice that most of the area representing the probability of H lies in the area of evidence B. So B strongly confirms H. Similarly B strongly confirms (A&H).

But does evidence B confirm theory A? Not at all: the two are and remain probabilistically independent. In fact, B confirms the strengthened theory (A&H) only because it confirms hypothesis H, and not because it increases the probability of A at all.

In the example of the aliens that was probably clear enough. The evidence gathered strongly confirmed a hypothesis about milk and cheese, and derivatively increased the probability of the theory T as a whole, but had no bearing on the probability of aliens in Münster.

There was one huge event of confirmation, in this story: the correlation in the phenomena involving souring milk and cheese, which we take to have become a certainty after the data were analyzed.

Meanwhile, the probability of T1 did not change—in my mind it was very low, say 1 in a million. The probability of T = (T1 & T2 & T3) increased, once that correlation was established. However, note well that the probability of a conjunction cannot be greater than that of any of its conjuncts. So the prior probability of T was very low (much below 1 in a million) and however much it was raised, it could never be raised to be higher than 1 in a million. It is perhaps a startling thought that this may be representative of theories in general which involve theoretical quantities.

Conclusion: The Difference Between Confirmation and Evidential Support

The point of the preceding argument is general:

> When does an increase in the probability of a conjunction yield an increase in the probability of its conjuncts? Only if the *prior* opinion *already* includes probabilistic relevance of these conjuncts to each other.

It is not the case that a rising tide lifts all boats. The rising tide, in this case, is indeed the evidential support for the theory as a whole, but it does not imply confirmation of all the boats riding on it. If we accept the theory, and translate this acceptance into action by relying on its empirical predictions, that is not because it has attained a high probability of truth overall, *but because it has strong empirical support*. In this respect, the scientist and engineer act just like the businessman who invests in a well-running profitable company.

So far the story I have been telling about the struggle to understand empirical support and confirmation of theories and models has been mostly negative, about ideas proposed and their misfortunes.

It is time now to be positive and to lay out the right understanding of how confirmation, so well understood at the merely empirical level, is related to, as well as distinct from, the evidential support that can be amassed for advanced scientific theories.

6 Empirical Grounding

Although it would be hard to find a sign of this in philosophy of science textbooks, there developed in the twentieth century an account of epistemic practice that shifted focus from confirming to evidential support. In essence and outline, with the authority of a thorough study of the sciences by one of its most eminent practitioners, the basic principles were presented in Hermann Weyl's *Philosophy of Mathematics and Natural Science*. Significant additions were made by Frederick Suppe in his account of experimentation and testing as the *credentialing* of theories,[15] and by Clark Glymour, who relied explicitly on Weyl, in his account of *relevant evidence* and what he called the *bootstrapping* method.

Below I will offer a summary of this account of the epistemic practices in the sciences, for which I use the term *empirical grounding*.[16] But it will help to first have a concrete historical example that brings the core idea clearly to light.

The Reverent Atwood Against the Cartesians

What exactly is measurement of theoretical quantities, quantities postulated for the sake of theory as opposed to directly measurable quantities?

That was the central question posed in the Cartesians' challenge to the Newtonians in the seventeenth and eighteenth centuries.

All you can measure, the Cartesians argued, are quantities of extension, that is, those deriving from 'clock and ruler' procedures—what we now class as the kinematic quantities of space, time, and motion. By introducing *mass* and *force,* Newton brought back the occult qualities of the medievals!

The Newtonians responded: but we can measure theoretical quantities! We can measure mass and force! Admittedly, any *direct* measurement is of lengths and time intervals, but these can suffice to fix the value of the dynamic quantities as well.

Famous among such theoretical quantity measurement set-ups is the Atwood Machine, named after the Reverent George Atwood, who was

[15] Suppe (1993).

[16] This term has a technical sense, introduced in van Fraassen (2008, p. 113), van Fraassen (2012)and van Fraassen (2014).

responding directly to the Continental critics.[17] The following diagram shows his measurement setup diagrammatically (Fig. 3).

Following Atwood, the apparatus has this description[18]:

> The Machine consists of two boxes, which can be filled with matter, connected by a string over a pulley.
>
> **Result:** In the case of certain matter placed in the boxes, the machine is in neutral equilibrium regardless of the position of the boxes; in all other cases, both boxes experience uniform acceleration, with the same magnitude but opposite in direction.

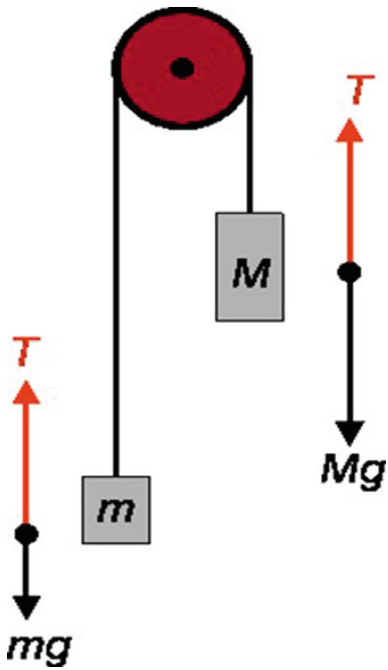

Fig. 3 Basic structure of the Atwood machine (© Bas van Fraassen)

[17] Atwood (1784, p. 30).

[18] Atwood (1784, pp. 299–300).

The acceleration, a kinematic quantity, can be measured directly. But this yields a result for the mass ratio M/m as follows: the acceleration is proportional to the ratio (M − m)/(M + m), which determines M/m.

But there is a glaring defect in this reasoning, in Cartesians' eyes: that the acceleration is proportional to (M − m)/(M + m) is a theorem in Newton's physics. So the refutation of the Cartesian challenge, that theoretical quantities cannot be measured, is a petitio principii, a logical fallacy, it begs the question!

Indeed, as an argument for the truth of Newton's theory, this would be blatantly circular. The Cartesian can only see it as begging the question, if truth is what is at issue. The result cannot be seen as making the theory more likely to be true. It bestows no confirmation!

Indeed, but it is nevertheless precisely what the theory needs, it is the evidential support that it needs to have to be a good scientific theory. For this result, and the fact that it accords with the results of all similarly designed experiments, shows that the values of theoretical quantities can be consistently determined relative to the theory itself. And that is what is needed to ground the theory empirically.

Empirical Grounding Made Precise

Concordance. The definite value which a quantity occurring in the theory assumes in a certain individual case will be determined from the empirical data on the basis of the theoretically posited connections. *Every such determination has to yield the same result.*[19]

The requirement of empirical grounding is that, for any quantity occurring in the theory it must be possible in principle to determine its value

a. from direct measurement results,
b. based on the *theoretically posited* connections,
c. and consistent with those connections, subject to:
d. *concordance*: every such determination has to yield the same result,
e. *non-triviality*: but could have had different results that would have contradicted the theory.

[19] Weyl (1927/1963, p. 121).

This requirement needs to be satisfied, at least for relevant quantities, for an application of the theory to be possible. If for instance a bridge is to be constructed, the predictions of the forces it can withstand will be based on a theoretical description of the construction material, the soil, the water current, and so forth. If the values of the dynamic quantities involved in this description could not be determined in the above fashion, from the direct measurement results, no such prediction would be possible.

So empirical grounding is crucial to the very possibility of applied science.

That in such a determination there is a reliance on the theory itself only indicates that the theory was accepted for this purpose. And the reasons for acceptance could have come from a combination of theoretical considerations (such as coherence with past accepted theories) and practical experience in which the theory had been relied on even if with less confidence.

Whether the theory is actually true as a whole is an academic question. But if empirical grounding is achieved, the theory and its models function like a well-oiled machine, and predictions and applications at our observable level become eminently possible.

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Modelling in Experimentation

Hans-Jörg Rheinberger

Depending on the field of investigation, the epistemic objects of scientific research can assume very different shapes. Nevertheless, a certain order can be brought into this multiplicity. First of all, a basic distinction between two modes of the space of the epistemic, where the generation of knowledge is at stake, has to be drawn. It is the distinction between the configurations of epistemic objects in the space of traces, inherent in the experimental setup, and their configurations in the space of data; in other words, the difference between graphematicity and representation.[1]

1 Preparations

There are forms of scientific objects that are traditionally called *preparations*. Preparations have played and continue to play an important role in the life sciences, in medicine, in materials research, geology, mineralogy, or chemistry. They come in widely varying guises, but all of them belong to the space of traces.[2] Generally speaking, preparations are characterized

[1] Rheinberger (2013).

[2] Rheinberger (2010), chapter 12.

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by the fact that in one form or another they all participate in the materiality of the phenomenon under investigation. They are configurations of traces emanating from it in the frame of the experimental setup.

2 Experimental Models

Another kind of scientific object, called *models*, is prominently present in almost all sciences. In contrast to preparations, they belong to the space of data and its temporary reifications. Whereas preparations share the graphematic space of the phenomena that are being researched, models presuppose a change of medium. It is a common characteristic of all sorts of models that they rest on an ontic cut between the space of the phenomena in question and the data space. Whereas traces and their configurations can be addressed as first-order epistemic objects, models are epistemic objects at one remove. With that, however, nothing is yet said about the medium itself. Models can be of a purely formal, schematic or diagrammatic nature and in need of paper and pencil alone for their representation. They can, however, also make use of other materials, thus allowing to deal with them as hands-on working models with which one can tinker.[3] Today, computer models and simulations have become ubiquitous and are being worked with in laboratories around the world.[4]

In this paper, I will have a closer look at models.[5] In doing so, I will adopt a special focus: I will concentrate on the relation between models and the process of experimentation.[6] Accordingly, models will be considered insofar as they are bound into and part of an experimental setup. Research experiments are rarely singular events; as a rule, they form series or sequences in whose course epistemic objects take shape. In their elaborated form, such series, typically extending over longer periods of time, can also be—and are—addressed as experimental systems.[7] If one looks closer at what happens here, a condensed answer could read as follows: An

[3] For three-dimensional models in the sciences, see, e.g., de Chadarevian and Hopwood (2004).

[4] Compare Morrison (2015); in particular also Varenne (2018), and Borrelli and Wellmann (2019).

[5] See also Rheinberger (2023), chapter 2.

[6] Literature on scientific model building abounds. Relevant for the context discussed here are Gelfert (2011) as well as van Fraassen and Peschard (2018).

[7] Rheinberger (1997).

epistemic object, that is, a phenomenon of interest to the experimenters, is being coupled with a technical environment in such a manner that their interaction leaves traces. Since these traces usually are of an ephemeral kind, the primary outcomes of an experiment have to be made durable in order to be able to work with them. This can happen either materially, such as photographs, or formally in the guise of "inscriptions."[8] It is precisely this step that requires a change of the medium. And it is here that the concept of data comes into play: Traces made durable and stored in repositories of a multitude of different kinds can be addressed as data. This step, in turn, makes the next one possible that is of particular relevance for our discussion: It consists in connecting data with each other. With that, models emerge as combinations of data.

From such a strict bottom-up perspective, which is at the same time a perspective of doing and making, models can, in a first approximation, be characterized as textures or configurations in the data space. In principle, they allow for the connection of a multiplicity of data, which makes it possible to capture them at one glance. With that, however, they also, and inevitably so, create the illusion to be able to *see* the whole. Such a totalization goes along with a peculiar form of inversion. As the French anthropologist Claude Lévi-Strauss once rightly put it, "with a scale model *the knowledge of the whole precedes that of its parts*. And even if this is an illusion, the reason of the procedure is to create or sustain the illusion […]."[9] With that, Lévi-Strauss addresses a cardinal point. Reducing synthesis is the paradoxical procedure with which this inversion of parts and whole gets effected. From the perspective of the epistemic objects at whom they are directed, the models appear as reduced. From the perspective of the individual traces generated in the experiment, they present themselves as synthetic. In the graphematic space of the experiment, one can never have the whole. How far one is allowed to go with such selective syntheses in the data space is subject to a permanent phenomenon-oriented negotiation, which at the same time is also historically conditioned.[10] Harvard ecologist Richard Levins voiced this situation with respect to population biological models with the following words: "The difference between legitimate and illegitimate simplifications

[8] See Latour and Woolgar (1986).

[9] Lévi-Strauss (2021, p. 28).

[10] Mahr (2004).

depends not only on the reality to be described but also on the state of the science."[11]

The strength of models precisely consists in simplifications of this kind that can be, however, rather complex in themselves. But concomitantly, it is their weakness. Their weak point lies in the fact that they invite and incite to forget the illusionary moment inherent in them. Their strength lies in the fact that they—in contrast to data in isolation—constitute a flexible framework that can sensibly react as a whole if one of its constituent data elements is being changed, exchanged, or reconfigured. They thus form a *system in the data space*. It follows from their systemic character that punctiform interventions can have consequences for the model as a whole. But this also means that they open the possibility of something like trial acting—*Probehandeln*—in the data space. The questions that arise from such tentative interventions into the model itself can then be fed back into the stream of the experimental production of traces. In this way, a cycle is put into motion that implies a media change in both directions: from the experimental system to the model system and vice versa.

I do by no means claim that with this description, all forms and filiations of models in the sciences, in mathematics and in architecture and art are exhaustively characterized. However, from the perspective adopted here the focus is on *bottom-up* models of that kind. Following Margaret Morrison, models that take theories as their starting point follow a reversed *top-down* path.[12] Accordingly, and referring to the terminology of Evelyn Fox Keller, we are dealing with *models for*, not with *models of*.[13] Nevertheless, these models are as well subject to a change of media as described, although in reversed order, if at all they are bound to intervene in empirically based research and do not remain plainly speculative. They are as well in need of a concretization in relation to the epistemic objects with which they are being connected. A different concept of model is used in mathematical logic as initially developed by Alfred Tarski. Here, models function as interpretations of an abstract structure,[14] whereas models in

[11] Levins (1966, pp. 421–422).

[12] Morrison (2015), Morgan (2012).

[13] Keller 2000.

[14] Tarski (1937).

art and architecture basically act as a precept. I cannot enter into a discussion of all these different concepts of model here. Suffice it to say that with models we are facing an intrinsically polysemic concept.

3 Model Organisms

At this point, allow me, as a historian of the life sciences, to make a short digression on the concept of *model organism*,[15] since model organisms have become a constitutive part of experimentation in the life sciences. In this compound expression, the notion of model is again used with a different connotation. Although the term came into general use only in the second half of the twentieth century, model organisms established themselves already at the beginning of the twentieth century under the notion of "experimental" or "research" organisms. With respect to the role model organisms play in the life sciences in general and in genetics in particular, the concept of model takes on a meaning of its own that needs briefly to be explicated and historically situated.[16]

In the course of the nineteenth century, a major turn happened in the biological sciences. If until then biologists had been particularly interested in the diversity of organismic appearances, now the common ground of these appearances moved center stage: The features they all shared and that could be investigated particularly well in certain organisms which therefore could be said to stand for all the others. It is exactly here that the concept of model organism comes into play. In a metaphorical sense, model organisms are ideal, that is, especially apt, targets for the investigation of a certain phenomenon. First, this aptitude consists in the assumption that they exhibit the biological phenomenon in question in a particularly pronounced fashion; second and above all, that they are exceptionally accessible and experimentally manipulable in this respect. This *ideality* has, in turn, *material* consequences: For the sake of standardization, one intervenes in certain properties of the organism in question, as for instance with the creation of pure lines or specific gene combinations in genetic model organisms. Therefore, *model* organisms are always organisms that have been *modified* for the sake of the

[15] Literature on model organisms is abundant. See, e.g., the pioneering article Burian (1993), Creager (2002), Rader (2004), Gachelin (2006), therein in particular Gayon (2006), Ankeny and Leonelli (2021).

[16] See also Levy and Currie (2015).

research questions actually pursued. That determines—and also restricts—their character as research tools. Model organisms are thus *not* objects of investigation in the proper sense, or epistemic things of which models are to be constructed. They rather belong to the technical conditions of an experimental system. They are research technologies of a biological character. In contrast to other research technologies, their interface with the epistemic things for the sake of which they are being investigated is internal. In contrast, analytic instruments approach the organism from outside.[17]

4 Structural and Functional Models in Biology

That much, in short, about model organisms. Another characteristic of *biological* research relevant for a discussion of models is the ubiquitous distinction between *functional* and *structural models*. Models of both kinds do not only act as incentives in the experimental research process, they also circulate as carriers of knowledge, as communal parts of the professional discourse, and they are permanently questioned and reworked by the scientific community participating in the exploration of the phenomena in question.[18] Empirical models are therefore not "immutable mobiles"—to pick up an expression coined by Bruno Latour—, they are highly mutable mobiles.[19] They serve as a permanent source for the iterative process of the creation of new traces that, transformed into data, can again be scrutinized with respect to their compatibility with the existing models. Incorporated into the model, they refine it, modify it, or question it altogether. In the end, what counts is less the "representational" character of the model in the sense of its trueness to nature than its "interventional" character.[20] In this sense, we can agree with what Alain Badiou stated in his early book on the *Concept of Model*: "Note that it [the model], as a transitory adjuvant, is actually destined for its own dismantling, and that the scientific process, far from fixing it, is bound to deconstruct it."[21]

[17] Rheinberger (2010), chapter 11.

[18] For the mediating function of models compare Morgan and Morrison (1999).

[19] For the concept of "immutable mobiles," see Latour (1990).

[20] Compare Hacking (1983).

[21] Badiou (2007, p. 58).

In biological research, functional models usually accompany research on biological processes down to the cellular and molecular level. In the language of the community, they are often addressed as “mechanisms,”[22] examples being the mechanism of protein biosynthesis or the mechanism of DNA replication. Since biological functions are always correlated with biological structures, a parallel modelling of these structures takes place, be it the three-dimensional modelling of macromolecules, of complexes of such molecules, of cellular compartments, or of organs in higher organisms. And there is an ongoing debate about whether ‘function follows structure’ or ‘structure follows function.’ In either case, structures and functions are intimately correlated. In an articulated research field in which whole batteries of highly specialized research technologies are being used, structural and functional analyses are usually carried out by different working groups. As a result, the members of the different groups have to communicate with each other, and they do so less by discussing procedural details with which they are reciprocally unfamiliar, than through these intuitively accessible models.

Consequently, at least part of the communication in such a widely spread community no longer follows the details of the original production of traces and the collection of data at the experimental bench, but is mediated through models at a level where synopsis becomes possible. That means that besides the cyclic feedback between models and the experimental production of data that lead to these models in each of the camps, we are confronted here with a second-order feedback *between different models* that either target one and the same epistemic object but rest on different sets of data, or focus on different aspects of an epistemic object such as its structure or its function. Such a confrontation of different models among themselves can again lead to a mutual adaptation of the models and can deliver incentives for the production of new experimental data. In this case, we no longer deal with the relation of a representation to a supposed phenomenon, where one typically asks for the meaning of the model with reference to the phenomenon at stake, but rather with a relation *between different representations*. We encounter a second-order space in which, to pick up a differentiation made by Gottlob Frege, something makes rather *sense* or not.[23] Or, to

[22] Craver and Darden (2005).

[23] Frege (1962).

state it again in the words of Richard Levins: "We attempt to solve the same problem with several alternative models each with different simplifications but with a common biological assumption. Then, if these models, despite their different assumptions, lead to similar results we have what we can call a robust theorem [...]. Hence our truth is the intersection of independent lies."[24]

The function of a model in experimental research processes is therefore not representation alone, and possibly not even predominantly so: The model is also, and in particular, a tool for the production of further knowledge. It functions as a temporary reification of an epistemic thing, the phenomenon that is the target of research. The emphasis here lies on *temporary*. For reification always also means restriction, abstraction, and simplification. Models do not only show, they also omit. The epistemic danger of a model consists in forgetting its partial character—and with that, its partiality. The multiplication of models is one of the possible epistemic remedies for this restriction. Alain Badiou's as well as Georges Canguilhem's remarks on the essentially deficient character of models and the dangers connected to it in research point exactly in this direction. Canguilhem stated it in the following way: The function of a model "consists in lending its type of mechanism to a different object," a role that it can only effectively fulfill, however, if it "does not impose itself as axiomatic."[25] The essential mode of existence of a model therefore embodies preliminarity.

5 Computer-Graphic Models

The practice to compare models that rest on different sets of data from alternative technologies of visualization demonstrates its knowledge generating potential, in particular with the increasing number of *computer-graphic models* that more and more dominate the scene of present-day laboratories. Since the different research technologies require different preparation procedures for the probes in order to create a trace-generating interface between the instrument and the object of investigation, they all, in one way or another, intervene with the configuration of the investigated objects. As a rule, native and untouched epistemic

[24] Levins (1966, p. 423).

[25] Canguilhem (1961, p. 514).

objects cannot be visualized, which means that the manipulation of their shape cannot be avoided. The permanent triangulation between the results of such manipulations is the only possibility to gain a robust image of the object in question in an indirect fashion. In the space of such triangulation, different models necessarily come to be confronted with each other, and the respective representations shape and reshape each other mutually.

The resources for computer-graphic modelling are extraordinarily diverse and manifold. But not everything is new here. In the realm of molecular biology and biochemistry that serves as a background for my considerations, the conventions of representation for the secondary structure of nucleic acids and of proteins, for instance, have become an integral part of its repertoire. These conventions were already established long before the time when computer modelling became fashionable, and so did other characteristics of classical three-dimensional molecular modelling—such as the chemical space-filling and rod models of atoms that have been in place for more than a century.

There are, however, also options that go beyond the classical forms of representation. One of the most innovative aspects of this kind of computer-graphic modelling can no longer be presented in the form of traditional, static models: It is the free mobility of such models—including their parts—in space. This additional option does not only present new possibilities of testing, say, atomic fittings, it also enables the representation of functional states of molecules or molecular complexes in their temporal succession, that is, the representation of processes.

However, computer models of this kind can never be better than the experimentally produced data on whose basis they are constructed. When, some years ago, I asked Nobel Prize winner Ada Yonath, a pioneer of models of such molecular complexes in the 1980s, about the role of the computer for her structural investigations of cellular organelles and their drug interactions, she gave me the short-shrift answer: “Forget it, it’s all chemistry!”[26] The lesson is that one has to be careful not to overestimate the role and the research benefit of computer-graphic modelling.

[26] Conversation on the occasion of a symposium on the Fiftieth Anniversary of the Max Planck Institute for Molecular Genetics in Berlin-Dahlem, in December 2014.

6 Computer Simulation

At this point and in closing, a short digression on the concept of *computer simulation* appears to be in order. I understand simulation here as having the precise meaning that computer images do not only rest on computer-driven algorithms, but also work with data that are computer generated. They represent a form of epistemic entities and processes that qualitatively differs from the concept of model on which I have focused here. They are not models *of*, they belong to the category of models *for* that I have mentioned at the beginning but eclipsed for the rest of this paper. As Jean Baudrillard once pointedly said, simulations are characterized by a "precession," an antecedence of the model.[27] In this paper, I have focused on models in the experiment-driven sciences that, besides always being accompanied by a change of medium, including the computer, are always fed by data derived from experimental traces. Simulations, however, can also operate with self-generated data and with that, can envisage origins and futures that remain beyond the scope of experimentation in real space and real time—virtual time, virtual space.

Of course, simulations also existed in times before the computer. In this sense, they are by no means radically new. However, they had a rather restricted range of manipulation. We could even look at mathematics, insofar as it rests on axioms, as a gigantic system of simulations that helps us to understand the world around us. Computer-implemented simulation, however, opens an additional space of experimentation, in which models themselves can become objects of research to an extent that by far transcends, by virtue of the usage of deliberately generated data, work with and on classical models.[28] Whether the technical and epistemic elements configured in this space can be seen as an alternative form of experimental systems—in-silico-systems or "simulation systems" as Margaret Morrison calls them, or "modeling experiments," as Evelyn Fox Keller prefers to say[29]—or whether they simply extend the technical conditions of 'wet' experimentation, is a question that I can only pose on the basis of the material discussed here, but not answer in any definitive fashion. Franck Varenne, in any case, is of the opinion that "integrative software-based computer simulation," as he calls it, and as it developed

[27] Baudrillard (1983, pp. 31–32).

[28] Gramelsberger (2010).

[29] Morrison (2015, p. 218), Keller (2003, p. 205).

since the 1970s, qualitatively transcends the computer-based implementation of formal models. With that, it would not only continue the tradition of dealing with formal models—essentially, models *for*—as they developed since the beginning of the twentieth century, with greatly extended means and put them on a new level. It would also make possible "experiments with simulation" or "virtual experiments,"[30] that as such would even "precede the model," to speak with Varenne.[31] That would then be a precedence of a second order. We would have to face experimental systems in virtual space that not only allow to manipulate models, but to create and to shape them.

7 Closing Remark

We know about the precession of models in their material, analogue shapes from other realms of culture than science. We are very familiar with them in art and architecture. Here, the relation between the model and the modeled is always already inverted, though in specifically characteristic forms for each of them. What it means that the precession of models is currently taking over in the sciences and how that may affect the relation between the sciences and the arts, this I must leave open for now—as both a question and a *desideratum* for further discussion.

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[30] Varenne (2019, p. 9).

[31] Varenne (2019, p. 10).

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Model-Based Science as Epistemic Warfare. Scientific Models in a Static and a Dynamic Perspective

Lorenzo Magnani

1 Scientific Enterprise as a Complicated Epistemic Warfare

Scientific models are no longer just seen as helpful tools for discovering new entities, rules, and theories or for elucidating existing ones in the present epistemological discussion: from the classical ones, abstract entities[1] and idealizations,[2] to the more recent, fictions,[3] surrogates,[4]

[1] Giere (1988), Giere (2009), and Giere (2007).

[2] Portides (2007), Weisberg (2007), and Mizrahi (2011).

[3] Fine (2009), Woods (2010), Woods and Rosales (2010b), Contessa (2010), Frigg (2010a), Frigg (2010b), Frigg (2010c), Godfrey-Smith (2006), Godfrey-Smith (2009), Woods and Rosales (2010a), Suárez (2009), and Suárez (2010).

[4] Contessa (2007).

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credible worlds,[5] missing systems,[6] make-believe,[7] parables,[8] functions,[9] epistemic actions,[10] revealing capacities.[11] Given the vast body of information on scientific models that has previously been developed in both cognitive science and epistemology, the proliferation of explanatory metaphors is astounding. The legitimacy of using the word 'fictions' in the context of scientific models is a topic of debate among some of the authors already mentioned.

Even though the aforementioned studies on fictionalism have improved our understanding of some facets of the function of models in science, I am convinced that they have occasionally also led to some philosophical ambiguity. Accordingly, I believe it is appropriate to "keep quiet on the ontology of models"[12] and to adopt a more skeptical theoretical stance. I believe that, for instance, models may be thought of as fictions or surrogates, but this only correlates with a commonsense view, which seems to be philosophically empty. Models are employed in science in a number of ways, such as teaching tools, for testing hypotheses,[13] or for explanatory purposes.[14] Yet, these latter uses of models in research are very well known and only mildly disputed in the epistemological literature. In this article, I will focus on scientific models in creative abductive cognition since this kind of cognition continues to be, in my opinion, the central problem in present epistemological research.[15]

I believe that models in scientific reasoning are neither merely fictions, simple surrogates, or make-believe, nor are they unproblematic idealizations. Contrary to popular belief, models are never *abstract*. This does not imply that the conventional epistemological notion of an abstract model is senseless, but rather that it must be interpreted in a Pickwickian way. In

[5] Sugden (2000, 2009), and Kuorikoski and Lehtinen (2009).

[6] Mäki (2009), and Thomson-Jones (2010).

[7] Frigg (2010a), Frigg (2010b), Frigg (2010c), and Toon (2010).

[8] Cartwright (2009b).

[9] Chakravartty (2010).

[10] Magnani (2004a) and Magnani (2004b).

[11] Cartwright (2009a).

[12] French (2010).

[13] Portides (2007).

[14] Bokulich (2011).

[15] Hintikka (1998).

the meantime, I want to support my argument against fictionalism while also outlining the key elements of what I call 'epistemic warfare,' which views the scientific enterprise as a difficult battle for rational knowledge in which it is essential to distinguish between epistemic (like scientific models) and non-epistemic weapons (like fictions, falsities, propaganda, etc.). I view the scientific enterprise as a complex epistemological warfare; therefore, it is reasonable to encounter fictions in this battle for rational knowing. All conflicts that define human coalitions of any type involve fictions, don't they?

In the 70s of the previous century, Feyerabend[16] emphasized emphatically how, despite the eventual success, the scientist's statements are frequently weakly supported by propaganda and psychological techniques in addition to whatever intellectual arguments he has to provide, as in the case of Galileo, as argued by Naylor.[17] Galileo's explanations of actual experiments—in both the *Dialogo* and also the *Discorsi*—turn rhetorical, to confound the critics and convince the readers as well as to meet didactic aims.

These tactics are very helpful and effective, but one thing is the *extra-epistemic* role of propaganda and rhetoric, which only plays a minor—positive or negative—ancillary role in the epistemic warfare, with respect to the *epistemic* role played by scientific models illustrated in this article, that directly govern the path to provide a new intelligibility of the target systems at hand. In the first case, we face various contributions to the epistemic warfare, whether in a favorable or negative way: these elements, so to speak, provide non-epistemic weaponry that might, for instance, convince other scientists who are members of a competing 'coalition' or develop and enhance the coalition in question, which supports a particular research program, for example, to get funding. I merely want to emphasize that models play a 'fundamental' part in scientific discovery processes and that these models cannot be characterized as fictional at all since they are *constitutive* of new scientific frameworks and new empirical domains and so of a new *knowability*.

I draw two basic conclusions:

[16] Feyerabend (1975).

[17] Naylor (1976).

1. It is important to distinguish between the constitutive role of modelling in the central creative processes, which occurs when novel and conceptually revolutionary perspectives are advanced, and the significance of models in ancillary areas of scientific investigation as 'expediency of the inference,' which has long been recognized in science;
2. Models are essentially just models that idealize and/or abstract; however, these last two characteristics need to be severely challenged in light of new epistemological/cognitive literature as distinct categories of epistemic actions, as I shall demonstrate in section 2 below: abstractness and ideality cannot be primarily tied to empirical insufficiency and/or theoretical incoherence,[18] just adopting a merely static perspective of the scientific enterprise.

2 Models Do Not Exist in Abstraction and Are Distributed: Model-Based Science as Epistemic Warfare

In the previous section, I advanced the hypothesis that models in science are neither mere fictions, simple surrogates or make-believe, nor are they unproblematic idealizations. I specifically argued that models are never *abstract* or *ideal*, contrary to the received view: they do not live—so to speak—in a kind of mysterious Popperian *World 3*. Let us delve more into the second issue, which is concerned with the idealized and abstract character of models used in scientific reasoning.

First of all, when obviously available at a certain point in a scientific discipline's growth, approved models in science are unquestionably built on the basis of several constraints pertaining to abstract laws, principles, and notions. When dealing with physical and computational models or with human 'mental models,' which are ultimately unique, unrepeatable, and constantly changing configurations and transformations of neural networks and chemical distributions at the level of human brains, we must simultaneously emphasize that the same models are always *distributed* material entities. According to this viewpoint, models are 'abstract' only in the Pickwickian sense, that is, as 'mental models,' which scientists share

[18] Suárez (2009, p. 168).

to varying degrees depending on the sort of research community at issue. So, this cognitive viewpoint can assist us in clearing up any ambiguity brought on by the idea that models are abstract.

I argue that the so-called *abstract model* may be better understood in terms of what Nersessian and Chandrasekharan refer to as the *manifest model*[19]: it is an internal model that is manifest because it is shared and allows group members to perform manipulations and thus form common movement representations of the proposed concept. The scientific collective decides whether the model is worthwhile to pursue and whether it would address the problems and concepts researchers are faced with. The manifest model also enhances group dynamics, according to Chandrasekharan.[20] Although each person's brain has a somewhat different internal representation, this does not stop the many distinct representations from being thought of as 'abstract' insofar as they are simultaneously 'conceived' as referring to a specific model. However, 'new' insights/modifications in the internal manifest model typically occur at the individual level, even though the approach to solve a specific problem through the model in question is typically shared by a specific scientific collective: the individual adjustment has the potential to solve the target system's issues and hence promote new understanding. New insights/adjustments, however, might also result in the decision to throw out the current model and construct a new one that is expected to be more successful and may even end up becoming the new manifest model. In addition, some common manifest models, such as the ideal pendulum, can develop a high degree of stability through time and across scientific and educational institutions, echoing the notion of a high degree of abstraction in scientific models.

Moreover, recent experimental cognitive research[21] further offers profound and new epistemological insight into the age-old issue of abstractness and ideality of models in scientific reasoning from the standpoint of distributed (and embodied) cognition.[22] The study presents two concrete external models that approximate the functionality and activity of neurons: one is physical (in vitro networks of grown neurons), and the

19 Nersessian and Chandrasekharan (2009).

20 Chandrasekharan (2009, p. 1079).

21 Chandrasekharan (2009).

22 Hutchins (1999).

other is a computational equivalent that was recently developed and used in a neural engineering lab. These models are clearly understood to be external systems—external artifacts created more or less intentionally. In the same way as concrete diagrams in ancient geometry interacted with internal equivalent models of the researchers, those prepared concrete models attempt to generate new concepts and control structures about their target systems. Yet, we are dealing with a case of manipulative abduction, that is occurring when we are *thinking through doing* (and not only, in a pragmatic sense, *about* doing). It is difficult to imagine this type of action-based cognition as being fully purposeful and aware.

Manipulative abduction,[23] which is widespread in the management of scientific models, is a procedure in which a hypothesis is generated and judged thanks to an essentially extra-theoretical and extra-sentential conduct that aims at producing communicable accounts of new experiences to integrate them into previously existing systems of experimental and linguistic (theoretical) practices. In order to handle things and pieces of knowledge that cannot be instantly represented or located internally, manipulative abduction is a type of redistribution of the epistemic and cognitive effort. The use of external models by humans in the neural engineering lab described by Chandrasekharan[24] is an example of manipulative abduction: these models are useful for making observations and performing 'experiments' to switch from one cognitive state to another in order to learn new information about the target systems. The term manipulative abduction also applies to those more unconscious and unplanned action-based cognitive processes that I have referred to as 'thinking through doing' techniques, as already quoted above.

In general, external models are more flexible than internal ones, and they put less strain on scientists' minds in terms of memory and cognitive burden. They also reflect the constraints imposed by the medium in question, which rely on the inherent and immanent cognitive/semiotic delegations (and the chosen conventionality) made by the model creator(s): artificial languages, arguments, proofs, fresh data, illustrations, computer simulations, etc.[25] It is obvious that information (about model

[23] Magnani (2009, chapter 1).

[24] Chandrasekharan (2009).

[25] For more information on the cognitive delegations to external objects, see Magnani (2009, chapter 3, section 3.6); see also Vorms (2010): the study provides a helpful explanation of how formats matter when it comes to external hypothetical models and

conduct) travels from models to scientists through perception (and not only through visualization as a simple representation and also through "movements in the visualization [which] are also a way of generating equivalent movements in body coordinates"[26]).

3 Are Scientific Models Fictions or Epistemic Weapons?

Models are created by the scientist's mind, which first assigns 'meanings' to external artifacts. In other words, the mind's 'internal' representations are 'extended' in the environment and later shaped by processes that are taking place through the constraints found in the external models; that is, in the externality that consists of the 'concrete' model represented by the artifact, in which the resulting aspects and modifications/movements are 'picked up' and in turn re-represented and reworked in the human mind/brain.

This viewpoint allows us to enjoy the speculative Aristotelian expectation that 'nihil est in intellectu quod prius non fuerit in sensu,' now within a naturalistic context. As a result of the information that comes from the model, the scientists' internal models are reconstructed and improved, and the modifications that result can easily be seen as guesses—both instinctual and reasoned, depending on the brain areas involved—, that is as plausible abductive hypotheses about the external extra-somatic world (the target systems). The process is best understood from the viewpoint of the notion of cognitive niches.[27] The mind develops alongside its representational delegations to the outside world, which has created itself over the course of cultural history by building the so-called cognitive niches. In this instance, the complex cognitive niche of the scientific lab is an *epistemological* niche that is specifically designed to advance knowledge using cognitive processes, where people, systems, and environmental affordances collaborate in an integrated manner.

Therefore, in my view, models cannot be regarded as either abstract (in the traditional ambiguous sense) or fictional: scientists do not provide

representations as well as how they offer various unexpected affordances and inferential opportunities.

[26] Chandrasekharan (2009, p. 1076).

[27] The concept of cognitive niche is described in detail in Odling-Smee et al. (2003).

fictions but models that reshape a generic cognitive niche as an epistemological niche with the intention of carrying out a true struggle for representing the outside world. Instead, they provide models as tools that enable this genuine struggle. Models, the war machines used in this conflict of epistemic warfare to emphasize the determined—strictly epistemic—dynamism of the adopted tools that are in play, are not illusional fictions or stratagems used, for example, to cheat nature or defraud human beings, but simply concrete, unambiguous, and well-disposed tactical intermediate weapons capable of strategically 'attacking' nature (the target systems) in order to further reveal its structure. Contrarily, fictions in literary works are intended to reveal human life and characters in fresh aesthetic perspectives and/or to offer moral criticism, while fictions and stratagems in military operations are intended to deceive the adversary and even kill the eco-human targets.

I argue that epistemologists should not forget that several cognitive processes, even if not evident in syntactilized human natural language and in abstract knowledge, do have a 'military' character.[28] It is hard to directly see this "military intelligence"[29] in the various situations in which natural language serves a variety of *epistemic* purposes, such as when it is simply used to communicate scientific findings in a lab setting or when we collect weather-related information from the internet that is conveyed in linguistic terms and numbers.

We must remember, though, that even the more abstract nature of knowledge packages encoded in some language usages (and in hybrid languages, such as mathematics, which has large symbolic components) still has a huge impact on how human collectives act morally. For instance, the creation and dissemination of new scientific knowledge within human social organizations not only involve the use of information but also the implementation and distribution of roles, capacities, restrictions, and actionable options. This process is essentially moral because it produces specific distinctions, powers, obligations, and opportunities that have the

[28] I illustrated in detail the intertwining between cognition and violence in Magnani (2011).

[29] I am borrowing this concept from René Thom, who, in my opinion, connects 'military intelligence' to the role that language and cognition play in what is known as *coalition* enforcement, that is at the level of their complementary effects in the affirmation of moralities and related conducts, and the consequence of carrying out potentially violent punishments.

potential to either spark the emergence of brand-new, violent intragroup conflicts or modify already-existing ones across groups. For example, two morally and socially opposing outcomes often result from a new theoretical biological understanding about pregnancy and fetuses: (1) an improved social and medical management of birthing and associated illnesses, and (2) the probable escalation or alteration of debates over the legality of abortion.

In conclusion, even declarative knowledge and deductive reasoning are being accompanied by argumentative, deontological, rhetorical, and dialectic aspects. These aspects govern the identity of groups and their aggressive potential as coalitions and even highly abstract bodies of knowledge, and more innocent pieces of information enter this process. For instance, it can be challenging to tell the difference in an eco-cognitive setting between a 'pure' (deductive) inferential role of language and an argumentative or deontological one. The first one can undoubtedly serve an associated argumentative purpose. However, it is in the arguments commonly described as fallacious, that we can more clearly capture the military role of human language and especially of some hypotheses gained from the exploitation of fallacies.

So, we must be conscious that while science imposes itself as a paradigm for creating knowledge in a particular 'decent' way, it also de facto participates in the inter-disciplinary warfare that is a hallmark of modernity: science has more or fewer conflicts with non-scientific fields such as religions, literature, and magic. Science also indirectly rules and regulates communities through technical advancements that enforce moral standards and behaviors. However, scientific cognitive processes—*sensu strictu*, inside scientific groups as coalitions—involve propaganda that is also directed externally at other private and public coalitions as well as at the general public, for example for acquiring funds (a fundamental issue frequently ignored in contemporary science is the cost of producing new models) or for advertising a hypothesis or a method, as Feyerabend says. Yet, the basic cognitive process of science is founded on avoiding fictional and rhetorical tricks when the production of its own attitude for truth is at risk. Lastly, science is precisely the enterprise which generates those kinds of truths which realize the patterns for *demarcating* fictions and so 'irrational' or 'arational' ways of knowing.

I am aware that epistemological fictionalism does not view fictions as forgeries or fakes; it rather views them as something that is far from being execrable or being cherished.[30] However, to say that both scientific and literary fictions are 'good' fictions is a theoretical oversimplification: science, rather than literature or poetry, is responsible for developing 'new' types of models that are committed to a specific production of truth and explicitly aim to be non-fictional.[31] I emphasize that when we speak of the ideal pendulum in the same way as we speak of Anna Karenina, we run the risk of unintentionally opening the doors of epistemology to a kind of relativistic post-modernism *à la mode*, even though fictionalists appear to avoid this potential confusion by producing—frequently useful—taxonomies about the slight differences between fictions in science and other cognitive practices.

Overall, I am convinced that adding the term 'fiction' to the study of epistemology only slightly enhances the analysis of concepts like inference, explanation, creativity, etc. It merely introduces an alluring new lexicon that makes use of some seductive concepts, such as those from the theory of literary fictions.[32] Anna Karenina and the in vitro model are very different.

In actual scientific research, a model gains a fictional status only *after* the collective of scientists has recognized it as such because it has *failed* in adequately representing the target systems. Under these circumstances, a model is just thrown away. If Anna Karenina had not accurately represented a female member of Russia's high society at the end of the nineteenth century, for example, Tolstoy might have discarded her as an inappropriate fiction for some contemporary aesthetic purpose; however, he would have replaced her with yet another similarly fictional character, doomed to *remain* fictional forever. Tolstoy did not aim at representing real people except in general but we know that a fundamental function of science and of scientific models is to represent real physical processes.[33]

Contrarily, as I previously stated, when a scientific model is judged to be unproductive, it is recognized as fictional in a cognitive (often creative)

[30] Frigg (2010c, p. 249).

[31] Cf. the last section of my article Magnani (2012), which describes Galileo's famous thought experiment regarding falling bodies.

[32] Curiously, in the recent epistemological discussion about fictions, even the entire 'experimental systems' are amazingly reframed as "materialized fictional worlds" (Rouse 2009, p. 51).

[33] Giere (2007, p. 279).

process by applying a kind of *negation as failure*[34]: it becomes fictional in the simple sense that it is falsified (even if 'weakly' falsified, by failure). From a methodological perspective, negation as failure is an elimination process analogous to what Freud describes in the case of constructions, which are stories the analyst creates about the patient's past psychic life, and which are abandoned if they do not advance the therapeutic psychoanalytic process. When the patient does not furnish new data capable to expand the already available construction, if nothing further appears, Freud states, we may conclude that we have made a mistake and we shall admit as much to the patient at some suitable opportunity without sacrificing any of our authority. The chance of refusing the already reached construction arises when new data arrive that are capable of generating a better construction and so of correcting our error. "In this way the false construction drops out as if it has never been made; and indeed, we often get the impression as though, to borrow the words of Polonius, our bait of falsehood had taken a carp of truth."[35]

Similar to this, in the scientific discovery process the scientific model is merely eliminated and labeled as 'false' because fresh information seems to provide a more accurate model, which in turn will lead to new knowledge that replaces or improves the earlier theory. As a result, the earlier model gets buried in the cemetery of useless or dead models. The ether model is an example of a successful scientific model that was simply eliminated from the scientific enterprise along with the theory to which it belonged. As a result, the old model is buried in yet another necropolis of the dismissed historical models, and it can be credibly reclassified as a fiction.

4 The Unwelcome Confusion Between Static and Dynamic Aspects of the Scientific Enterprise

In the case of creative processes, the produced external scientific model is the exact antithesis of both fiction and a general make-believe process (it is neither a simple surrogate[36] nor a bare credible reality[37]). Instead, it

[34] Clark (1978) and Magnani (2001).

[35] Freud (1953–1974, vol. 23, 1937, p. 262).

[36] Contessa (2007).

[37] Sugden (2000) and Sugden (2009).

serves as a regulatory tool that has been made stable in some outer form, acting as a trustworthy anchoring rather than being consciously established as fiction, as a romance author could do while describing Harry Potter's character.

The usage of the term 'fiction' in epistemological fictionalism concerning models is typically justified by the absence of empirical systems that match, for example, the ideal pendulum (and its equation). However, the term creates a paradox that is easy to grasp using the example of scientific models being referred to as "missing systems," a brand-new metaphor that is similar to the fictional one. Thomson-Jones highlights that science is rife with "descriptions of missing systems," which are ultimately seen as abstract models.[38] By the way, Cartwright, in a more informal and straightforward manner, refers to a "prepared description" of the system in order to make it susceptible to mathematical treatment.[39]

Further complicating the missing systems' framework by adding a supplemental metaphoric conceptual apparatus, Mäki usefully acknowledges that scientific models are "pragmatically and ontologically constrained representations" and adds another metaphoric conceptual apparatus: missing systems are also "surrogate" systems expressed as credible worlds, as models.[40] Godfrey-Smith makes similar claims:

> To say that talk of model systems is a psychologically exotic way of investigating conditionals (and the like) is not itself to solve the problem. It is natural to think that the useable output we get from modeling is generally a *conditional*—a claim that if such-and-such a configuration existed, it would behave in a certain way. The configurations in question, however, are usually known *not* to exist, so the problem of explaining the empirical usefulness of this kind of knowledge reappears.[41]

I argue that, at least in a discovery cognitive process, the missing system (Thomson-Jones) is not, paradoxically, the one represented by the 'model', but rather the target system itself, which will only appear as 'known' in a new way after the research process results are accepted,

[38] Thomson-Jones (2010, p. 283).

[39] Cartwright (1983, p. 15).

[40] Mäki (2009).

[41] Godfrey-Smith (2009, p. 115).

admitted into the theory T, and considered worth to *persisting* in T thereafter.

The same can be said of models as configurations (Godfrey-Smith), which are undoubtedly conditional, but do not need to be regarded as "known not to exist" in Godfrey-Smith's sense because in the instant in which a scientific model is adopted in a discovery procedure, it is instead just the only object we sufficiently *know* to exist (for example a diagram in a blackboard, or an in vitro artifact, or a mental image). Only within the context of a robust metaphysical realism can we assert that, once a final scientific result has been attained, along with the description of the associated experimental side, everything that does not fit that final structure is a fiction, including models that contributed to the achievement of that result. The overuse of the term 'unrealistic' to describe fictional scientific models only because they appear on the surface is addressed by Morrison quite directly: this would be an error, largely because it provides very little information regarding the function that unrealistic representations serve in the creation of knowledge.[42]

Further, Kuorikoski and Lehtinen assert that: "The epistemic problem in modelling arises from the fact that models always include false assumptions, and because of this, even though the derivation within the model is usually deductively valid, we do not know whether our model-based inferences reliably lead to true conclusions."[43] Yet, the false premises (also due to the presence in models of both substantive and auxiliary assumptions) are not exploited in the cognitive procedure, because, in several heuristic processes, only the *co-exact* ones are used. The concept of co-exact properties, as suggested by Manders,[44] merits additional research in areas outside the sphere of classical geometry's discovery procedures, where it has been well emphasized.[45]

[42] Morrison (2009, p. 133).

[43] Kuorikoski and Lehtinen (2009, p. 121).

[44] Manders (2008).

[45] Mumma (2010, p. 264) demonstrates how Euclid's diagrams contribute to proofs only by virtue of their co-exact features. Euclid never deduces an exact property from a diagram unless it follows logically from a co-exact property, in other words: "Euclid never infers an exact property from a diagram unless it follows directly from a co-exact property. Exact relations between magnitudes which are not exhibited as a containment are either assumed from the outset or are proved via a chain of inferences in the text. It is not difficult to hypothesize why Euclid would have restricted himself in such a way. Any proof, diagrammatic or otherwise, ought to be reproducible. Generating the symbols

Furthermore, some false assumptions are only considered to be false when viewed in the context of the target system, which is still 'to be known'. As a result, they only appear to be false in a 'post hoc' analysis, even though they are absolutely true within the model itself during the relative autonomy of the smart heuristic cognitive process associated with its use. So various features of the model are the licitly true foundation for the subsequent examination of its behavior and the generation of the abductions to plausible hypotheses regarding the target system. In my opinion, Morrison is totally right: "I see this not as a logical problem of deriving true conclusions from false premises but rather an epistemic one that deals with the way false representations transmit information about concrete cases."[46]

In conclusion, I believe it is deceptive to examine scientific models by combining static and dynamic features of the scientific inferential processes. Scientific models appear—but just appear—to be fictional in a static viewpoint (for instance, when they are included in a textbook) since they are contrasted with the target systems and their intricate experimental equipment: in this case, also the so-called *ideal* nature of models becomes manifest and so does the *explanatory* function of them.[47] In contrast, scientific models seen within the concrete dynamics of scientific creative processes, which has been the central concern of epistemology at least since Karl Popper and Thomas Kuhn, appear *explicit* and *reproducible* tools that have been purposefully constructed and manipulated to produce further scientific knowledge not yet available.

Morrison is undoubtedly not inclined to view models as fictions because she emphasizes that in science they are specifically related to ("finer grained") ways of understanding and explaining "real systems," far beyond their more supporting predictive capabilities and their advantages in approximating.[48] She goes on to say that the models that are suitable

which comprise it ought to be straightforward and unproblematic. Yet there seems to be room for doubt whether one has succeeded in constructing a diagram according to its exact specifications perfectly. The compass may have slipped slightly, or the ruler may have taken a tiny nudge. In constraining himself to the co-exact properties of diagrams, Euclid is constraining himself to those properties stable under such perturbations."

[46] Morrison (2009, p. 111).

[47] Cf. Weisberg (2007).

[48] Morrison (2009, p. 115).

for labeling as *abstract* resist—in the so-called process of de-idealization—corrections or relaxing of the unrealistic assumptions (this is the case of mathematical abstractions or when models provide the immediate chance for the applicability of equations), since they are "necessary" to reach particular outcomes. As noted by Cartwright, their ability to provide an overall new depiction of an empirical (and/or, as in the case of mathematics or logic, theoretical) framework is what matters most, not the fact that in these models "relevant features" are subtracted to focus on a single—and thus isolated—set of properties or laws: "We have a description of a physically unrealizable situation that is required to explain a physically realizable one."[49]

Some models, which are simpler to define and are best categorized as *idealizations*, permit "the addition of correction factors that bring the model system closer (in representational terms) to the physical system being modelled or described."[50] As an illustration, consider the simple pendulum, where we might apply adjustments to address real-world events. Idealizations exaggerate or omit characteristics; in contrast, abstractions bring about a certain type of representation that is not accessible to rectification and is essential for the explanation/prediction of the target system,[51] which imparts knowledge and offers information. Morrison's description of scientific models as abstract is consistent with my emphasis on models as *constitutive*, going beyond the simple function played by models as idealizations, which instead allow corrections and refinements.[52] According to this viewpoint, 'abstract' models, either related to preparing and favouring mathematization or directly involving mathematical tools, must be intended as poietic means of producing new intelligibility of the fundamental characteristics of the target systems phenomena, and not simply as expedients for facilitating calculations.

Mäki says that "[i]t may appear that a fantastically unreal feature is added to the model world, but again, what happens is that one thereby removes a real-world feature from the model world, namely the process

[49] Cartwright (1989, p. 130).

[50] Morrison (2009, p. 111).

[51] Morrison (2009, p. 112).

[52] Again, cf. the final section of my article Magnani (2012) devoted to Galileo's well-known thought experiment regarding falling bodies.

of adjustment"[53]: I can observe that, at least in the case of several creative inferences, the model is not necessarily realized through 'removal' or 'neutralization' of real-world aspects, because some aspects of the target system—that is what it usually classified as real world—have trivially 'not been discovered yet', and so, amazingly, they are the ones still 'missing'. As the model was created to achieve a specific goal, it is thus impossible to think that some of its traits came from the real world's features being removed; instead, they could only have come through the cognitive process that built the model itself to reach the result. In addition, and for the same reason, it is challenging to consistently claim that models represent 'surrogate' systems since the systems we desire to subrogate are extendedly not unknown.

5 Conclusion

First of all I have argued in this essay that scientific models are not fictions. I have also contended that related epistemological approaches to model-based scientific cognition (in terms of surrogates, credible worlds, missing systems, and make-believe) also exhibit serious deficiencies that can be identified by utilizing both the concept of manipulative abduction and recent cognitive research, embedding them in the framework of what I call 'epistemic warfare'. In this perspective, scientific enterprise is viewed as a challenging struggle for rational knowledge in which it is essential to distinguish between extra-epistemic weapons (such as fictions, falsities, and propaganda) and epistemic ones (such as scientific models). The illustrated criticism, which was also conducted in the context of distributed cognition, provided additional information regarding the study of the two primary traditional properties assigned to scientific models: abstractness and ideality. I come to the conclusion that when models are fictions in scientific contexts, it is because they were simply abandoned as heuristic unsuccessful steps, by applying the methodological principle called 'negation as failure'. By adopting a blend between static and dynamic aspects of the scientific enterprise, I have also shown how it is misleading to analyze models in science maintaining this mixture. In fact, the static perspective causes an overemphasis of the potential fictional nature of models because the creative/factive role of modelling is openly or purposefully ignored.

[53] Mäki (2009, p. 31).

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Modelling Objectively

Nancy Cartwright and Faron Ray

1 Introduction

When models are to be used to guide decision-making about real world happenings, this creates a *duty of care* towards those whose lives the decision-making is likely to affect. In this paper, we argue that this duty should be understood as involving a duty to *model objectively*. Borrowing Cartwright et al.'s account of *Objectivity To Be Found*,[1] we draw a close connection between objectivity and *getting it right,* where getting it right demands both (1) finding the right purposes and (2) finding the right methods given those purposes.

Our approach differs from other recent discussions of duties in modelling which focus on a modeller's duty to *clarify* the intended

[1] Cartwright et al. (2022).

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purposes of a model.[2] Whilst clarifying purposes is important, we think that the duty of care demands more. We illustrate with an instance of modelling for the Vajont Dam in the Dolomites, the site of the 1963 disaster that killed over 2000. Here, the engineers carrying out the modelling failed their duty of care and yet there was no lack of clarity as to the intended purposes of the modelling. Instead, the problem was that the engineers and the institutions overseeing the design and building of the dam focussed on the *wrong* purposes—purposes that emphasised ensuring that the dam would hold in spite of subsidy and landslides. Ensuring that the inhabitants of the towns and villages around the dam would be safe *if* a landslide were to occur unfortunately received much less attention.

We close by identifying a problem that we think makes failures to model objectively all too natural: a failure of institutional humility in the institutions in which the modelling is embedded, e.g. the institutions that train modellers or hire them or regulate or otherwise affect modelling practices—an inappropriate *presumption* that their practices are the right practices.

The paper is structured as follows. Section 2 introduces the duty of care in modelling. Section 3 introduces Cartwright et al.'s account of *Objectivity To Be Found*. Section 4 uses the account to spell out a modeller's duty of care and highlights the important differences between our proposed focus on *finding* the right purposes and a focus on clarifying intended purposes. Section 5 illustrates with a case of unobjective modelling—two instances of modelling conducted for the Vajont Dam. Section 6 turns to the question of why failures to model objectively are often so natural in certain circumstances, where we conjecture that this is at least partly explained by failures of intellectual humility in the institutions in which the modelling is embedded. Section 7 concludes.

2 A Duty of Care in Modelling

On 15 April 1989, 96 supporters were killed and 766 injured at Hillsborough Football Stadium in Sheffield, South Yorkshire, in the UK when a fatal crush occurred in the stadium's enclosed pens. South Yorkshire

[2] Winsberg and Harvard (2022).

Police[3] were de facto in charge of crowd safety and thus had both a moral and legal *duty of care* to ensure that those entering the ground were not exposed to unreasonable levels of risk.[4] They failed to fulfil this duty. What went wrong? One could explain the failure by tracing the chain of mistakes made by various officers on the day. First, officers stationed outside the ground lost control of crowds as they waited to enter, leading to the onset of a dangerous crush by Leppings Lane turnstiles. Next, to ease the crush outside a senior officer requested for an exit-gate (Gate C) to be opened in order to allow maximum flow into the ground. Finally, Chief Superintendent David Duckenfield granted the officer's request, leading crowds of supporters to be funnelled down the natural channel that existed from Gate C to one of the already full enclosed pens. Whilst accurate, however, this story only goes so far as an explanation for South Yorkshire Police's failure to fulfil their duty of care, for the failures of the South Yorkshire Police as an institution were not limited to the actions taken by individual officers that day. Rather, they extended to the manner in which South Yorkshire Police set about *preparing* to act. That is, they extended to the *modelling* conducted by South Yorkshire Police.

Talking about the failures of South Yorkshire Police in terms of modelling may seem odd. There were no mathematical equations to solve, no computerised simulations being run; the information gathered was almost exclusively stored in the lead officers' heads. Yet, to understand this failure to fulfil the duty of care, one must nevertheless look to the pre-match preparation conducted by South Yorkshire Police and this *was* a case of modelling.

Preparation for the FA Cup semi-final at Hillsborough that day included no attempt to estimate the amount of people that could be safely let into the stadium's pens. Nor did it involve any attempt to gather vital information about patterns of crowd flow *into* the pens, information that would have been available from past match reports and from

[3] 'South Yorkshire Police' here is meant loosely—including not only the police officers themselves but the institutions charged with hiring, training and overseeing them.

[4] The duty of a care is a foundational concept in Tort Law closely tied to the notion of fault liability. The most famous articulation of the duty of care is that given in Donoghue v Stevenson ([1932] AC 562): "You must take reasonable care to avoid acts or omissions which you can reasonably foresee would be likely to injure your neighbour," i.e. "persons who are so closely and directly affected by my act that I ought reasonably to have them in contemplation […]." See: https://www.bailii.org/uk/cases/UKHL/1932/100.html.

the past experience of previous lead officers at the ground.[5] Finally, pre-match preparation did not involve using this would-be information to estimate how crowd flow patterns would change under various safety–critical interventions, e.g. the opening of the particular exit-gate which would eventually be opened with fatal consequences.[6]

Whilst the failures of South Yorkshire Police at Hillsborough might seem a far cry from issues of scientific modelling, the principles are much the same. Officers' actions that day were guided by models just as policy interventions or engineering projects are guided by models. Indeed, acting intelligently in any domain will require that you have a model, or models, of that domain. Now, since South Yorkshire Police had a duty of care to those in the stadium that day, so too did this duty of care extend to their modelling. Indeed, it was precisely that the police were working with *bad models*[7] that led to the catastrophic mistakes they made that day.

So, what exactly was so bad about the modelling carried out by South Yorkshire Police? They had not estimated certain factors, sure, but then they had not estimated lots of things, many of which turned out to be inconsequential. What was it about the pre-match modelling by South Yorkshire Police that proved so fatal that day? And, what practices might have ensured that South Yorkshire Police had modelled 'correctly' rather than 'incorrectly'? The sections to follow will aim to sketch general answers to these kinds of questions. In particular, we will spell out some of what we believe the duty of care requires in the context of modelling. In doing so, we will make heavy use of the concept of *objectivity*. Specifically, we will argue that a duty of care requires that modellers *model objectively*.

Before we move to discuss what it means to model objectively, we must first say a few words about the concept of objectivity itself. We begin below by addressing some of the recent criticism that has been levelled

[5] There had been severe overcrowding (injuring 38) seven years prior to the disaster. See Taylor (1989, p. 21).

[6] During the 2015 inquests, Chief Superintendent Duckenfield claimed that the biggest mistake he made on the day was not 'foreseeing' where fans would go when he opened Gate C, calling this failure of foresight "one of the biggest regrets of his life" (see Atkinson 2016). Whilst Duckenfield reports that he regretted this lack of foresight, the fact that he lacked such foresight ultimately stems from failures to investigate likely crowd flow patterns in advance of the match.

[7] Perhaps more accurately 'an incomplete set of models'.

against the use of 'objectivity' in science before moving to say how we suggest the concept should be understood.

3 Why Objectivity?

Any list of philosophically fraught concepts is likely to include 'objectivity' somewhere amongst the ranks. Ian Hacking puts it bluntly, claiming that 'objectivity' should be thrown in the bucket alongside 'reality' and 'rationality' as "fancy words conceived in philosophical sin".[8] Worries about 'objectivity' come in two main forms. The first is that the concept is too sprawling, too full of content and too *unwieldy* to play any useful role in science. The second is that the concept is too bound up with the undesirable notion of *value freedom* to do useful work. According to this second worry, 'objectivity' has unhelpful baggage and as such is more trouble than it is worth. Since we believe that the concept *can* do useful work in science and shall be putting the concept to such work in the discussion to follow, it will pay to say a few words about these complaints before introducing the account of objectivity that we endorse.

The worry that objectivity is too sprawling and ill-defined to play any useful role in science has been voiced most clearly by Hacking.[9] According to Hacking, 'objectivity' is simply a catch-all for a tangle of largely unrelated epistemic virtues. To say that X is or is not objective, according to Hacking, is simply to say that X possesses or lacks this or that epistemic virtue. 'Objectivity,' therefore, can always be *replaced* by something more specific. Better get down to specifics, concludes Hacking, than trade in redundant talk of 'objectivity'.

Hacking's complaint gets something right. To the degree that praising a colleague's work for its objectivity and reprimanding another's for its *lack* of objectivity is shorthand for more substantive praise or criticism, it is undeniable that the concept has little, if any, value. Yet, such descriptive applications of the adjective 'objective' fall far short of exhausting the ways in which the objectivity concept can be used. Consider the injunction, 'be objective'. Is reference to objectivity here *replaceable* by something more specific? No, far from it. Rather, just like 'respectful' in a parent's injunction to their child to *be respectful*, the prescriptive use of objectivity

[8] Hacking (2015, p. 4).

[9] Hacking (2015).

does not need to refer to a single activity or set of activities in order to play a useful role. Indeed, we take it that it is the very open-endedness of injunctions to *be objective* just like those to *be respectful* that give them their action-guiding role; it is part of the injunction to be objective that one should *find out* what it takes to be objective in each individual case. Much more will be said about this notion of *finding* below.

What about the second worry, namely, that 'objectivity' is too bound up with the undesirable notion of *value freedom*? According to Brown, such connotations ultimately make demands for objectivity counterproductive[10]; whilst philosophers of science are keen to point that science is rife with ethical decision points,[11] demands for objectivity imply the mechanical following of procedure and the *removal* of all value judgements.[12] Accordingly, whilst demands for researchers to 'be objective' are not strictly *redundant* as Hacking worries, it is nonetheless the case that the concept is more trouble than it is worth. Indeed, it's being wrapped up with notions of mechanical rule-following and a removal of value judgements makes the concept positively *harmful*—it encourages scientific ideals that are at odds with the way (good) science is done.

This worry is well motivated, yet we think that it overestimates the counterproductive baggage of objectivity-talk. Far from objectivity implying an absence of value judgements and a blind commitment to procedure, we suggest that in many cases complaints that someone is not *being objective* will, in fact, constitute complaints that one has not used their judgement *properly*—'Wait, you just blindly follow procedure? That's not being objective! You must use your considered judgement!' In fact, what everyday injunctions to be objective demand, we take it, is not that one *avoids* the influences of judgement but that one uses their judgement *correctly* given the demands of the case. Far from being in opposition to the presence of value judgements, injunctions for researchers to be objective are very often injunctions that those

[10] Brown (2019).

[11] As Richard Rudner pointed out, something as apparently mundane as setting the criteria for acceptance or rejection of a hypothesis will itself "be a function of the importance, in the typically ethical sense, of making a mistake in accepting or rejecting the hypothesis" (Rudner 1953, p. 2). See also Douglas (2000).

[12] The concept of objectivity has, of course, a rich history and the baggage associated with objectivity here is most associated with what Daston and Galison (2007) refer to as *mechanical objectivity*—a notion that has its origins in the nineteenth century.

researchers make *good calls* and good calls imply good value judgements. What 'good' means here will come out below.

So, how do we suggest 'objectivity' be understood? First, we think it is important to recognise that the fuzziness of the concept is here to stay. The concept of objectivity as it shows up in science, law and everyday natural language is what Otto Neurath would call a *Ballung concept*[13]; it is sprawling, dense and unruly, with many separately identifiable senses.[14] Following the suggestion of Eleonora Montuschi (further developed in Cartwright et al. 2022), we call this loose sense of objectivity 'Objectivity As We Know It.' As noted above, however, uses of 'objectivity,' like uses of other Ballung notions, needn't be otiose. Used prescriptively, objectivity can do real work. For another analogy, it is common in commercial contracts to stipulate that parties use their 'best endeavours' to bring about what has agreed to be done, and companies and individuals can be on the hook for paying significant damages if they can be shown *not* to have used their 'best endeavours.' But what *are* such 'best endeavours'? Whilst this will be a matter fixed by context, this by no means implies that the concept lacks usefulness. Similarly, we suggest, for prescriptions to 'be objective.' Indeed, we suggest it is instructive to draw a tight connection between objectivity and *getting it right*. Given the circumstances, there will often be a fact of the matter as to whether one has *got it right*, but there is no clear notion of 'getting it right' that can be defined free from context. And, in fact, to enjoin others to get it right just is in part to enjoin them to find out what getting it right means and requires in the relevant context. This emphasis motivates the shift towards what Cartwright et al., again following the original suggestion of Eleonora Montuschi, call 'Objectivity To Be Found'—it is part of injunctions to be objective to *find out* what being objective means and requires in a particular case. This helps us see what the notion of 'good judgement' means when we noted above that objectivity demands one make *good calls*. Good calls are calls that *get it right* relative to the needs of the context.

[13] Ballung stems from the German *Ballungsgebiet*: a congested urban area with ill-defined edges.

[14] Heather Douglas identifies three operationally distinct types of objectivity and eight total 'senses' in which the concept is used, calling objectivity "an inherently complex concept, with no one meaning at its core" (Douglas 2004, p. 454).

With this general picture on the table, let us turn to a more careful examination of what objectivity understood through the lens of *getting it right* requires and how, in particular, it can help us think through the duty of care in modelling.

4 Modelling Objectively

We follow Cartwright et al.'s lead in identifying *two* general components demanded by objectivity.[15] The first is to find the *right purposes*; the second, to find the right methods, or means, given those purposes.[16] Applied to modelling, we can think of the first as demanding that one answer the following question: what *should* this model be for? And, more broadly, the question: what should our *modelling* (or our *models,* plural) be for in this particular context? Finding the right methods, or means, on the other hand, will involve amongst other things: (1) finding out what type or class of model should be used given the model's purposes, (2) finding out how certain features of a target system *should* be represented given the model's purposes and (3) finding out how the various error probabilities should be weighted given the model's purposes. So construed, a duty to model objectively is demanding; it requires earnestly seeking out both what it means and what is required to get it right in the case at hand. As we will see, sometimes this may require rejection of standard procedure and received wisdom.

We claimed above that South Yorkshire Police failed to fulfil their duty of care at Hillsborough in part because of their failures to model objectively. We are now in a position to further spell out what this means. We suggest that South Yorkshire Police's failure to fulfil their duty of care was in part caused by their failure to find the *right purposes* for their modelling. How so? First, it seems clear that the police conceived of their role at the ground to be first and foremost a disciplinary one.[17] This

[15] Cartwright et al. (2022).

[16] We use the term 'purposes' throughout, but we might just as well refer to ends or goals.

[17] In the 2000 case brought against Duckenfield and Murray, lead prosecutor Alun Jones, Q. C., would claim that Murray and Duckenfield's "slow-motion negligence" was a product of their "mindset". That mindset, Jones effectively argued, was one that focussed on the neutralisation of would-be troublemakers *over* the interests of crowd safety (Scraton 2004).

was wrong. As the only party capable of ensuring crowd safety at the ground, the duty to do so naturally fell upon them.[18] Their failure to adequately focus on the full nature of their role thus led to their identifying the wrong purposes of their pre-match preparation—pre-match preparation which consequently concentrated on the narrow mechanics of crowd *control* rather than the much more complex task of crowd *safety*.[19] In sum, it was South Yorkshire Police's failure to find the right purposes for their pre-match preparation that constituted their failure to model objectively and this, in turn, helps explain their failure to fulfil their duty of care.

How does our emphasis on modelling objectively differ from other recent work on the duties involved in modelling? In a recent article focussed on the responsibilities of modellers involved in epidemiological modelling, Eric Winsberg and Stephanie Harvard stress the importance of *clarifying a model's intended purposes*. They write: "We argue that (1) clarifying the intended purpose of a model and (2) assessing its adequacy for that purpose are ongoing moral epistemic duties that must be upheld throughout the modelling process".[20] Winsberg and Harvard's proposal contributes to recent debates around the ethical responsibilities involved in Covid-19 modelling. Their emphasis upon a duty to *clarify* a particular model's intended purpose finds motivation in what they judge to be a persistent lack of clarity surrounding the purpose of Covid-19 models,[21] where they insist that such modellers must clarify whether a model is intended for prediction, forecasting or causal inference. As they rightly point out, clarification of such matters is crucial, for a failure to clarify the intended purpose of a model blocks one's ability to assess whether the model is good or bad; a model might be successful at prediction but useless for guiding interventions; we need to identify what we are aiming *at* in order to assess whether we have hit the target.

[18] See Taylor (1989, p. 36).

[19] We are making this claim on the basis of scholarship by Scraton (2004) but see also the witness statement by Superintendent Mole (South Yorkshire Police 1989). Here, Mole describes the pre-match planning meeting undertaken by himself and Superintendent Duckenfield. The focus as described in this statement is exclusively on worries about supporter violence and does not mention issues pertinent to crowd safety such as overcrowding.

[20] Winsberg and Harvard (2022, p. 512).

[21] For general discussion of these worries, see Fuller (2021).

We think Winsberg and Harvard's contribution is important and commend their emphasis on what we believe they rightly call the 'moral-epistemic duties' in modelling. However, we stress two very important differences between our proposal and theirs. First, we wish to emphasise the importance of finding the *right* purposes rather than on clarifying *intended* purposes. As we will see in the section to follow, clarifying intended purposes is insufficient for fulfilling a modeller's duty of care. Second, we wish to depart from Winsberg and Harvard's analysis in emphasising that the duty to model objectively applies to both single models—*this* particular model right here—and integrated modelling efforts more broadly as they are carried out by entire institutions and organisations. The questions Winsberg and Harvard pose are questions targeted at specific models: is *this* particular model for prediction or causal interference? In contrast, we think of the duty of care to model objectively in much broader terms. The duty of care involves not only the earnestly seeking out of the right purposes for specific models but also the earnest seeking out of the right purposes for entire modelling efforts for which an individual model will be but one single part. The relevant injunction to *find the right purposes* is, on our view, an injunction that applies at both of these scales, or levels, simultaneously (see Fig. 1). We proceed in the section below with another case that will allow us to further bring out these two differences between our view and one that emphasises the clarification of intended purposes.

5 Unobjective Modelling – The Vajont Dam Disaster

At 10:39 pm on 9 October 1963, inhabitants of the Italian town of Longarone were woken by the deafening sound of a landslide—273 million cubic metres of rock detaching from the northern side of Mount Toc. The rock would quickly find itself plunging into a 700-metre-high man-made reservoir at the rear of the monumental Vajont Dam, sending a wall of water 20 metres high over the dam's edge. Over 2000 people living in Longarone and the surrounding villages would die. The dam was a magnificent feat of engineering, yet the landslide is one of the worst man-made catastrophes in history. With hindsight, the dam should never have been built the way that it was. So what went wrong? How could such magnificent engineering go hand in hand with such catastrophic failure?

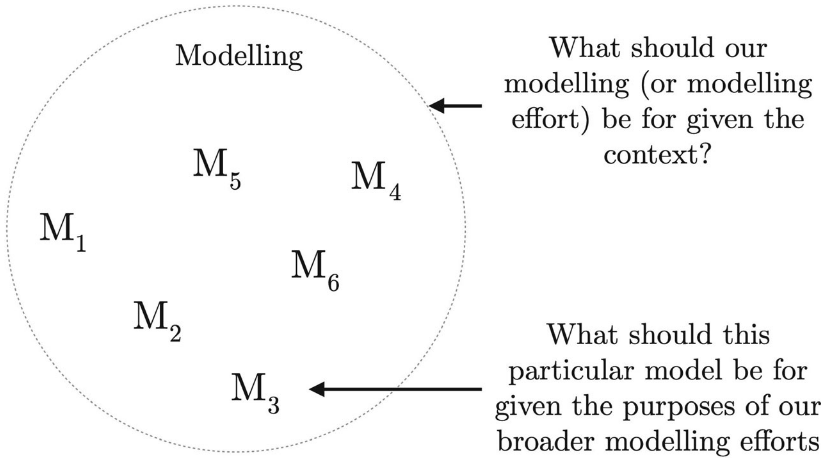

Fig. 1 © Nancy Cartwright and Faron Ray

We focus below on two aspects on the modelling for the Vajont Dam. First, we look at the initial feasibility studies conducted prior to the dam's construction. Second, we look at one instance of modelling that was carried out *after* the threat of landslides to the surrounding towns had been acknowledged. In the first case, we suggest that just as in the case of South Yorkshire Police at Hillsborough, the engineers for the Vajont Dam were focussing on the *wrong purposes* for their initial feasibility studies; in this case, an *incomplete* conception of what this modelling was for. In the second case, we suggest that whilst the modellers were in this instance working with the right purposes, they had nonetheless failed to find the right means to achieve those purposes. Hence, in both cases we see a failure to model objectively.

Feasibility Studies for the Vajont Dam

The first feasibility studies began in the 1920s and ran until the land was finally purchased for development in 1943. In some ways, the Vajont Valley at the bottom of Mount Toc was the ideal location for a hydro-electric dam. The acute angle of the gorge would make Vajont the tallest dam of its kind in the world; it would harness incoming water from three rivers, the Piave, the Mae and the Boite, and hold a total of 168 million cubic metres of water, supplying electricity for large portions of northern Italy. Yet, the location was not ideal, far from it. Residents living near the valley famously said as much. Indeed, the mountain was known by the locals for being geologically fragile and prone to landslides, with 'toc' (short for 'patoc') meaning *rotten* or *spoiled* in the local Italian dialect. Despite this information, the engineers at Società Adriatica di Elettricità (SADE), the company leading the project, did not demand that extensive geological studies of the region as a whole be carried out. Rather, their primary focus in these initial studies was the stability of the *abutment area*—the natural supporting structures either side of the would-be dam. Why were the investigations limited in this way?

Just as South Yorkshire Police were working with a misplaced emphasis on crowd control over crowd safety, so too, we suggest, were SADE working with the *wrong purposes* for these initial investigations. We here follow Pierluigi Barrotta and Eleonora Montuschi's account of the disaster in proposing that the engineers at SADE saw these investigations as focussed,[22] first and foremost, on the question: is this rock good enough to construct a dam that will *stand*? Yet, whilst obviously crucial, assessing the abutment area for threats against the stability of the dam was not the only purpose these initial studies should have served. The important questions to answer were *both:* (1) is the rock good enough to construct a dam that will stand? And, (2) can a reservoir of this scale be safely built here without threatening the geological stability of the region in a way that endangers human life? Whilst there can be no doubt that safety concerns must have occupied the SADE engineers during these initial feasibility studies, it nonetheless seems clear that the assessments of safety took a back seat relative to the task of assessing the ability for the abutment area to support a dam of this size. For instance, the chief engineer at SADE at the time, Carlo Semenza, is reported to have said: "From a geological point of view the rocks [of the Veneto region] are generally very good [...]. Overall, limestone is honest because it reveals its flaws on its surface".[23] Here Semenza deployed a generic—that limestone reveals its flaws on its surface—in conjunction with his alleged observation that there were no major flaws exhibited by the rock to conclude that the

[22] Barrotta and Montuschi (2018).

[23] Carlo Semenza quoted in Gervasoni (1969, p. 11).

region was sufficiently stable for construction of the dam.[24] Semenza's weak epistemic standards here only make sense, we suggest, if we understand the importance of safety assessments to be down-weighted relative to the importance of assessments of engineering feasibility.[25] Indeed, contrast Semenza's willingness to rely on the loose claim 'limestone wears its flaws on its face', with the magnificent levels of precision he demanded of the models used to design the dam itself—a system of 146 equations with as many unknown variables perfected and solved.[26]

Now, suppose that we are right and that Semenza and the other engineers at SADE were working with the wrong purposes when they carried out these initial studies, why is it not enough to say that they should have just *clarified the intended purposes* of their modelling? Why is it necessary to say that the duty of care involves a duty to find the *right* purposes? The problem with a focus on merely clarifying intended purposes is that it is entirely possible for a whole scientific community to clarify that the intended purpose of a particular modelling effort is X whilst the full, correct, purpose of that effort should, in actual fact, be Y. Indeed, it seems reasonable to assume that this was the very situation at SADE.[27] That is, it seems reasonable to assume that the intellectual climate at SADE was such that there might have been full agreement in a claim that the purpose of the feasibility studies was to ensure that the rock surrounding the abutment could support a dam of the relevant size. Yet, full agreement (and thus no lack of clarity) around the intended purposes of modelling is not sufficient for ensuring that modellers fulfil their duty of care. The duty of care requires more. Indeed, it demands that modellers go and actively find out what the model *should* be for, something that may require one to go *against* the consensus view of a particular community. Understanding

[24] As Barrotta and Montuschi (2018) point out, this was to completely ignore the local knowledge attesting that this generic did *not* hold in the Veneto region.

[25] Barrotta and Montuschi write that in this initial stage, "the formidable engineering challenges of the project took precedence over the geological problems posed by the natural environment" (Barrotta and Montuschi 2018, p. 21).

[26] Barrotta and Montuschi (2016).

[27] It seems like the same was likely also true at Hillsborough. That is, it is likely that South Yorkshire Police would have all *agreed* at the time that the purpose of their pre-match preparation was to facilitate effective crowd control on match day. Whilst there may not have been any lack of clarity about this purpose, however, it was nonetheless an *incorrect* account of the full set of purposes. This will be discussed below when we turn to the matter of how institutional failings may support unobjective modelling.

the duty of care in modelling as a duty to model objectively brings out the crucial importance of *finding* and *seeking out*.

Scale Modelling to Assess Safe Reservoir Levels

So far we have said very little about the second aspect of modelling objectively—finding the right methods (or means) to achieve the model's correct purpose. We turn to this now. As we will see, even in the case where one has identified the right purposes for a model a failure to find the right methods for achieving those purposes can lead to catastrophic failure. Making significant efforts to find the right purposes is therefore not sufficient for modelling objectively, one must also take pains to find the right tools for the job.

Signs of geological instability in the valley appeared shortly after construction of the dam began in 1957. On 22 March 1959, three million cubic metres of material fell into the artificial lake of Pontesei, close to the Vajont Valley. The dislodged material was compact and the landslide swift; Semenza and his colleagues took notice. Semenza quickly commissioned a thorough geological survey of the region and the team's findings led them to a worrying hypothesis: there had been an ancient landslide on Mount Toc, and this landslide could potentially be reactivated by erosion from the dam's reservoir. Whilst such talk of major future landslides was met with initial pushback, by 1960 the evidence had become too great not to take the threat seriously. Indeed, by the end of 1960, a 2.5 kilometre-long fracture had opened on the northern slope of the Mount Toc. Shaped like an M, the fracture marked the contour of a huge sliding mass composed of two distinguishable bodies—bodies that would come to be known as the eastern and western lobes. The threat was now undeniable. Semenza and his colleagues turned their attention away from the question of *whether* major landslides were possible to the question of how catastrophe might be avoided.

One key question at this time was how high the reservoir could be safely filled, where 'safely filled' was effectively understood as 'filled so that there would be no danger to the surrounding towns of Longarone, Erto and Casso from landslides into the reservoir.' To answer this question, Semenza made an innovative move, requesting that Augusto Ghetti (then director of the Institute of Hydraulics at the University of Padua) build a 1:25 scale model to study the effects of landslides into the reservoir.[28] The purpose of the model was straightforward: find the level at which the reservoir could be safely filled. This was, we take it, the *right* purpose for this model. The problem, however, was that the model's design and the tests that Ghetti himself ran on the model were not sufficient to achieve this purpose. That is, whilst Ghetti had the right purpose for his model, he did not take the right steps to achieve it.

There were two main issues with Ghetti's modelling. First, the materials used by Ghetti in the scale model[29] to simulate the real landslide mass could not provide the kinds of reliable inferences needed to make estimates of safe water levels in the reservoir. In particular, Ghetti used rounded gravel contained within metallic netting as a substitute for the real rockslide mass, a material that is significantly less compact and fell with significantly lower speeds than the real mass eventually would.[30] Second, Ghetti only ran simulations for *single* lobe failure scenarios despite the fact that the real landslide would, in actual fact, involve the simultaneous failure of both lobes.[31] Altogether, Ghetti's modelling produced an estimate of 700 metres (above sea level) as the level at which there was to be no threat from overspill in the event of landslides. This

[28] The model was the first purpose-built scale model in Italy (Barrotta and Montuschi 2018, p. 28).

[29] Whilst 'scale models' are so called because they are geometrically scaled versions of their target systems, the types of behaviour that scale models are used to investigate in science and engineering do not simply 'scale down' in the way geometric properties do. Using scale models to study the behaviour of materials or fluids demands sophisticated understanding of the transformations between the things happening in the model and the things being represented by those happenings. See Sterrett (2019) for an excellent treatment of the problems involved in scale modelling.

[30] Later modelling at the Vajont dam was done to scale (i.e. 1:1)—indeed, it was done in the real setting, as the dam was filled, then drawn back as problems were observed, then refilled, three times. This to-scale modelling clearly did not deliver a good enough prediction either, due, it seems, to overoptimism both about the fill height that was safe and about the chance of massive landslides.

[31] Here, we have drawn on conclusions by Franci et al. (2020) in their recent computer simulations of the Vajont disaster. Franci et al. simulate Ghetti's own results and examine how variations in Ghetti's modelling techniques would have altered the safety estimate he provided. They identify the use of the gravel proxy and the focus on single lobe failure scenarios as the two key reasons why Ghetti's safety estimates proved inaccurate.

would be the very level at which the dam was filled when the eventual landslide did occur, killing 2000.[32]

One might push back here and insist that whilst Ghetti's modelling turned out to have problems, Ghetti did nonetheless fulfil his duty of care to model objectively. For instance, one might argue that whilst relative to the actual facts his modelling *was* inappropriate, relative to what Ghetti could reasonably have taken those facts to *be,* his modelling was not inappropriate. Scale modelling was, after all, in its infancy when Ghetti designed his model, and simultaneous lobe failure scenarios were thought to be extremely unlikely at the time. We agree that the criticism of Ghetti's use of inappropriate proxy materials is difficult yet suggest that his failure to test simultaneous lobe failures *was* a failure of the duty of care given the stakes. The purpose of this model was to estimate levels at which the reservoir could be filled so that the residents of the surrounding towns would not be put at risk from landslides. Given that the M-shaped fracture and therefore the existence of the two independent bodies of material were well known, it was unacceptable not to test such joint failure scenarios. On this count, Ghetti thus failed to do what he should have done to achieve the model's purpose and this means that he failed to fulfil the duty of care to model objectively.

Now, whilst the case of Ghetti's scale modelling is one in which Ghetti had a duty of care to model objectively, in this as in most cases, the duty of care to model objectively will equally—if not more so—fall to institutions or collections of institutions. We naturally say it was 'SADE' who conducted the initial feasibility studies, for instance, and we naturally think of the failures in pre-match preparation at Hillsborough to fall upon 'South Yorkshire Police', where we understand this loosely to refer not only to the police officers themselves but also those institutions involved in hiring, training and overseeing these officers—all of these institutions were implicated in the failures in preparation that led to the disaster. We turn to discuss these matters of distributed responsibility next.

[32] Franci et al.'s (2020) simulation modelling suggests that Ghetti's figure of 700 metres was up to 75 metres *too high*; simultaneous lobe failure would have still reached over the top of the dam had the dam been filled to roughly 625 metres above sea level.

6 Objective Modelling: Whose Responsibility?

We have argued so far that when modelling is used to guide actions that have effects in the real world, those involved in modelling have *a duty of care to model objectively*, where a duty to model objectively demands that one (1) find out what the model (or modelling effort) should be for and (2) find out which tools and methods you should be using to achieve that purpose. In slogan form, objective modelling is modelling that *gets it right* and those involved in modelling have a duty of care to *earnestly try to get it right*.

With this said, however, it is important to stress that getting it right does not happen in a vacuum. Because of this, we urge caution in affixing causal responsibility for failures to model objectively to particular individuals or even particular groups. For instance, it is very likely that other teams of engineers would have done exactly as Semenza and his colleagues did during their initial feasibility studies. As Barrotta and Montuschi note, a primary focus on the geological stability of the abutment area was, in fact, standard practice at the time—neither the norms within the engineering community nor the legal and regulatory norms in Italy required extensive geological investigations prior to the construction of dams.[33] Hence, it is most likely that the other teams of engineers would have similarly adopted an incomplete set of purposes for their modelling—focussing, as Semenza and his colleagues did, on matters pertinent to the dam's construction over those pertinent to the safety of the inhabitants in the surrounding towns and villages. Similarly in the Hillsborough case, it is most likely that other police departments would have made similar mistakes in preparing for the FA semi-final that day.[34] When Superintendent Murray was asked why he and Duckenfield had not ordered the tunnel leading from Gate C to the pens to be closed, he replied that this "was something that did not occur to me at the time and I only wish it had".[35] But we should think about *why* it did not occur to him or

[33] Barrotta and Montuschi (2018).

[34] Concerns with hooliganism at the expense of crowd safety dominated 1980s football. Indeed, the very choice to design stadiums (like Hillsborough) with *enclosed* pens was a product of a mindset that neglected crowd safety in the interests of crowd control; the enclosed pens were designed to prevent pitch invasions but were, from the very beginning, a risk factor for lethal overcrowding (Scraton 2004).

[35] Scraton (2004, p. 192).

Duckenfield. What made it so natural for them to think and act as they did?

To begin to address these issues, we take a lead from UK child protection expert Eileen Munro in describing attempts to understand failures at child protection. Munro explains that when a tragedy occurs "the standard response is to hold an inquiry, looking in detail at the case and trying to get a picture of the causal sequence of events that ended in the child's death [...]. We are tracing a chain of events back in time to understand how it happened".[36] What do we tend to conclude? Munro continues: "The events that bring the investigation to a halt usually take the form of human error".[37] Investigators look for deviations from the norms of professional behaviour, she notes: "Practitioners did not comply with procedures or lapsed from accepted standards of good practice".[38] This way of viewing failures is labelled the 'person-centred' approach. The trouble with the person-centred approach is that it isolates unsafe acts from their context, thus making it very hard to uncover and eliminate recurrent error traps within the system. By contrast, Munro urges a 'systems-centred' approach and argues that for children and young people protection is a *systems problem*.[39]

The US Institute of Medicine's *To Err Is Human: Building a Safer Health System* also urges a systems-centred approach, explaining:

> The title of this report encapsulates its purpose. Human beings, in all lines of work, make errors. Errors can be prevented by designing systems that make it hard for people to do the wrong thing and easy for people to do the right thing. Cars are designed so that drivers cannot start them while in reverse because that prevents accidents. Work schedules for pilots are designed so they don't fly too many consecutive hours without rest because alertness and performance are compromised.[40]

Like Munro, the pamphlet urges: "The focus must shift from blaming individuals for past errors to a focus on preventing future errors by

[36] Munro (2004, p. 377).

[37] Munro (2004, p. 377).

[38] Munro (2004, pp. 377–378).

[39] Munro (2004).

[40] Institute of Medicine (1999, p. IX).

designing safety into the system".[41] It is, we think, just these kinds of systems failure that we have seen in the cases of the Vajont Dam and Hillsborough and that we suggest are likely characteristic of failures of objective modelling more generally. Here, 'the system' is constituted by the tangle of institutions and institutional norms into which modellers and modelling activities are embedded, from the institutions that train the modellers to those that fund research or oversee and regulate practice, including as well things like the cultural norms that pervade and the media pressure modelling may be consciously or unconsciously influenced by.

Systems failures that affect the objectivity of modelling will occur in various different institutions and at various different levels in different cases and they will surely take different forms and have different causes. But there is one fundamental factor that we think is likely to be widely relevant. This is due to what is often called 'silo-isation': the tendency of each area of expertise and practice to be closed in on itself and neglect what is going on elsewhere. Of course, sharing a common vision and language and common methods and practices is crucial to being able to get on with the hard work of getting a job done. But this can readily lead to a failure to take notice of what other areas of knowledge and practice and other perspectives have to offer, both in aid of getting the job in view done and in understanding just what the job is that should be done.[42]

Such failures to recognise relevant lessons—information, practices, methods, etc.—from elsewhere are often not deliberate nor even conscious. It is not that lessons from elsewhere are rejected or ignored but rather that often they do not come into view. Sometimes it is explicitly asserted that the practices within the silo are superior to what is available outside: *we* know how to do it. And sometimes the reverse: institutions explicitly undervalue what they have to offer (for instance when schools of qualitative and interpretive methodology agree that they can

[41] Institute of Medicine (1999, p. 5).

[42] This was certainly visible in the ways in which the SADE engineers interacted with others with different forms of expertise. For instance, whilst Ghetti (a geologist) himself made mistakes in his own modelling, he nonetheless insisted that his safety level estimates were to be treated with extreme caution. This caution was *not* heeded by the SADE engineers who, disregarding Ghetti's own recommendations, took the 700-metre safety estimate at face value as a precise level to which they could safely fill the dam. See Barrotta and Montuschi (2018, p. 29).

only *suggest* causal hypotheses but must leave confirming them to quantitative methods). But often this is not explicitly announced; it is just *presumed*, without notice. Altogether, we suggest that silo-isation thus often breeds a deep-seated failure of *intellectual humility* within the institutions that affect modelling, where this failure of intellectual humility involves an inappropriate presumption that the institution's own practices are the *right practices.*

We conjecture then that failures of intellectual humility in the institutions in which modelling practices are embedded can readily lead to failures of objective modelling. Whilst intellectual humility has been primarily studied from the point of individual human agents,[43] we believe that many of the insights from this previous work fruitfully carry over to the study of institutions, and in particular, scientific institutions. Indeed, we think that many of the characteristic features of intellectual humility identified for the case of individual persons—e.g. an appropriate sensitivity to one's epistemic limitations and strengths; an awareness of one's own fallibility as a knower—can be rightly said to have been *absent* in the institutions involved in the modelling at Vajont and Hillsborough.

We end by noting that understanding the role of intellectual humility in scientific institutions is now an active research project by both ourselves[44] and others.[45] Two important goals of this research are to (1) better spell out the causal pathways—including and along with silo-isation—through

[43] The last ten years have seen an increased interest in intellectual humility across philosophy, psychology and the social sciences, especially encouraged by the John Templeton Foundation. In philosophy, intellectual humility has been proposed to consist in (1) an awareness of one's fallibility as a knower (Spiegel 2012; Hazlett 2016), (2) a treatment of other intellects as worthy of as much respect as one's own (Priest 2017) and (3) an awareness of one's intellectual limitations in the right amount and for the right reasons (Church and Barrett 2016).

[44] In our John Templeton Foundation project, the 'Successes and Failures of Science Through the Lens of Intellectual Humility: Perspectives from the History and Philosophy of Science' (PIs: Nancy Cartwright and Robin Hendry).

[45] Other current research on intellectual humility in scientific institutions includes work on the relationship between intellectual humility and the 'replicability crisis' in psychology as well as work on intellectual humility and the institutional biases against certain sub-fields in the social sciences such as those studying religion. See the projects by Mijke Rhemtulla, Alexa Tullett and Kimberly Rios, respectively, at https://www.templeton.org/project/intellectual-humility. See also Higgins (2019) for recent work on intellectual humility in the institutions around social work and Davis et al. (2018) for discussion of intellectual humility in the context of institutional mechanisms such as peer review.

which a failure of intellectual humility might arise and (2) investigate potential strategies for fostering intellectual humility within scientific institutions. If we are right and failures to model objectively are often a result of a failure of intellectual humility in the institutions within which the relevant modelling practices are embedded, then understanding how to better foster intellectual humility is of critical importance.

7 Conclusion

When models are used to guide decisions that can possibly affect people's lives, those involved in modelling have a duty of care towards those who are likely to be affected by those decisions. In this paper, we have spelled out some of what the duty of care in modelling requires. In particular, we have argued that modellers have a duty of care to *model objectively*. As we have seen in the cases of both the Vajont Dam and Hillsborough disasters, however, objective modelling does not occur in a vacuum. The activity of modelling is inherently embedded in a tangle of institutional norms, expectations, habits, patterns and practices, and modelling objectively will often if not always be a *systems-level problem*. We thus stress the importance of developing *systems-level solutions*. We have conjectured here that failures of *intellectual humility* in the institutions within which modelling practices are embedded are likely to be one such systems-level problem. If we are right in this, then future work must focus on developing appropriate solutions—ways of fostering intellectual humility within the institutions in which modelling practices are embedded.

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Basic Operations of Model Building in Literary Studies

Darin Tenev

1 Introduction

The operations that form the basis of model building in the field of literary studies are not the specific operations in the particular cases of analyses of artistic texts and theorization about literature. The basic operations give the general framework within which the particular analyses and theorizations take place and, in this sense, they function rather as meta-operations.

In the first part of this paper, I will offer a description of the general forms of model-building operations in literary studies. In the second and shorter part of the paper, I will focus on a particular strategy for model building that is based on the conclusions drawn from the first part.

I will begin with an outline of my use of the term 'model' in its general sense. Following Bernd Mahr's conception that being a model is not an intrinsic quality but depends upon the apprehension of something as a model, an apprehension that takes into account what the model is a model of, what it is a model for and what is the element or quality (cargo) carried by the model-object,[1] I will provisionally define the model as *an interpretation of a formal system in view of some action*, where the action can

[1] See Mahr (2011).

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be cognitive, ethical, political, esthetic or other. That is to say that model building has an intrinsic performative aspect. The interpretation can be mental or virtual or can have material expression. The system after which the model is build is formal in the broad sense which includes, on the one hand, the pre-predicative and predicative logical forms in which we think,[2] and, on the other, the ontological forms of things. The model as an interpretation of a formal system therefore includes body models, models of society, models of scientific discovery and models of anything that has a form.[3]

The descriptions of model building in literary criticism in this paper, needless to say, are already the product of modelling activity. Whenever someone speaks of models, one is already building a model of what a model and modelling is. We can only have models of modelling. This singular doubling of modelling is discernible in the way Bernd Mahr builds his model theory on the basis of what he calls "a model of model-being."[4] In the case of literary studies, things are perhaps even more complicated because, as Jurij Lotman and others have pointed out, literature itself is a modelling system and one that is built upon the primary modelling system of natural language.[5] What does this fact entail will not

[2] On this understanding based on a phenomenological reading of B. Russel and L. Wittgenstein, see Deyanov (2001, pp. 110–155) (in Bulgarian). Deyanov's analyses lead him to the conception of incommensurable logical forms grounded in incommensurable social practices, and on this basis, he builds a nonclassical transcendentalism allowing for more than one world.

[3] The form understood in this sense is akin to the concept of form in system theory. See Luhmann (2000, pp. 102–132). On the relation between the notion of form in model literary theory and that in system theory, see Erdbeer (2015). Erdbeer argues that the form is simultaneously what modelling presupposes and what it aims at, and claims that "in this sense model poetics is a form-observation of the second order" (p. 21, my translation). He points however to the crucial part transformability plays in modelling as something that necessitates a distinction between the notion of form in system theory and in model theory (p. 22).

[4] See Mahr (2011) and Mahr (2015).

[5] See Lotman (1977, chapters 1–4). Even if one does not accept the argument that literature is a secondary system vis à vis natural language (such was the understanding, for example, of the Bulgarian Guillaumist School who criticized Barthes and the structuralists who claim that literature is secondary to natural language; their argument is reconstructed in Tenev (2019)), at the present time it is hard to neglect the modelling activity of literature itself. This paper is based on the assumption that literary "texts are model-building" (Erdbeer 2015, p. 5).

be discussed here, but in the second part of the paper I will point to one of the opportunities this opens before model theory and model building.

The discussion of model building in literary studies is important not only for the field itself and its future developments but also for the chances it brings for a dialogue and a cooperation between different fields. Thus, the research on literary modelling should be seen as a part of the groundwork for an opening of literary studies to other fields and using the tools of literary theory for non-literary purposes. Even though this paper will not deal directly with the possibilities for a literary theory of models to address the discourse on energy transition, such possibilities form its horizon.

2 Actualizations

I will take as a starting point the observation that ever since the beginning of the twentieth century (and even before that) in the field of literary studies it is taken for granted that a literary work can be interpreted in more than one way. The different interpretations can be incompossible, they can be mutually exclusive, yet this does not mean necessarily that they cancel each other out. This was not and for the most part is still not the case, not only in the sphere of the natural sciences but also in other fields in the humanities such as history or psychology or linguistics or economics or law and so on (and if it has become the case, then it is undoubtedly under the influence of late twentieth-century literary theory). For all the debates and quarrels among literary scholars in the last hundred years, the possibility for a work to be read differently was never questioned as such. This does not mean and has almost never meant that any reading is possible but that the possible readings are not enumerable.

It can be said that what we call 'literature' today—that is, after the end of the eighteenth century and especially after the rise of Modernism—is constituted as carrying a special sort of *potentiality*, one where not all possibilities are determined beforehand. This is not the case with all discursive formations as Michel Foucault and others have demonstrated.

Some scholars see this potentiality as immanent to literature. The Polish phenomenologist Roman Ingarden claimed that when dealing with a literary work readers face its potentiality and through acts of apprehension actualize it. This actualization he called 'concretization.' "The concretization of a literary work is […] distinguished by the fact that a truly explicit *appearance* of represented objectivities occurs only here, whereas in the work itself they are only indicated and held in a state of potentiality by aspects held in readiness."[6] He insisted that one should distinguish between the work itself and its concretizations that are based on the reader's acts of apprehension, but at the same time pointed out that "[w]e can deal aesthetically with a literary work and apprehend it live only in the form of one of its possible concretizations."[7] Ingarden, therefore, saw literary potentiality as something immanent to the works. The American New Criticism in a homological manner saw the literary work as being "only a potential cause of experiences" where "[e]very single experience (reading, reciting, and so forth) is only an attempt" to grasp the "set of norms and standards" specific to the work, that is, to grasp its structure.[8] Structuralist thinkers like Roland Barthes grasped this potentiality as immanent to the texts but saw it as due to the codes and the way language in general works. Like Ingarden, he thought that it is up to the reader to thread the text actualizing some of the potential meanings.[9]

Later critics like the neo-pragmatist Stanley Fish in the 1980s advocated a view according to which there is nothing immanent to the literary text, even its literary character. Literature was constituted as literature, he claimed, not because of some immanent characteristic of the literary text but because there was an interpretative community that decided to treat some texts in a specific way, neither the artistic text, nor the individual reader being autonomous.[10] In other words, the potentiality of literature should be seen not as pertaining to the text but as produced by the interpretive communities of readers.

It can be said that Fish's understanding is stressing the conventional aspect of the literary text. The potentiality it has today is not a universal quality residing in fictional literature. And it has it only because of the convention that makes us see it in this way, that is, see it as a field of potentiality where more than one reading is possible.

Paradoxically, Fish's argument does not make irrelevant what Ingarden and others said. First, by limiting the contemporary notion of literature, the argument reveals literary potentiality as something fragile. We can read

[6] Ingarden (1973, p. 341).

[7] Ingarden (1973, p. 336).

[8] Wellek and Warren (1956, p. 150).

[9] See Barthes (1977, pp. 142–149).

[10] See Fish (1980).

the same texts in a different manner that no longer takes into account precisely the possibility for them to be read otherwise. The potentiality can be obliterated. And this can be seen in some of the contemporary naïve approaches to literature. The unconditional potentiality is under condition. Unconditionality is opened by a condition. This is a limitation of the older arguments about literary potentiality and its actualization, but not their negation. If one follows Fish, one will see that some forms of actualization institute the potentiality in the first place, but once instituted in such and such a manner, the potentiality will become a constituent of literature supported by the convention. Second, Fish's argument makes it even clearer that the possibilities are not predetermined, nor are they foreseeable. Some of them are pregnant with what could put an end to the way possibility works in literature. In this, Fish is radical, but he only radicalizes a tendency that was already there, well-articulated since Ingarden.

What does all this mean for the models build by literary studies? Succinctly put, *any model in the field of literary studies*, no matter what its aim is, *is based on actualization.* The first and most basic operation of modelling in literary studies is actualization.

It should be added right away, however, that as the potentiality is not predetermined, the concretization makes the role of the reader significant even if it does not depend entirely on it. In literary studies just like in any other field of modelling activity, the building of a model may use materials and elements taken both from what we build a model of and from elsewhere. There is a wonderful example of the role played by materials borrowed from elsewhere, given by Reinhard Wendler in the beginning of his book *Das Modell zwischen Kunst und Wissenschaft* when he describes Linus Pauling's discovery of the structure of α-keratin in 1948. Pauling drew a polypeptide on a sheet of paper and then started playing with the paper, twisting it, which led him to the idea that the protein has a helix-like structure. The sheet of paper has a chemical structure quite different than that of the α-keratin protein and is also different in size. So the paper was an element foreign to the α-keratin that was used in the model building. Wendler points out that in this case as well as in many others the model itself has an active role.[11] What I want to stress here is the fact that Pauling was searching for the actual structure of the protein, something

[11] See Wendler (2013, p. 23–26).

given and real. In literature, however, even some of the formal aspects and the structure are only *in potentia*. The actual structure which the literary scholars will find will be the product of their actualization and not in the object under study as such. Therefore, the materials and elements brought from elsewhere (be it in the form of theories and conceptions, or of practical preconceptions and habitual attitudes) play a different role in the literary model building and at the same time are necessary and unavoidable. I will call the materials and elements of model building in the case of literary studies 'tools of actualization.'

The operation of actualization is always directed at some goal; it is teleologically oriented. The most visible goal of an academic discipline is epistemic. The researcher wants to know more about the object under study. The study of genres, of narrative forms, of versification and so on, but often also the criticism on particular authors and works have an epistemic goal. However, the history of literary criticism teaches that epistemically oriented work rarely has taken into account the hurdle of literary potentiality, or if it has, it reduces it to something remaining outside of its scope and often as something predetermined. This is most visible in the structuralist theories where literary phenomena are taken to "manifest an abstract structure, that is articulated elsewhere"[12] and not on the level of these phenomena. This implies that the operation of actualization is accompanied by another, not less basic, operation. And this is the operation of *generalization*. The form actualized in the act of interpretation is generalized so it can be applied to other phenomena and explain them. Generalization stipulates that the said form is pregiven and characteristic for more than one work. Any literary theory that extracts and describes a structure is based on generalization. Depending on whether the structure is conceived as the product of the modelling activity or as inherent to the analysed object a third operation can supplement actualization and generalization.[13] In the case where the structure is seen as inherent to the object, the structure as a product of generalized actualization is further

[12] Todorov (1976, p. 21).

[13] Tzvetan Todorov's work is an example for the second approach, namely the one where structures are grasped as immanent to the objects under study (but being abstract it also transcends the singular work). Interestingly, when claiming this, Todorov refers to Claude Lévi-Strauss, who is actually defending the other position, the constructivist one, that is, the position that structures are constructed on the basis of modelling and are not part of the empirical reality. See Lévi-Strauss (1963, pp. 279–280).

naturalized. *Naturalization* means that the product of the modelling activity is seen as independent of that activity and simply pertaining to the object. Naturalization conceals the very activity of model building to which it belongs. This operation implies that the readers take their reading of a work, for instance, for the work itself. In nineteenth century when Hippolyte Taine interpreted literature in terms of natural history[14] he was not being metaphorical, he was building a biological model of literature naturalizing it, that is, believing he was discovering something about literature in the same way decades later Pauling discovered the helix structure of α-keratin.

Naturalized generalizations extract types and make typology in literature possible. In this sense, the structures which they are positing as pregiven and actual are typified concretizations. Often in the naturalizing generalizations, the theoretical building of models relies on tools of actualization taken from the field of literature and sometimes from the works themselves and this is possible because, as I pointed out above with a reference to the work of Robert Matthias Erdbeer, literature is already modelling and it builds its own home-grown models. The first generalized naturalization of models takes place in and as literature. In the case of literature, however, generalizations of the home-grown models have a different status—not only are they open for interpretation, but being part of literature, they are inherently transformable and partake in the potentiality which they help shaping.

Generalized naturalizations, both literary and theoretical, are capable to create what I would call '*thresholds of meaning*.' The thresholds of meaning constitute frameworks for the apprehension of the individual literary works. Reading a sonnet by Petrarch as a sonnet, knowing what a sonnet is, is different than a reading of the same sonnet if one does not know anything about the genre. Reading a short story knowing Gérard Genette's narratological theory will make one notice things one would not notice otherwise—things that maybe are not there in the first place.[15] The threshold of meaning functions in at least a twofold way—on the one hand, with regard to the work or works it was extracted from; on

[14] See Taine (1899).

[15] This is the case with the notion of narrator and the idea that every story should have a narrator as a subject of enunciation. See the criticism on the universalized notion of subject of enunciation and narrator in literature developed recently by Kai Gohara in Gohara (2022).

the other, with regard to other literary objects. The fewer thresholds of meaning there are, the less literary potentiality is limited (that is, literary potentiality will be more perceptible), and vice versa, the more thresholds of meaning there are, the more literary potentiality is limited (and becomes imperceptible). But one cannot do away with the thresholds of meaning altogether, for this would mean to also get rid of what constitutes the contemporary notion of literature and thus of the very literary potentiality one wants to save. A model archeology can trace back the construction and the introduction of the different thresholds of meaning, but I will not address this here.

There can be naturalizations without generalization. When critics attempt to describe the form of an individual poem but take their own reading for the poem itself, there is a naturalization but there is no generalization as far as this reading remains an interpretation of the particular poem. I will give but one example, with T. S. Eliot's *Four Quartets*, a set of four poems published as a separate booklet in 1943. In the year of the publication, F. O. Matthiessen outlined the general form of each of the poems (he claimed that the five parts of each poem had the following structure: (1) statements and contrastatements; (2) highly formal logic and sudden contrast; (3) account of movement; (4) short lyric; (5) resumption and resolution of themes). Fifteen years later, in 1957, Herbert Howarth argued that Eliot's quartets follow the structure of Beethoven's sonata *A Minor Quartet, Opus 132*. Two years later, Harvey Gross claimed that it was not Opus 132 but the *C Sharp Minor Quartet, Opus 131*, that the quartets were built after. The same year Hugh Kenner wrote that the structure of Eliot's work is not borrowed from Beethoven but from the quartets of Béla Bartók (and this claim was supported later by Mildred Meyer Boaz). Yet ten years later Thomas R. Rees said that the true form of *Four Quartets* is resembling Berlioz's *Symphonie fantastique* but in general they follow the standard form of sonata allegro: (1) exposition, (2) development and (3) recapitulation.[16] This example deserves a separate analysis, but it is noticeable if one reads the different interpretations that their authors were attempting to grasp the actual form and the actual structure of Eliot's work and in doing so they were building models which they did not account for as models and thus were naturalizing them. The tools of actualization were in each case

[16] See Matthiessen (1943), Howarth (1957), Gross (1959), Kenner (1959), Boaz (1979), Rees (1969), and Rees (1971).

taken from elsewhere, from the history of the sonata form in European classical music. As long as the critics refrained from applying the models they built, anywhere else besides Eliot's quartets, they were not generalizing them. Rees was the only one stressing that Eliot's work can be read in different manners and in this way highlighting its potentiality but even he searched for the truest form. Each of them builds a model of the set of poems and mistook the model for the true actual form of each poem ignoring the fact that the set of poems may not have an actual form at all but just the potency of a transform making the different readings possible.

There can also be a non-naturalizing generalization where the modelling activity is taken into account and the model built is seen as a product of the theoretical activity and not as inherent to the literary object. In ethnology and cultural anthropology, this was the case of Claude Lévi-Strauss, but in the field of literary studies this attitude was not as widespread as one would have expected. Non-naturalizing generalization makes possible a cooperation with other sciences and other fields in a much more elaborate way.

So far, I have outlined three operations of model building—actualization, generalization and naturalization. Given literature's potentiality, actualization is the only ineluctable operation. The other two, generalization and naturalization, can accompany it, modifying it, separately or together. I introduced the two accompanying operations as characteristic for the modelling with an epistemic goal.

However, if one looks at the history and the actual state of the field of literary studies, one will notice that often the goal is not simply epistemic, and sometimes is not epistemic at all. There are ethical, social, political, esthetical and other agendas that permeate any dealing with literature. The actualization in these cases takes place in the form of *strategic concretization*. Strategic concretizations involve modelling where the interpretation of the literary object is supposed to be applied not to the object under study but elsewhere, to systems of a different order. Trends as that of feminism, neo-Marxism, postcolonialism, gender and queer studies, and animal studies focus on literary works in view of social, political or ethical criticism directed not just at the works but at the culture and at the society in which the works are read.

The strategic concretizations sometimes can be generalizing and naturalizing, as is in some feminist works from the 1960s and the 1970s. Kate Millett's influential *Sexual Politics* offers readings against the grain that are supposed to reveal how the ruling sex maintains its dominion over the subordinate sex.[17] However, as "[e]very detail is organically subordinated to the political message,"[18] this simultaneously limits the possibility for these texts to be read otherwise and generalizes the political claim. Moreover, the model Millett builds is seen as immanent not only to society, but to all the works she focuses on. Interestingly, similar naturalization and generalization of the strategic concretization operated by the interpretation one can find, for example, in Martin Heidegger's readings of poetical works. There the goal is no longer political but, one might say, ontological; yet the poems are all read strategically and are seen as a historical revealing of being through a model which is generalized and naturalized in the above sense.[19]

Quite often, however, the strategic concretizations are accompanied neither by generalizations, nor by naturalizations. If one turns to the postcolonial deconstructionist Gayatri Chakravorty Spivak one will see how the general claims, the subversive interpretations and the intentionally 'mistaken' readings are embedded in a careful threading of the texts which she discusses, always indicating her own position as a scholar.[20] This stress on the position of the critic or the literary scholar indicates the place which makes one or another reading possible, suggesting that no reading is universal. Such an attitude implies that in the modelling activity the operation of actualization brings about another operation, that of particularization.

Particularization focuses more on the role of the readers and what they can contribute to the discussion than on the literary object (be it a text, an intertextual relation, a constellation of figures or something else). Most of the approaches practising strategic concretizations are anti-essentialist and debunk the idea of a neutral knowledge. They no longer take the reading for the work, but at the same time it seems that they are also not that interested in the work which is for them rarely but an instrument for achieving their goal which goes beyond literature.

Particularization and generalization can be combined if associated with different aspects or different levels of the work.

[17] See Millett (1977).

[18] Moi (1985, p. 26).

[19] Heidegger's model—if one can speak of a model here—is very complex as it cannot be addressed from the viewpoint of a model theory without putting into question that very theory and all its presuppositions. I cannot address this problem in this paper.

[20] See Spivak (1999).

To sum up, actualization as the most basic operation of model building in literary studies is accompanied by other operations such as generalizations and particularizations, and also on occasion by naturalization, depending on the goal of modelling. Every modelling being teleologically oriented, the goal, or what the model is a model for, its application, in the terms of Mahr and Erdbeer, is the deciding factor for what tools of actualization will be used and what will be transferred by the model (that is, Mahr's 'cargo'). The tools of actualization help in building the model. They can come from literature or from elsewhere. By now, it must have become clear that the very distinction between what is 'in' and what is 'outside' literature is not obvious; it is historically variable and a product of modelling. When coming from literature, the tools rely not on literature as an object of study but on literature as building its own models. This leads to a particular epistemological problem as it implies a form of recursivity in literature that cannot be taken for granted and this problem should be discussed on its own.

3 Repotentialization

For the most part, the models built in the field of literary studies remain not thematized as such, even the term 'model' is rarely used. They are what Lévi-Strauss has called "unconscious models."[21] But why call them models, then? What is the heuristic point in describing these interpretations in terms of modelling? It is at least twofold. On the one hand, being conscious of the process of model building would help one perceive the action the model exerts back on the object, back on literature, as well as its influence as a model on scholarship, on science, on society, on culture, on education and so on. This makes it possible to escape from the trap of naturalization. On the other hand, it is important for building a strategy for model building. If we want to go back to an epistemic goal, how can we avoid the trap of generalization of our own reading? In the light of what was already said, it is important to rethink potentiality. In the second part of this paper, I will focus on a particular strategy for model building that takes into account literary potentiality.

Apart from the approaches already pointed at, there are others where literary potentiality is addressed as such. Phenomenology, deconstruction

[21] Lévi-Strauss (1963, pp. 280–282).

and some forms of hermeneutics discuss potentiality, and the theoretical and interpretative models that they build account for it.[22] All these approaches as well as any modelling that wants to take literary potentiality into account, however, have to face a problem related to dealing with the potential as potential. And that is the problem stemming from the fact that in our dealing with potentiality we actualize it. Actualization is the most basic operation in literary studies. Reading a poem, we are left not with the work but with our reading of it. How can we address, then, the poem not as an actual artefact but as something that makes possible unpredictable readings? Not the form we reach in our interpretation but the transform? How can we overcome our own actualizations?

This way of putting the question should have made it clear that modelling in literary studies has to deal in the first place with modalities, it is a 'modality management,' to borrow a term of Erdbeer's.[23] The question of modalities in literature is multifaceted, but here I will address only the aspect that has to do with the basic operations of modelling.

Our own actualization has to lead back to the potentiality of the work. It must *re-potentialize* what has been actualized. In order to do that, it has to indicate its own insufficiency which can be done by offering *more than one* reading. In the beginning of his *Allegories of Reading*, Paul de Man, for example, takes up the figure of the rhetorical question and offers a double interpretation of the famous line by Yeats "How can we know the dancer from the dance?", once as a rhetorical question that claims that we cannot tell the one from the other, and a second time as a literal question about the possibility to avoid the confusion of the sign with its referent or with its meaning.[24] The two readings are incompatible and yet both are possible. I would argue that taken separately each is but an actualization of the possibilities of Yeats' line but taken together in their incompatibility they start indicating something that surpasses each of them and something that surpasses actualization. The effect is that the line is re-potentialized. The different readings we take up need not even be our own—in order to re-potentialize the work it is just as efficient to discuss the ground of several readings at the same time. This is the effect, for instance, of reading together all the different interpretations of the

[22] See, for example, Iser (1978) and Bloom et al. (1979).

[23] See Erdbeer (2015, pp. 17–19).

[24] De Man (1979, pp. 11–12).

form and structure of T. S. Eliot's *Four Quartets*, mentioned above. The model built in this way is not entirely based on what is given in our (or someone else's) actualization.

Things are not as simple, however. In the example with Paul de Man's double reading, we should notice that he uses the line as part of his own tools of actualization. According to his interpretation, in the way the poem addresses the problem of the possible difference between the dancer and the dance, it poses the question of what it does itself, the question about the status of the sign and its relation to meaning and referent. And this very question is left unanswered univocally because of the two incompatible readings. What is important is that using elements of the poem as tools of actualization Paul de Man lets these elements themselves indicate the potentiality of the poem. In other words, these elements are turned into 'formal indications' (if I use Heidegger's term) and are revealed to function in a self-referential way. The 'self' in this self-reference is not the poem as an artefact but its field of potentiality. The indices thus refer no longer to a context but to a modality, they are *modal indices*. What Paul de Man does is to let the poem describe self-referentially itself indicating its own possibilities without being exhausted in any of the actualizations.

If one wants to build a model that is re-potentializing the work, or the object under study, back from its ineluctable actualization, one should use tools of actualization from the work and let them indicate in a formal manner the field of potentiality. (This poses the important question of indexicality and its relation to modality I cannot address here.)

Finally, in order to be able to use elements of the literary object as tools of actualization that reverse the direction of actualization making it indicating the potential as potential, one needs a starting theory, a modelling tool brought from outside. In the example with Paul de Man's reading, it is semiotics that plays the role of such a tool but later speech act theory plays a similar role.

To sum up, the strategic model building that allows one to actually address literary potentiality as potentiality involves the combination of three different operations. It requires that one adopts a starting theory which later can be modified or just left aside. It supposes double or multiple actualizations, double or multiple interpretations. Finally, and most importantly, it necessitates the use of elements of what we analyse as tools of actualization in a self-referential way that would let them indicate in a formal manner the potentiality and thus reverse the direction of actualization.

In the field of epistemology and philosophy of science, there is an old opposition between modelling and experimentation.[25] In the field of literary studies, experimentation necessarily takes place through modelling—a form of modelling that not only has to be self-aware as modelling but also has to take into account the potentiality of literature and realize its role in the modality management finding a way to let literature recursively indicate its own field of potentiality. The basic operations of model building in literary studies can help in this task and yet just as easily hinder it from getting ever accomplished. They are the hinge that can open literary studies to other fields and discourses.

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Modelling the Energy Transition 1: Technology in Practice

On the Art of Electric Power System Modelling and Simulation for Integrated Transmission-Distribution Analysis

Uwe Kühnapfel and Veit Hagenmeyer

1 Introduction

Future electricity supply needs to ensure a reliable and affordable low-carbon power generation, which will greatly depend on renewable energy sources (RES) such as solar photovoltaic and wind power. Growing demand for energy from environmentally friendly sources is challenging modern grids to provide a reliable power supply that includes high fluctuating sources. Power grid operators must ensure that energy networks continue to provide the highest levels of reliability and performance at reasonable cost. Grid modelling and analysis supports the design and engineering of the power grids transition process with various states of grid evolution from its present centralized, carbon-based architecture to a future de-carbonized state. The present contribution discusses various power grid modelling applications within the context of the energy transition process in Germany. In doing so, electric power system modelling and simulation is shown as a technological 'art form,' highlighting that

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the experience of the engineer is of paramount importance when it comes to defining the system under consideration.

2 Electricity Network Modelling and Analysis—Overview

In the domain of electrical and power systems engineering,[1] there are basically three different types of electrical network modelling and studies.[2] The first one is the *steady-state study*, which involves load flow analysis of AC (alternate current) systems that gives an idea about the level of voltage in different buses—understood as the nodes of the grid—of active and reactive power, and of the load conditions of transmission lines, generators and transformers. Software like PSS/E and PowerFactory[3] are commonly used as commercial tools for this purpose, while software systems like MatPower, GridLab-D and PypSA are mainly used in the research and academic field. The second type of studies is called *stability analysis* and deals with short circuit studies in the time order of 1 second. Software tools such as PowerFactory,[4] PSS/E and PSS-Sincal are available for this kind of studies. The third one is *transient studies* for the electro-mechanical (RMS, root-mean-square) and for the EMT (electro-magnetic transients) time domains, which also deals with short circuit analysis and load step effects, but in very short periods of time in the order of microseconds in EMT to milliseconds in RMS studies. Software applications like MATLAB/Simulink, PowerFactory[5] and PSCAD are used in the latter kind of studies. For real-time studies (PHIL, power hardware in the loop), digital-twin and control system design, specific hard-/software systems are available, like RTDS or Opal-RT. All this is accomplished by integration of modern power electronics systems like converters as used for the interconnection of renewable energy (RE) sources, like wind and solar power generators,[6] to the traditional AC grid where mainly synchronous machines were and still are used as generators.

[1] Schwab (2012).

[2] Çakmak et al. (2015).

[3] Gonzalez-Longatt et al. (2014).

[4] Gonzalez-Longatt et al. (2018).

[5] Gonzalez-Longatt et al. (2020).

[6] Bundesnetzagentur Power Plant List (2023).

In addition, we need to model compensation units (FACTS—flexible AC transmission systems) as used for voltage and reactive power control in the integrated transmission network. Examples for FACTS are stepped reactors and capacitor banks, but also power electronics-based systems like STATCOM units, which combine both inductive and capacitive reactive power.

In order to study future electricity supply which needs to ensure a reliable and affordable low-carbon power generation greatly depending on renewable energy sources (RES) such as solar photovoltaic and wind power, we deal with all of the above listed types of power grid modelling and analysis, and hence with a high complexity of interconnected and large-scale models. For this reason, our very complex electricity network and system models (see Table 1 and Figs. 1–3) include network models of all voltage layers as used in electrical power supply. This ranges from low-voltage level (LV), as used in the end-user installations of the distribution network (400 V), the medium-voltage level (MV, in Germany typical: 6/10/20/33 kilovolts), the high-voltage level (Germany: 60/110/150 kV), up to the very high-voltage layer (Germany: 220/380 kV nominal) as used in the transmission grid and the interconnected European power transmission network ENTSO-E. In addition, this is accomplished by HVDC links (high-voltage direct current), which are used to transmit high volumes of electrical power over long distances (> 300 km) with minimum losses (< 2% over a + 500 km distance). Typical losses in the 380 kV grid are about 1% per 100 km transmission distance.

When we combine network models of different voltage layers into one integrated study, we call this 're-bundling,' since due to European market

Table 1 Number of elements in the power grid models as mentioned in the following sections

Model	*Nets*	*TSOs*	*Trans*	*Lines*	*Buses*	*Stations*	*Switches*	*Comp*	*Gen*	*Loads*
ENTSO-E CE	28	32	5622	15,255	18,728	9206	78,278	1801	19,325	11,198
Germany	2	4	219	1492	2894	1291	10,281	137	4139	1250
BW	6	1	1970	1187	2036	586	13,408	40	689	972
KIT CN	1	1	125	522	198	46	1060	63	17	430
KA-N-4018	1	1	11	179	31	12	109	–	9	116

Abbreviations: Trans.: Transformers, Comp.: Compensation devices, Gen.: Generators

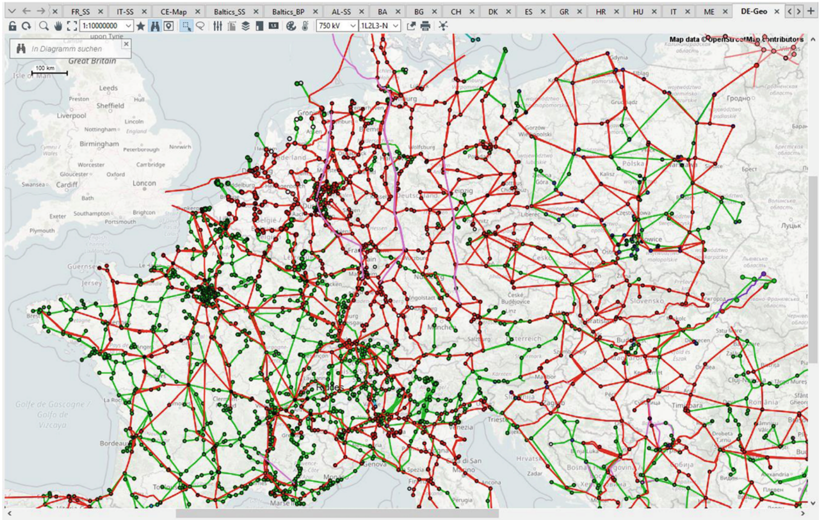


Fig. 1a Interconnected Electricity Transmission Network in Central Europe, ENTSO-E CE (© KIT Karlsruhe Institute of Technology)

regulations the previously regionally integrated power supply networks had to be split over the last 20 years into independent companies and operators for generation, transmission and distribution of electricity. This process is (was) called 'un-bundling.' Its initial intention was competition between electricity generation and supply companies, thus reducing the cost of electricity for the end-user. In consequence, the various Transmission System Operators (TSOs) and Distribution System Operators (DSOs) look—and model—only at their own power region and voltage layer. However, as we like to get an integrated view at the whole interconnected system—over all voltage layers and regions—we 're-bundle' (physically and operationally). Thus, a change of load or generation in Denmark or Bulgaria will affect the power system state in Portugal or Poland, and a power step in the lowest voltage layer on household level will slightly effect the state in the transmission grid, i.e. the voltage on busbars and the loading of lines and transformers.

This very high complexity of interconnected and large-scale models cannot be derived as mathematical equations are derived: for every task of study, a respective modelling perspective has to be taken into account, in

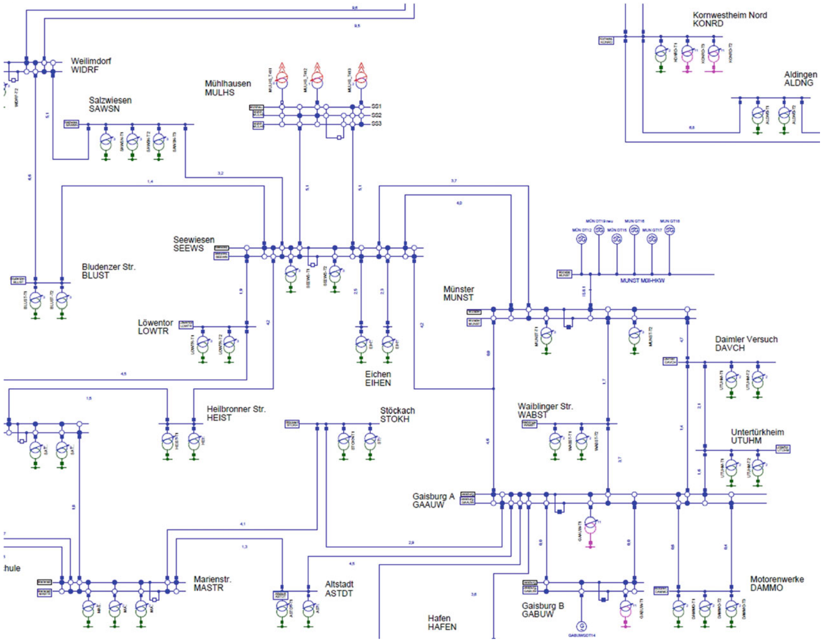


Fig. 1b Section of the 110-kV network (© KIT Karlsruhe Institute of Technology)

view of the defined task, in order to be able to overcome calculation problems and to achieve meaningful results. This process depends heavily on the experience of the engineer, a point of view which has been confirmed recently—especially for future power systems—by a statement of Martin Schmieg, Chairman of the Advisory Board of DIgSILENT GmbH, the company that produces the PowerFactory modelling and simulation tool:

> It is quite obvious that increasing numbers of power electronic converters leads to a clear overlap of the EMT- and RMS-based analysis functions, whereby the complexity of models in conjunction with the model scope leads to calculation problems that are sometimes difficult to solve. Here,

the experience of the engineer is of paramount importance when it comes to defining the system under consideration.[7]

Examples of the various complex power system models and their combinations are presented in the next sections.

3 Transmission Grid Modelling

The largest models we model and study constitute the interconnected transmission grid in the Central Europe region (region ENTSO-E, European Network of Transmission System Operators for Electricity),[8] as shown in Fig. 1a. In addition, we have developed grid models of large portions of the 110 kV voltage network in Germany, including the entire region of Baden-Württemberg (BW), as shown in Fig. 1b. The 110 kV model BW includes the transformation-layer down to the medium-voltage grids, 10/20 or 30 kV, depending on the region and operator. As shown in Fig. 1b, displayed is a small part of the 110 kV cable grid in Stuttgart, the 10 kV is used for the medium-voltage feeders into the living quarters and industrial users. Accumulated loads and generation, i.e. the summarized electric loads of all end-users connected to this feeder (households, small industry and commerce), as well as all generators (e.g. rooftop PV, Biomass small wind, biomass, block-heating stations and run-hydro generators), are connected to the electricity network on this voltage level (MV busbars). The 110 kV and the VHV transmission networks have a meshed topology, and the MV and LV networks are operated as radial topology.[9]

For the transmission grid, various controller structures are required for balancing load and generation and for balancing the international and inter-regional energy trade between grid operators. For each control region, a frequency/power-controller is implemented,[10] which controls the operation (power and voltage setting) of the operational thermal power stations in the specific control region. Renewable generators (wind, solar, biomass, run-hydro, block-heating) have priority in energy supply,

[7] Schmieg, Foreword, in Gonzalez-Longatt and Torres (2020, p. V).

[8] Kopernikus-Projekt ENSURE (2023).

[9] Föllinger (2013).

[10] Föllinger (2013).

and the thermal stations are used to balance the electricity generation with the regional and temporal reactive power load demand of the end-users. In general, the load demand is not regulated, and so-called load shedding (temporal restriction of electricity supply) is only used in emergency situations.

For grid compensation (voltage, reactive power demand and control), passive elements (reactors and capacitor banks for inductive and capacitive reactive power, respectively) and active power electronics devices like STATCOM (Static Synchronous Compensator) are used. A STATCOM is a fast-acting device capable of providing or absorbing reactive current and thereby regulating the voltage at the point of connection to a power grid. It is categorized under flexible AC transmission system (FACTS) devices. STATCOM allows for linear reactive power compensation, thus for voltage control, over a broad range in both directions (inductive and capacitive). All FACTS devices, active or passive, require a controller model. In addition, most transformers are equipped with a stepping unit, which is used to change the transformation in steps within a certain range (typical: ± 10%) with respect to its nominal value.

4 Distribution Grid Modelling

Examples of distribution grid sub-models are shown in Fig. 2a, 2b. Such models cover, in terms of type, complexity and region, street-level MV/LV subsystems of urban housing areas and industrial plants.

Each urban supply area (Fig. 2b) has one MV feeder with a 20/0.4 kV transformer. Radially connected are LV loads and generation units, with manually operated switchboards for topology change, to enable construction work. Typical characteristics for this type of model are: a 20 kV feeder substation and 400 V supply cables to the buildings with up to 100 loads, which are separately metered, and up to 3 megawatts (MW) power per substation and transformer. In the example shown in Fig. 2b, a 630 kVA transformer is used. Connected to the LV grid are RE generators (rooftop PV systems), electro-mobility load stations, a mix of public and private buildings and households. This type of models can be used in 'smart-grid' studies as well.

Another application of a HV/MV/LV model, as shown in Fig. 2a, can be characterized as an industrial area. The example shows the electricity

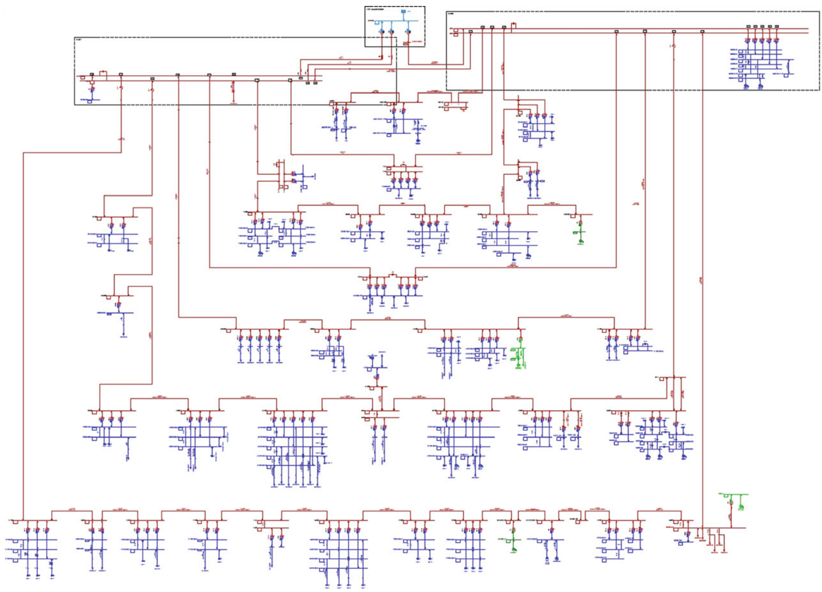


Fig. 2a KIT-Campus North Grid (© KIT Karlsruhe Institute of Technology)

network of the KIT Campus North (KIT CN).[11] Our model shows the 110/20 kV connection to the public electricity network with 3 transformers 110/20 kV with power ratings of 2 × 23,5 MVA and 40 MVA. Four CHP (combined heat and power) generators use natural gas as primary fuel and are rated in sum with 13,5 MW (rating 2 × 4,5 MW, 2,5 MW, 2 MW). In addition, 8 diesel generators provide emergency power in case of electricity outages. A 1,5 MW solar PV field, together with a battery storage rated at 1 MWh, is used as experimental RE units.[12] The PV unit feeds directly to the public power grid. Maximum load in the KIT CN power grid is up to 20 MW.

[11] Energy Lab 2.0 (2023).

[12] Erdmann et al. (2019).

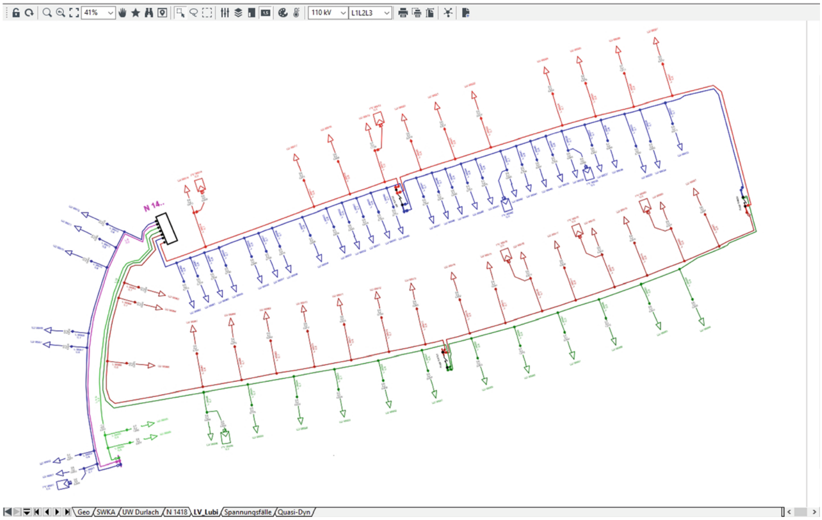


Fig. 2b Typical living quarter, 20 kV Feeder in a suburb of Karlsruhe with 74 houses, 12 roof-top PV, highly detailed components (cables, interconnectors, protection) (© KIT Karlsruhe Institute of Technology)

5 Study 1: Demo Region—Power Balancing in High-Wind Region

For the ENSURE demonstration region (Schleswig–Holstein), the grid model of the demo region was created.[13] This comprises the transmission grid of TenneT and the 110 kV distribution grid of SH-Netze in the Steinburg district and in the entire area between Hamburg, Augsburg and Heide. While the wind farms in the demo region are directly connected to the 110 kV stations, the remaining wind farms are connected to the MV busbars of the respective HV/MV transformers. For modelling the time series data, the data for the real year 2019 (load, generation by category) have been taken from the TenneT transparency platform and adjusted according to the weekdays and holidays of the target year. The model created was then dynamized by FAU, i.e. equipped with plant controllers,

[13] Kopernikus-Projekt ENSURE (2023).

and is used to prepare for the demo phase, which includes the integration of MVDC (medium-voltage DC) plants and a solid state transformer (SST).

The regional area Schleswig–Holstein is identical with the transmission grid zone D21, operated by the TSO TenneT. Three offshore wind regions with a combined generation rating of 2130 MV are connected to the 380 kV station Büttel with HVDC cables. These are: SylWin1 (sea station SylWin Alpha, ± 320 kV DC, 864 MW), HelWin1 (sea station HelWin Alpha, ± 250 kV DC, 576 MW) and HelWin2 (sea station HelWin Beta, ± 320 kV DC, 690 MW). According to the power plant list of the Bundesnetzagentur (BNA Kraftwerkliste), the accumulated peak generation of onshore wind parks in the D21 region is 7227 MW. The maximum power load within the D21 region is about 2 gigawatts. Combining these numbers, there is an over-production of about 7,3 GW in the D21 region, if we want to avoid positive re-dispatch measures (limitation of generation power by grid control limitation from the TSO, generation reduction). To balance this over-generation capacity in the D21 region, there are a number of grid balancing projects either already in operation or under construction: in the 380 kV station Brunsbüttel, the SuedLink A HVDC link (± 525 kV, 2000 MW) will connect the D21 zone to the station Großgartach in the Transnet-BW control zone D41 (operational 2026). In the 380 kV station Wilster-West, the HVDC link SuedLink B (± 525 kV, 2000 MW) connects the D21 zone to the 380 kV station Grafenrheinfeld-West in Bavaria. The NordLink HVDC sea-cable (± 525 kV, 1400 MW) connects the HVDC converter station Wilster-West to the HVDC converter station Tonstad in southern Norway (operational since December 2021). And another HVDC link called Baltic Cable, rated with ± 600 MW transmission capacity, connects the station Herrenwyk (close to Lübeck) with the station Krusenberg in southern Sweden.

Study case for the year 2026: For the year 2026, when all national HVDC links (SuedLink A, B) and the interconnectors NordLink and Baltic Cable will be operational, we define a grid balancing case study. For this, the target is the transfer of wind energy from the D21 zone to southern Germany and through the HVDC interconnectors NordLink and Baltic Cable to Norway and Sweden, respectively. A real weather situation (Sept. 2020) is used to define a quasi-dynamic load flow case, as shown in Fig. 3a. The load and generation scenarios are transposed into

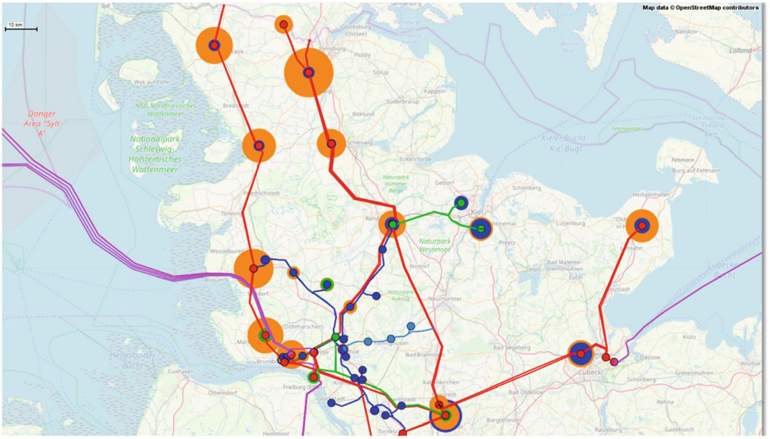
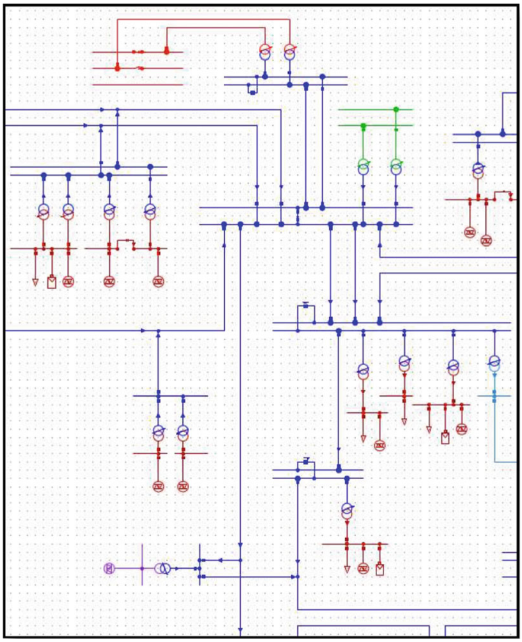


Fig. 3a Electricity infrastructure in the study region D21 and load/generation diagram (© KIT Karlsruhe Institute of Technology)

Fig. 3b 110 kV infrastructure in the demo region (district Steinburg) (© KIT Karlsruhe Institute of Technology)



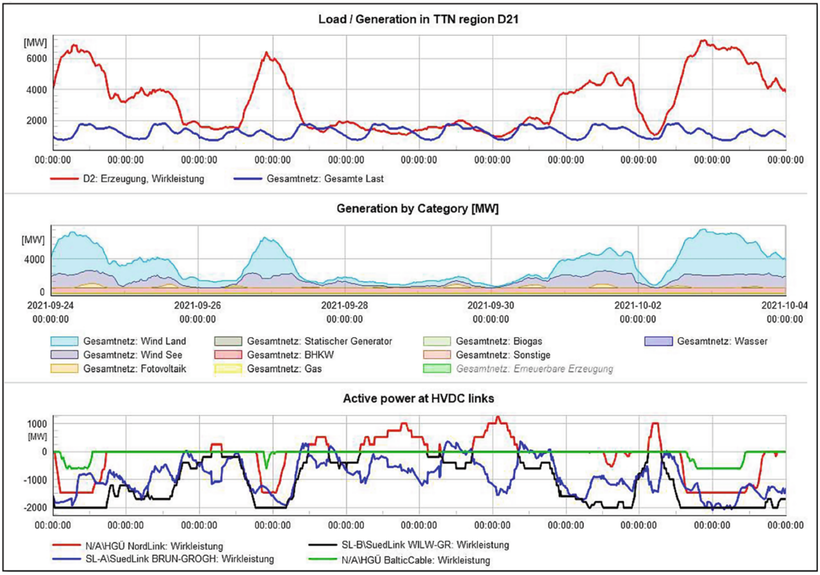


Fig. 3c 10-day QDSL simulation with a high generation surplus due to very high wind generation on- and offshore (24.9.–4.10.2020) (© KIT Karlsruhe Institute of Technology)

the comparable period in 2026. A controller model is defined for operation of the HVDC links and other generators in the zone D21. The 10-day generation/load QDSL simulation with extreme weather situations (max./min. wind) shows that the very high over-production of wind power[14] can be balanced with the 2 GW load in the region, in combination with the transfer.

6 Study 2: Region Transnet-BW—Grid Balancing Using 2 HVDC Links

In study 1 as described in the previous section, we proved that a massive over-production of RE generation in one region (D21, Schleswig–Holstein) can be balanced through HVDC links and interconnectors. In

[14] Kyesswa et al. (2020).

study 2, we look at a similar region in Baden-Württemberg with control zones D41 and D42 for the same year (2026), located in the control region of the TSO Transnet-BW (D4).

Figure 4 shows the grid model in Baden-Württemberg and a 7-day QDSL study during an extreme situation. As well as in study 1, we use real weather data for PV and wind generation in the target period (April 2026). For the study, we chose the Easter holiday, which is characterized by minimum consumption load due to industry closure of the public holidays, together with an already very high PV generation in the D4 zone due to cold temperatures in combination with already high solar radiation. In our study case, the maximum PV generation is 4,5 GW.

For the study, we have developed a simulation model of the Transnet-BW transmission grid (220/380 kV AC), together with the 110 kV grid of all DSOs (Netze-BW, Stadtwerke Karlsruhe, Stuttgart, Ulm, Freiburg, Heilbronn, MVV in Mannheim and the SYNA grid). In the D4 region, there is a population of around 11 Mio. people, and a combined maximum power load of about 10,5 GW. In the D4 region, the generation of the previously used nuclear power stations Neckarwestheim-2 and Philippsburg-2 (final closure end 2019 and April 2023), with a summarized generation capacity of about 3 GW, has to be compensated by the two HVDC links ULTRANET (± 320 kV, 2 GW, Osterrath-Philippsburg) and SuedLink A (± 525 kV DC, 2 GW, Brunsbüttel-Großgartach). The latter two HVDC links are projects with the intention to transfer wind power from the north-sea offshore wind

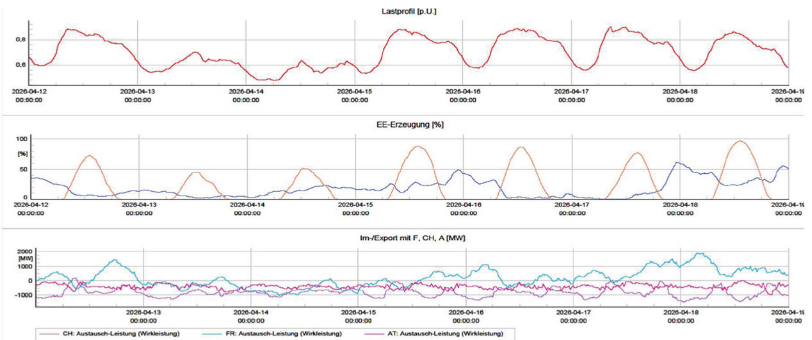


Fig. 4a Electricity Network Baden-Württemberg with HVDC, 380-/220-/110-kV-model layers (© KIT Karlsruhe Institute of Technology)

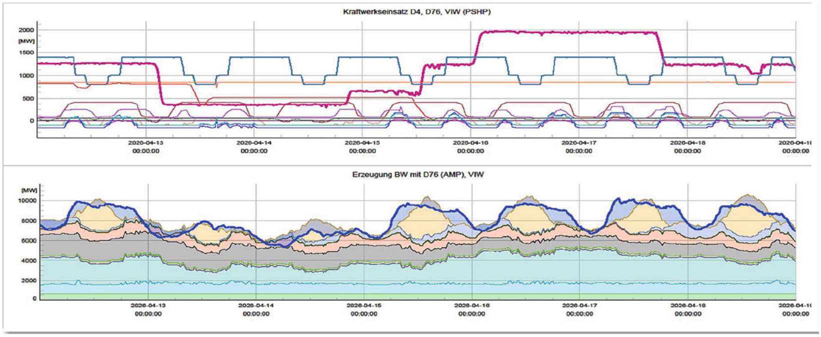


Fig. 4b Result diagrams of 1-week Quasi-Dynamic-Simulation (load, wind/solar, import/export, generation by power station, generation by primary energy sector) (© KIT Karlsruhe Institute of Technology)

parks to southern Germany. In addition, the control region D4 has to cope with a high transfer power from and to the neighbouring countries France, Switzerland and Austria with the German neighbouring zones of the TSOs Amprion and TenneT.[15] Baden-Württemberg had a high portion of solar PV in 2022, with an accumulated peak generation of 7,8 GW. Another feature of the Transnet-BW control zone is the high portion of pumped storage hydro plants in the southern black-forest region and in Vorarlberg/Austria (rated in sum approx. 4 GW). Along the rivers Rhine and Neckar, there are run-river hydro plants, rated with about 800 MW. About half of the generation capacity is connected to the DSO grids, the other half is under direct control of the TSO. In terms of grid operation, the daily load and generation balance is a challenge in terms of maximum security of grid supply and of the economic goal of a low rate of re-dispatch measures with regard to the high rate of flexibility needed in view of the highly volatile RE generation (mostly PV) in Baden-Württemberg.

Figure 4b shows results of study for the year 2026, when both HVDC links (ULTRANET, SuedLink) are supposed to be in operation:

- The goals are reachable with 2 HVDC links (both rated 2 GW).
- All requirements of the grid-code are fulfilled (voltage limits, load limits of transformers, lines, cables and switchgear).

[15] Weber (2021).

- Pumped storage and NG stations compensate primary and secondary control power with high $\Delta P/\Delta t$ rates of PV-KW in the morning and evening hours.

7 Conclusion

The present contribution discusses some highly advanced power grid modelling applications that are key to the energy transition process in Germany. Yet by presenting ways of tackling this immensely complex mesh of resources and data management, the modelling and simulation of electric power systems shows itself not only as a strategy of regulation and control, but also as a technological 'art form,' introducing a variety of visual representation formats to enhance its arguments and make its data fit. Moreover, the report we gave from deep inside the modelling activities within our EnergyLab also highlights the often neglected and sometimes precarious fact that the experience of the engineer is of paramount importance when it comes to defining the system under consideration, especially in view of overcoming calculation problems and competing modelling alternatives. However, the importance of the engineers' experience for obtaining meaningful results does not call into question the profession of modelling, nor does it minimize its efficiency, as long as it is taken into account. In our example, a detailed and complex modelling of power grids provides the basis for a number of operational and grid studies in electrical power supply, e.g. in order to act for grid expansion in the future. Based on the respective high complexity models described above, the combined studies 1 and 2 show that the operational control of a future power grid with a very high share of renewable energy is possible in view of the TSO perspective with respect to balancing the generation/load flows of their individual control regions. However, in the studies 1 and 2, we cover only the steady-state load flow analysis. Since our grid models include—on a different complexity level—the dynamic control models of the generators, in other modelling applications we will look into the short time transient dynamics aspects of some of the components (generators, HVDC links, FACTS) of our power grid models. Meaningful results are obtained when a fitting picture of all the modelling aspects is achieved in the eye of the engineer, based on calculations and experiments, but also on the lifelong training of the modeller.

To sum up: the very high complexity of interconnected and large-scale power system models cannot be derived as mathematical equations are derived: for every task of the study, a respective modelling perspective has to be taken into account in view of the respective task and on the basis of the experience of the engineer in order to be able to overcome calculation problems and to achieve meaningful results. This modelling process is absolutely necessary in order to be able to develop the design of future power grids mainly based on renewables.

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Daily Streamflow Forecasting Using an Enhanced LSTM Neural Network Model

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Nomenclatures

ACF	Auto-correlation function
ADALINE	Adaptive linear element
ADAM	Adaptive moment estimation
AI	Artificial intelligence
ANFIS	Adaptive neuro-fuzzy inference system
ANNs	Artificial neural networks
AR	Autoregressive

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ARCH	Autoregressive conditional heteroscedasticity
ARIMA	Autoregressive integrated moving average
AVMD	Adaptive VMD
BORBDA	Benin-Owena River basin development authority
BPNN	Back-propagation neural network
BPTT	Back-propagation through time
CA	Combined accuracy
CNN	Convolutional neural network
CoC	Correlation coefficient
CPU	Central processing unit
DPA	Data preprocessing algorithm
DWT	Discrete wavelet transformation
EEMD	Ensemble empirical mode decomposition
ELM	Extreme learning machine
FFNN	Feed-forward neural network
GCA	Grey correlation analysis
GEP	Gene expression programming
GHGs	Greenhouse gases
GIS	Geographical information system
GPR	Gaussian process regression
GRNN	Generalized regression neural network
IPFO	Improved the pathfinder optimizer
IRENA	International renewable energy agency
LinReg	Linear regression
LM	Levenberg-Marquardt
LSSVM	Least-square SVM
LSTM	Long short-term memory
MA	Moving average
MAE	Mean absolute error
MAPE	Mean absolute percentage error
MARS	Multivariate adaptive regression splines
ML	Machine learning
MLPNN	Multi-layer perceptron neural network
MLR	Multiple linear regression
MSE	Mean square error
NAR	Nonlinear autoregressive
NARX	Nonlinear autoregressive exogenous
nRMSE	Normalized RMSE
NSME	Nash-Sutcliffe model efficiency

OP-ELM	Optimally pruned ELM
PACF	Partial ACF
R^2	Coefficient of determination
RBFNN	Radial basis function neural network
RFs	Random forests
RMSE	Root mean square error
RMSprop	Root mean square propagation
RNN	Recurrent neural network
SARIMA	Seasonal ARIMA
SDGs	Sustainable development goals
SGDM	Stochastic gradient descent with momentum
STL	Seasonal-trend decomposition using loess
SVM	Support vector machine
SVR	Support vector regression
SWATs	Soil and water assessment tools
VMD	Variational mode decomposition

Symbols

$f_{s_{\text{norm}}}$	Standardized f_s
f_s	Streamflow
f_{s+1}	Day-ahead streamflow
g_{ap}	Accuracy gain percentage
n_r	Initial learning rate
α	Weight
β	Bias
ε_r	Relative error
μ	Mean
ξ	Error terms
σ	Standard deviation

1 Introduction

Oil and gas consumption for power generation has caused irreversible damage to humanity. Emission of greenhouse gases (GHGs), acid rain, and climate change are notable damages ensuing from oil and gas-based power production.[1] To address the attendant effects of oil and gas utilization and meet the United Nations' sustainable development goal 7 (SDG-7), which enunciates improving access to affordable, clean, modern, and reliable energy, renewable energy is a good alternative. Transnational organizations, such as the international renewable energy agency (IRENA), give support in the form of policy, resource assessment, financial knowledge, technology, etc. to countries in their transition to a green energy future. This implies that the use of renewable energy is widely supported. It is therefore recommended to utilize renewable energy as it is environmentally friendly. One such type of renewable energy is water energy. Water cycle has streamflow as its central component, and it has a crucial significance in an extensive range of applications. Having reliable information about future streamflow time-series data is essential in hydrological research, as it can help water managers and engineers to plan hydropower generation; particularly for damless hydropower plants and scale through modelling procedures that are necessary to make informed decisions.[2] To also ensure preparedness and mitigation of floods and drought as well as water infrastructure design, water resources and hydropower production planning and management, precise streamflow prediction is considerably essential.[3] Specifically, water resources management is gaining more attraction as a result of population growth leading to increase in water and energy demand.[4] Consequently, the development and validation of sound models for precise prediction of hydropower streamflow are required, generally, for sustainable water resources management, planning and informed decision-making.[5] It may be demanding though to make an accurate streamflow forecast because of the complex non-stationary, nonlinear, and dynamic effects of topography

[1] Cai et al. (2020).

[2] Barino et al. (2020) and Niu and Feng (2021).

[3] Luo et al. (2019), Mehdizadeh et al. (2019), Hadiyan et al. (2020), and Zuo et al. (2020).

[4] Uysal et al. (2016) and Sun et al. (2020).

[5] Hadiyan et al. (2020), Zuo et al. (2020), Adnan et al. (2020), and Ni et al. (2020).

and human activities, evaporation, precipitation, runoff yield, and confluence. To account for these complexities, suitable tools must be deployed in streamflow time-series data modelling.[6]

At different periods, several modelling methods have been used lately to forecast hydropower streamflow, namely: physical methods, data-driven approaches such as autoregressive integrated moving average (ARIMA), shallow artificial neural networks (ANNs), and deep learning techniques such as the long short-term memory (LSTM) neural network implemented in this study. ANNs are promising soft computing techniques with the ability to model nonlinear processes. Artificial intelligence (AI)-based methods, such as ANNs, have long been acknowledged as accurate techniques for robust streamflow prediction;[7] although conventional machine learning (ML) methods, such as regression analysis, shallow neural networks, support vector machine (SVM), random forests (RFs) have been applied successfully in the field of hydrology.[8] Nevertheless, they may not approximate complex relationships as accurate as deep learning techniques. Some of the drawbacks of traditional ANNs are less generalizability, slow convergence speed, over-fitting and falling into local minimum. On the other hand, deep learning methods can be designed to surmount these shortcomings. Deep learning techniques are more famous in time-series data forecasting than traditional ANNs. As well-known data-driven methods to obtain useful information from highly nonlinear physical processes, they require thorough analyses of several input amalgamations, appropriate model structure selections, optimization parameters assignment, etc.[9] Generally, the performance of neural network models is substantially connected with additional analysis techniques. Modelling of streamflow on different spatiotemporal scales using ML is an emerging field.[10] It is useful to hydropower computation which is an essential part of water resources planning, development, and management.[11] By and large, renewable resource modelling and forecasting will remain an

[6] Mehdizadeh et al. (2019).

[7] Zeng et al. (2012).

[8] Hagen et al. (2021).

[9] Uysal and Şorman (2017).

[10] Hagen et al. (2021).

[11] Hammid et al. (2018).

evolving field provided that researchers in the field continue to investigate model accuracy improvement techniques. Seeking methods that can further improve prediction accuracy is typically crucial for streamflow time-series data forecasting, as hydropower system economy can be directly dependent on the accuracy of forecast models.

In this study, an innovative deep learning technique using LSTM neural network adapted with data preprocessing algorithm (DPA) is proposed for seasonal streamflow forecasting. The resolution of the historical streamflow time-series data is 24 hours, i.e. predictions are made a day ahead. As flow rate is a key parameter in hydropower potential assessment, accurate streamflow forecasting for a stable supply of hydropower cannot be overemphasized. Other areas of application include flood mitigation; flow regime establishment, and water resources planning and management in general.

Literature Appraisal

A synopsis of some previous studies on the modelling and forecasting of streamflow are presented in this section. Luo et al. forecasted monthly streamflow using a hybrid support vector regression (SVR) method,[12] in which the frameworks combine error suppression, data regression, time-series decomposition, and factor analysis. The streamflow with lag and current streamflow correlation coefficient (CoC) are examined based on Grey correlation analysis (GCA), auto-correlation function (ACF), and partial auto-correlation function (PACF). To make monthly streamflow prediction, the authors amalgamated generalized regression neural network (GRNN) and SVR models with trend and seasonal decomposition. To enhance accuracy, multi-model combination error and autoregression methods were utilized. Fourteen models were built with data collected in China used for proposed model evaluation, and comparisons were made against a stochastic autoregressive integrated moving average (ARIMA) as benchmark model. Their results revealed that the combined GCA, seasonal-trend decomposition using loess (STL), and SVR model expressed as GCA-STL-SVR demonstrated a better streamflow forecast performance. Specifically, the proposed model's standard deviation is decreased by more than 30% and the average error is reduced to less than

[12] Luo et al. (2019).

0.1. In another study presented by Adnan et al., data collected from two different stations in Pakistan were utilized for monthly streamflow forecast based on heuristic techniques comprising M5 model tree, multivariate adaptive regression splines (MARS), least-square support vector machine (LSSVM), and optimally pruned extreme learning machine (OP-ELM).[13] The authors validated and tested their forecast models with four input cases considering mean absolute error (MAE), combined accuracy (CA), root mean square error (RMSE), and normalized RMSE (nRMSE). As the results, MARS and LSSVM models presented more precise forecasts in comparison with other approaches. For one of the stations, it is observed that only temperature data is sufficient to successfully forecast monthly streamflow and rainfall inputs only can give good result as well; but they produce inaccurate forecasts with respect to the other station. Attempt was made to compare the results of seasonal ARIMA (SARIMA), but in all, LSSVM and MARS models were proposed for monthly streamflow forecast. Mehdizadeh et al. have applied moving average (MA) and autoregressive (AR) approaches for the estimation of monthly streamflow also, and the results were compared with models in which the latter and former were integrated with autoregressive conditional heteroscedasticity (ARCH) method.[14] The authors also considered two AI techniques, namely, gene expression programming (GEP) and MARS. Analyses of local and exterior data in Iran and Canada were carried out to evaluate individual model performance in terms of the accuracy of monthly streamflow. CoC, MAE, and RMSE metrics were utilized to compare the performance of all the estimating models considered. As the result, MA-ARCH and AR-ARCH performed better than the traditional models. Additionally, when local data analysis technique was utilized, the integrated MA-ARCH and AR-ARCH models outperformed AI approaches. However, the approach of exterior data analysis is more accurate than the local for monthly streamflow assessment. According to the conclusion the authors drew from the exterior data-based AI approach outcomes, it is evident that neighbouring data can be utilized to approximate the streamflow of a station when the streamflow data of the particular station are not obtainable.

[13] Adnan et al. (2020).

[14] Mehdizadeh et al. (2019).

In another study performed by Uysal et al. different input variables comprising air temperature, evapotranspiration, rainfall, evaporation, and historical streamflow data were considered for monthly streamflow estimation based on multi-layer perceptron neural network (MLPNN) model.[15] To dampen the noise in the fifty-seven years' estimation data, the authors carried out data decomposition by applying discrete wavelet transformation (DWT). Estimation model evaluation was based on the computation of coefficient of determination (R^2), RMSE, Nash–Sutcliffe model efficiency (NSME), and MAE, and the result showed that the deployment of data preprocessing presents better ability for high flow capture particularly in comparison with increasing the number of input vector. Specifically for decomposed streamflow data alongside other meteorological variables, the training and testing NSME and R^2 respectively range between 0.73 and 0.85. For a region dominated by snow in Turkey, Uysal et al. predicted streamflow utilizing two different ANNs with ten years of satellite data.[16] The study considered recent satellite snow products as substitute model inputs to enhance melting snow modelling accuracy. The results of MLPNN and radial basis function neural network (RBFNN) were compared using satellite snow-covered area products as the climatic data-based model inputs. Levenberg-Marquardt (LM) training algorithm with gradient was used in the MLPNN for streamflow modelling. The nonlinear nature related to hidden nodes makes the difference between the RBFNN and MLPNN. A sigmoid function was used to implement the nonlinearity in MLPNN while nonlinearity of RBFNN is based on the training dataset. Other areas examined in this study include optimization algorithms, model architecture determination and techniques to circumvent over-fitting. In another study reported by Dou et al., computation models of free flow discharge based on four regression models and three types of ANNs were established.[17] The ANN models consist of MLPNN and GRNN. The model was fully validated with observed data and the results indicated that the MLPNN and the third-order polynomial regression model have improved adaptability. In addition, the authors analyzed the merits and drawbacks of the various models in order to identify error source. The study gives a hypothetical basis for handling the

[15] Uysal and Şorman (2017).

[16] Uysal et al. (2016).

[17] Dou et al. (2020).

discharge computations of medium and small dams. Sun et al. developed a novel uncertainty prediction architecture by linking data decomposition process, feature extraction,[18] multiple AI procedures, and composite scheme to implement wind speed and streamflow prediction. Implicit information is first excavated from the initial time series using adaptive variational mode decomposition (AVMD), thereafter, RF is employed for the selection of appropriate inputs. To produce nonlinear probabilistic and deterministic results, various neural networks consisting of Gaussian process regression (GPR), ELM, BPNN, RBFNN, and GRNN were incorporated. The efficiency and applicability of the projected model are validated with stochastic streamflow and wind speed data and subsequently compared with eleven other benchmark models. The result of the study showed that the proposed model improves the prediction accuracy and can give more information for decision-making. For both streamflow and wind speed predictions, the proposed method outpaced all benchmark models with at least 50% average performance gain.

Niu et al. assessed the daily streamflow forecasting potential of five different AI approaches comprising of ANN, GPR, SVM, ELM, and adaptive neuro-fuzzy inference system (ANFIS).[19] The results from two large reservoirs showed that the five AI methods can attain adequate daily streamflow predictions, although GPR, SVM, and ELM processes can perform better than ANN and ANFIS in both training and testing phases with respect to the four quantitative benchmark indexes. Therefore, the selection of suitable models is largely dependent on the actual reservoir characteristics. Multi-day ahead streamflow prediction using 1-D convolutional neural networks (CNNs) has been proposed by Barino et al.[20] The authors applied their proposed model to a river near a hydropower plant without dam structure and compared the proposed correlated-input one-dimensional CNN to a single-input one-dimensional CNN technique and some other traditional approaches. According to the result of the study, one-dimensional CNN outperformed all benchmark models and the correlated-input prediction model is one-fifth of the single-input counterpart with accuracy improvements. Inflow discharge forecasting articulated by Hadiyan et al. utilized feed-forward neural

[18] Sun et al. (2020).

[19] Niu et al. (2021).

[20] Barino et al. (2020).

network (FFNN), nonlinear autoregressive (NAR) neural network model, and nonlinear autoregressive exogenous (NARX) neural network model, and the forecasting strength of the networks were compared using a range of distinct input parameters.[21] Rainfall and inflow discharge dataset with different time delays were used in training all models and another input parameter denoted as time index is incorporated into the proposed models to improve prediction accuracy. As a result, NAR model outpaced NARX and FFNN. Moreover, the best accessible results were obtained using twelve time delays for inflow discharges and rainfall dataset and the inclusion of time index improved the accuracy of forecast. The model results can be very useful for inflow simulation of dam reservoirs, which is significant to water resources planning and management. In another study reported by Zeng et al.,[22] ANNs with temperature, precipitation, and historical discharge measurements as inputs were utilized for future streamflow projections. The study articulates streamflow estimations at two hydrological stations considering three GHG emission scenarios in the river basin from 2011 to 2050. As the results, the streamflow of both stations possesses no observable trends and their decadal changes are also small under the emission scenarios considered. Furthermore, some river seasonal streamflow present different trends from 2011 to 2050 and discharge ratio in the four seasons of a year tend to vary. The importance of streamflow and precipitation forecasting to the planning and management of water resources has also been articulated by Ni et al.[23] In this study, two different LSTM neural network-based models were utilized for monthly streamflow and precipitation forecasting. The first LSTM neural network model is amalgamated with a trous algorithm of wavelet transform to implement series decomposition, while CNN is integrated with the other LSTM neural network model for temporal feature extraction. To evaluate the performance of the models, the authors used two streamflow and two precipitation sets of data; the forecast accuracy was compared with that of a standalone LSTM neural network model and MLPNN. From the results though, it can be avowed that the LSTM neural network model can be applied for time-series data

[21] Hadiyan et al. (2020).

[22] Zeng et al. (2012).

[23] Ni et al. (2020).

forecasting; nevertheless, LSTM neural network models enhanced with wavelet transformation and CNN were superior alternatives.

Zuo et al. studied the impact time-series data decomposed into sub-signals has on the accuracy of streamflow forecasting using ensemble models.[24] As streamflow data is highly nonlinear and non-stationary, ensemble models incorporating robust and efficient decomposition techniques are crucial to accurate streamflow forecasting. The decomposition methods assessed include VMD, ensemble empirical mode decomposition (EEMD), and DWT. Relevant futures were extracted with these data preprocessing approaches with VMD being robust to mode mixing and noise, and the LSTM neural network model was used as it is a proficient deep learning method capable of memorizing previous streamflow. The results of the investigations carried out on the daily streamflow of two rivers in China showed that VMD outpaced DWT and EEMD. Furthermore, as the proposed VMD-LSTM neural network-hybridized single-model approach outperformed other competing models, in view of its NSME values greater than 0.8 for virtually all the forecast scenarios; it can be utilized to forecast highly nonlinear and non-stationary streamflow. Hagen et al. used ML to identify, from large-scale atmospheric circulation, daily streamflow major drivers.[25] Features were extracted with roughly pruned nested loop of RFs. To evaluate the impact of model complexity on the major drivers identified, RF, MLPNN, and SVM were compared to multiple linear regression (MLR). The results indicated that to some degree, accuracy gets better as model complexity increases. However, in the smallest catchment area for which all model performances are poorer, factors such as local variability, sub-grid topology, and catchment characteristics are considered in relation. The study gives a yardstick for direct downscaling from large-scale atmospheric parameters to daily streamflow using deep learning.

Besides the research works on direct streamflow forecasting, some scholars have also presented the results of their studies on the prediction of hydropower production and the selection of suitable sites for the installation of hydropower plants. In forecasting the power generation volume of a small hydropower plant (SHP), for instance, Hammid et al. utilized FFNN based on back-propagation considering streamflow, net turbine

[24] Zuo et al. (2020).

[25] Hagen et al. (2021).

head, and plant's historical power output for a period of ten years.[26] The nonlinear prediction approach models the input-output uncertainties, and training is achieved using 3570 experimental data. According to the result, the proposed forecasting model presents a CoC between the estimated and observed power output that is higher than 0.96. Cai et al. estimated power production capacity and identified proper sites for the installation of hydropower plants.[27] Different versions of the soil and water assessment tools (SWATs) were used to approximate streamflow, which helped to improve accuracy and can be beneficial in identifying hydropower potential accurately. The estimation model is constructed to incorporate the SWAT tool which improves model performance, an ANN, and improved the pathfinder optimizer (IPFO) which reduces error at the model learning phase. To assess potential sites along the rivers, the authors integrated geographical information system (GIS) software with their hybrid IPFO-enhanced SWAT-ANN. For proper selection of sites for the installation of SHP, the authors evaluated hydrological and physiographic characteristics; with streamflow and slope computed. As the results, over 2000 points suitable for SHP stations were identified. A comprehensive study by Bordin et al. examined ML's current and future role in the hydropower sector.[28] To account for most of the frequent issues that have been tackled in scientific works in the past years, the authors gave a synopsis of the core applications of ML in the hydropower field. The overarching objective of the study is to give recommendations for innovative research directions that can be followed in the near future so as to embrace research topics that are yet to be studied. Based on existing literatures, the study pinpointed and examined new roles ML can play in addressing the conundrums of short-term hydropower scheduling.

Considering recent scholarly articles on streamflow time-series forecasting, one can of course avow that researchers have been able to employ lag value predictors for future streamflow extrapolation. Although deep learning techniques can offer good potentials for streamflow prediction with complex physical relationship, however, to the best knowledge of the authors, only very few studies have applied LSTM neural network

[26] Hammid et al. (2018).

[27] Cai et al. (2020).

[28] Bordin et al. (2020).

for streamflow forecasting which can be beneficial for sustainable planning and management of water resources. In addition, there have been attempts to estimate river streamflow in Nigeria using some traditional methods; but the effect of seasonal variation on streamflow forecasting has never been investigated in Nigeria. This is the maiden research in Nigeria that considers seasonal variation in LSTM neural network model-based streamflow forecasting. Accordingly, the novelty and key contribution of our state-of-the-art research is the development and implementation of a low-cost intelligent deep learning technique based on LSTM neural network enhanced with DPA for day-ahead streamflow forecasting. To further demonstrate the streamflow modelling capability of our technique, we have examined the performances of two different baseline approaches namely, linear regression (LinReg) model and adaptive linear element neural network (ADALINE-NN) model.

Study Area

Nigeria has a tropical climate with variable seasons, depending on location. In Owan area in Benin City, Edo State, Nigeria, two main seasons occur, namely the rainy and dry season. The rainy season spans from April to October while the dry season occurs from November to March. Our research considers the Owan River in the Owan sub-basin on Latitude 6° 54′ N and Longitude 5° 56′ E. The Owan sub-basin is located in the Northern part of Edo State. It flows from North to South in the area, and it discharges into the Osse River. The main river course is nearly 80 km long with elevation coverage between 50 and 400 m above mean sea level. The sub-basin has a drainage area of approximately 1216 km^2, representing 2.65% of the Benin-Owena River basin area. The maximum temperatures during the rainy and dry seasons range between 21–26 °C and 30–35 °C, respectively. The Owan sub-basin receives average annual rainfall ranging between 1630 and 2133 mm. Also, its runoff ranges between 400 and 2000 mm and the evapotranspiration varies between 800 and 1200 mm. For the rainy and dry season, its respective average daily streamflow is 15.02 and 5.86 m^3/s. The sub-basin's main types of land cover are mixed and dense vegetation. Research has shown that it is rich in hydropower resource and can play a crucial role in the economic development of Edo State, Nigeria. According to Fasipe et al.,[29] twenty points have been identified in Owan with hydropower potential ranging approximately between 0.423 and 5.456 MW at available head greater than or equal to 10 m, considering the sub-basin's catchment characteristics. However, to harness this potential and bolster economic development in the region, streamflow modelling of the river is still very crucial. Constructing a hydropower dam in the Owan River can help meet municipal and industrial water demand, control possible flood, as well as provide hydroelectric power for residential, industrial, and agricultural purposes. Per se, accurate forecasting of streamflow is necessary for optimum operation of the Owan Dam if constructed. A schematic of the Owan sub-basin is depicted in Fig. 1.

Baseline Models

In this study, daily streamflow forecasting, for two different seasons, based on DPA-enhanced LSTM neural network model is proposed. But to make forecast model performance comparisons and demonstrate the forecasting accuracy of our proposed model, we have additionally examined the daily streamflow prediction capabilities of two distinct benchmark models. The benchmark models are the linear regression model and the adaptive linear element neural network model, respectively articulated as LinReg and ADALINE-NN.

LinReg Model

Linear regression has been widely used to forecast energy generation.[30] It requires a large number of characterization variables for the improvement of accuracy in complex modelling processes.[31] For the LinReg model under consideration, only one outcome exists, and the day-ahead streamflow (f_{s+1}) is simulated with a linear function. The LinReg provides a first-order approximation of the sensitivity of f_{s+1} to the present-day streamflow (f_s).[32] Here, the independent variable explains the outcome with the results presented as a linear model alongside a coefficient to describe the relations. This baseline model employs the correlation

[29] Fasipe et al. (2020).

[30] Kafazi et al. (2017).

[31] Kim et al. (2020).

[32] Graf et al. (2019).

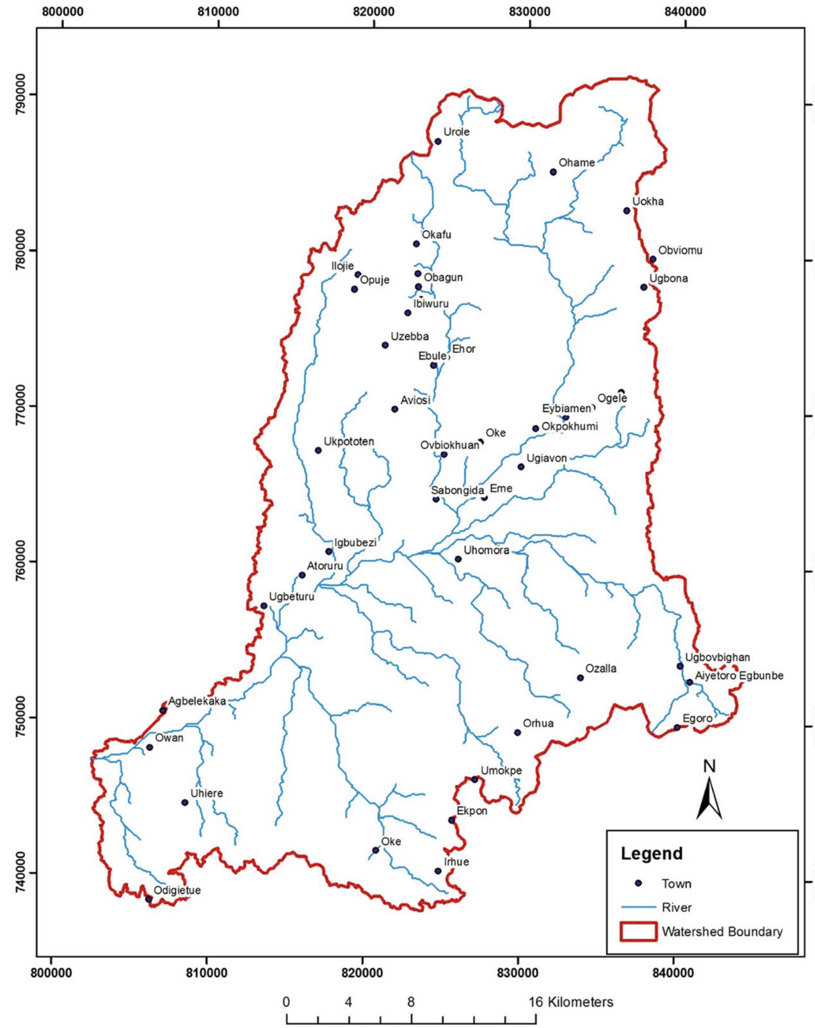


Fig. 1 The Owan sub-basin watershed map (Fasipe et al. 2020)

between the time-series lag and lead f_s values to make forecasts. f_{s+1} at day $d + 1$ is extrapolated using f_s on day d. The training dataset is used to fit the first-order polynomial that correlates f_s with f_{s+1}. Consequently, the daily streamflow linear model is as expressed by Eq. (1):

$$f_{s+1} = \alpha \cdot f_s + \beta + \xi \tag{1}$$

where f_{s+1} and f_s are the day-ahead and present-day streamflow respectively, in m^3/s; α and β are respectively the weight and bias computed by the first-order polynomial fitting of the training dataset, which is based on least-squares sum, and ξ is the error terms.

ADALINE-NN

ANNs are generally computing techniques designed to mimic the functionality of the human brain and the nervous system.[33] They are data-driven models made up of several numbers of linked neurons. They are also made up of three kinds of layers namely input, hidden, and output layer. ANNs can learn from input-output relationship, and their learning procedure involves tweaking input weights so that the model output approximates the desired output. However, the reliability of ANN model results is a function of the volume and quality of the historical data available.[34]

In 1960, Hoff and Widrow conceptualized and presented an idea on ADALINE-NN, while twenty-two years later John Hopfield used the model for data storage in powerful stable structures. Hoff and Widrow first applied the model and coined the term ADALINE denoting adaptive linear elements.[35] To reduce error, ADALINE-NN is adaptively trained by tweaking the weights in the neural network. The learning algorithm of ADALINE-NN has relatively low computational complexity, due to its simple nature, which makes the technique appropriate for real-time adaptive control applications. However, ADALINE-NN has very slow convergence.[36]

[33] Niu and Feng (2021), Zeng et al. (2012), Pellakuri et al. (2016), and Shang et al. (2019).

[34] Hammid et al. (2018).

[35] Pellakuri et al. (2016).

[36] Pellakuri et al. (2016).

LSTM Neural Network Model

ANNs are ML models and they have the ability to accommodate the non-stationary and nonlinear nature of time-series-data. In order to forecast the desired variable, in this case, daily streamflow, they carry out input-output data mapping. The foremost features of ANNs that define their computational capability include their learning power and generalizability, flexibility, and parallel processing.[37] ANNs, particularly deep learning methods, have wide applications. An ANN typically comprises of a number of neurons structured in multiple layers. Each of the layers carries out linear transformation succeeded by nonlinear activation, in which the output of a given layer becomes the input to the neuron of the next layer, with the exemption of the last layer.[38] A superior type of ANN that helps in understanding temporal dynamics is the recurrent neural network (RNN). An RNN is made up of input, hidden, and output layers and it learns by employing previous timestamp observations to approximation current value. The hidden and output layers are composed of activation functions and each layer may contain one or more neurons with each neuron in a layer connected by weights to the neurons in an adjacent layer. RNN is principally designed such that its architecture incorporates feedback connections to memorize former information. Improvements in RNN configuration and training enabled them to handle tasks involving sequential input tasks involving sequential input data in different problem domains, for instance, machine translation, processing of natural language, and modelling of time-series data. For this reason, an RNN is regarded as a suitable model for modelling complex hydrological time-series data. Nevertheless, the learning process of an RNN can be challenging because of the problem of learning long-range dependencies. Moreover, when the error of back-propagation is drifted through many time steps, it will result in varnishing and exploding gradients.[39] Several solutions have been developed to address this drawback of the RNN, among which is the LSTM neural network model.

The unique feature of the LSTM neural network, a special kind of RNN, is its memory cell, which can maintain its state over time. As proposed by Schmidhuber and Hochreiter in 1997, LSTM neural

[37] Hadiyan et al. (2020).

[38] Zuo et al. (2020).

[39] Ni et al. (2020).

network controls the flow of information into and out of its cell using nonlinear gating units, namely the forget gate, the input gate, and the output gate. The output gate governs the data to be presented as output, while the input and forget gates respectively establish the data to be upgraded and discarded. The forget gate particularly controls the degree to which the preceding results affect the current learning process. Transfer functions most frequently used in LSTM neural network are sigmoid and hyperbolic tangent functions. The architecture of LSTM neuron, as shown in Fig. 2, is such that it can ascertain cells to be repressed or excited considering the preceding state, existing memory, and current input.

LSTM neural network is designed to overcome the varnishing or exploding gradient conundrum that occurs during RNN training using back-propagation through time (BPTT). It has more complex operations inside the recurrent modules than a conventional RNN. An LSTM neural network consists of concatenated structures of recurrent modules with self-linked hidden units to help it memorize former information. Owing to the simple linear process of LSTM neural network cell state at a particular time step, information can simply flow very easily along the cell state unchanged. Thus, when training the LSTM neural network using BPTT, the gradient does not explode or varnish and the model

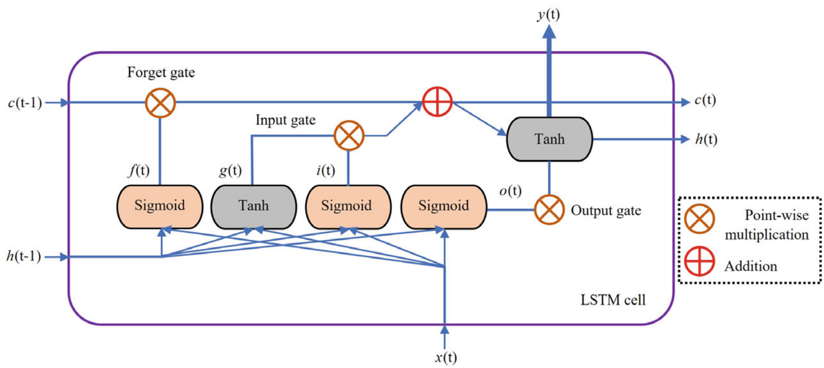


Fig. 2 LSTM neuron architecture (Wang et al. 2020)

can recall long-term information.[40] LSTM neural network has superior feature extraction ability and it can establish complex input-output relationships given sufficient number of neurons and layers. In many applications, such a technique tends to present better performance in comparison with traditional models. It has been proven that LSTM neural network is more efficient than a traditional RNN. Consequent upon the success of LSTM neural network in several fields of time-series forecasting, a few studies have explored its capability for climatological and hydrological problems and have reported good level of success.[41] However, there is a need to further explore its effectiveness and examine its adaptability with performance optimization algorithms.

The complete mathematical procedure of LSTM neural network is as follows:

i. Decision-making on what information to be disposed of from the cell state: x_t and h_{t-1} values will be obtained and via a sigmoid function to ascertain whether to discard;

$$f_t = \sigma\left(W_f \cdot h_{t-1}, x_t\right) + b_f \tag{2}$$

ii. Establish what new information will be stored in the cell state: firstly, a sigmoid layer determines what information will be earmarked in the cell state. Afterwards, the values obtained by the x_t and h_{t-1} via the Tanh( ) are taken as new candidate value $\widetilde{c}_\mathrm{t}$;

$$i_t = \sigma(W_i \cdot \left[h_{t-1}, x_t\right] + b_i) \tag{3}$$

$$\widetilde{c_t} = \mathrm{Tanh}(W_c \cdot \left[h_{t-1}, x_t\right] + b_c) \tag{4}$$

iii. Update the preceding cell state c_{t-1} into the new cell state c_t: the cell state c_{t-1} is multiplied by f_t to forget the information we have decided to disremember and added to the product of i_t and $\widetilde{c_t}$ to obtain a new cell state c_t;

$$c_t = f_t * c_{t-1} + i_t * \widetilde{c_t} \tag{5}$$

40 Zuo et al. (2020).

41 Ni et al. (2020).

iv. Decide what information will be output: Firstly, a sigmoid layer chooses what information will be output in the cell state. Subsequently, put the cell state c_t through Tanh( ) and multiply it by the sigmoid gate output;

$$o_t = \sigma(W_o \cdot [h_{t-1}, x_t] + b_o) \tag{6}$$

$$h_t = o_t * \mathrm{Tanh}(c_t) \tag{7}$$

where W_f, W_i, W_c, W_o represent the weight matrices and b_f, b_i, b_c, b_o denote the bias vectors, respectively. $\sigma(\cdot)$ is the sigmoid function applied as the gate activation function while Tanh(·) is the hyperbolic tangent function employed as the input/output block activation function. The former and latter activation functions are as expressed by Eqs. (8) and (9), respectively:

$$\sigma(x) = \frac{1}{1 + e^{-x}} \tag{8}$$

$$\mathrm{Tanh}(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}} \tag{9}$$

The proposed streamflow forecasting model is built on LSTM network architectures with optimal results achieved by trial-and-error procedure. The historical streamflow data was collected from Benin-Owena River basin development authority (BORBDA), Benin City, Edo State, Nigeria. The data was used to predict seasonal streamflow a day ahead. At first, the entire dataset comprising of input and target outputs were preprocessed and utilized for deep learning procedure. Secondly, the LSTM neural network was trained to gain the capability of mapping the nonlinear relationships between data features, and two baseline models were eventually deployed to compare the performance of the proposed technique by computing their forecast error metrics and performance over the number of observations. The rest of the chapters of this article are structured as follows: data preprocessing is elucidated in Sect. 2; the research methodology is described in Sect. 3; Sect. 4 explains the performance evaluation metrics; the simulation results and discussion are presented in Sect. 5; while a conclusion is drawn in Sect. 6.

2 Forecast Data Preprocessing

The availability of data is pertinent to training, validating, and testing neural network models applied in time-series data forecasting. With sufficient data, good data mining results can be achieved. In data mining, knowledge is discovered and useful information is obtained from raw dataset. Acquiring useful information from unrefined data necessitates preprocessing. Candidly speaking, large unrefined datasets acquired from data loggers and sensors are vastly susceptible to noise, missing data points, and abnormality ensuing from issues related to equipment malfunction. This can consequently affect the extraction of information from the set of data. To conquer this conundrum and improve the performance of forecasting models, suitable DPAs are employed to reduce redundancy in data before data is exported for model construction. Fundamentally, preprocessing entails cleaning, transformation, and reduction of data. A deep learning method is a data-driven approach that learns better with more robust datasets and its performance can be enhanced when it is augmented with an appropriate DPA. For hydrology and water resources, many studies have recently established that combining ML techniques with data preprocessing procedures has better accuracy than standalone models.[42]

In this study, simulation data is obtained from BORBDA, Nigeria. The experimental dataset, which is a daily streamflow time series measured in m^3/s at gauging stations, spans from January 1989 to December 1999, corresponding to a data size of eleven years. Firstly, for each year's data, missing data points are replaced with the average of the immediate preceding and succeeding data points. Any absurd streamflow value is also adjusted to a realistic average. Afterwards, each yearly data is divided into two sets based on existing seasons in Nigeria's climate, with the rainy season spanning from April to October while the dry season occurs during November–March. This season-based data division is presumed to be a good procedure, as the direct use of extremely high streamflow values in the rainy season and extremely low values of streamflow in the dry season can introduce spikes and undulations into the forecast data. Therefore, it is beneficial to split data by season, as seasonal variations in streamflow time-series data may negatively impact the learning of ANN models. The next step is to combine seasonal data of the eleven years to form

[42] Ni et al. (2020).

two distinct datasets, corresponding to the rainy season and dry period, both of which are finally exported to the simulation tool. The combined seasonal data reproduced 2354 streamflow data points for the rainy season and 1663 for the dry season. That having been said, both the rainy season and dry season dataset are partitioned into training and testing using a predefined data division ratio that will extract 85% of the entire seasonal data for model training and the remaining 15% for testing. The training quota is used to compute and upgrade model weights and biases while the performance of the model is experimented with the testing data. Consequently, the rainy season has 2000 streamflow data for training and 354 for testing while the dry season has 1413 and 250 streamflow data for training and testing respectively. Figure 3(a) and (b) illustrate the streamflow data logged at time interval of 24 hours for the rainy and dry season, respectively.

Before the implementation of forecast models, it is essential to standardize all training inputs and target outputs; so as to improve the efficiency of training. With the existence of outliers in the dataset, standardization is more suitable as they are maintained without skewing the distribution.[43] In the simulation tool, the seasonal streamflow data is then standardized with the exclusion of the last timestamp when the forecast model under consideration is the LSTM neural network. The normalization ensures that changes in the signals of different inputs have the same effect on the model behaviour regardless of their magnitude. The process of standardization transforms the seasonal streamflow data to have mean and standard deviation of [0, 1] in order to optimize neural network parameters that influence model convergence, speed and accuracy, and fitness. The standardization transfigures the numeric dataset and returns z-scores based on the mean and standard deviation using the inbuilt 'mapstd' function in the simulation tool. The standardization process, as expressed in Eq. (10), is applied to improve forecast model efficiency using the same structure for all inputs and target outputs.

$$f_{s_{\text{norm}}} = \frac{(f_s - \mu)}{\sigma} \tag{10}$$

where $f_{s_{\text{norm}}}$ is the standardized f_{s}, μ and σ are mean and standard deviation of the streamflow observations in m^3/s, respectively.

[43] Hagen et al. (2021).

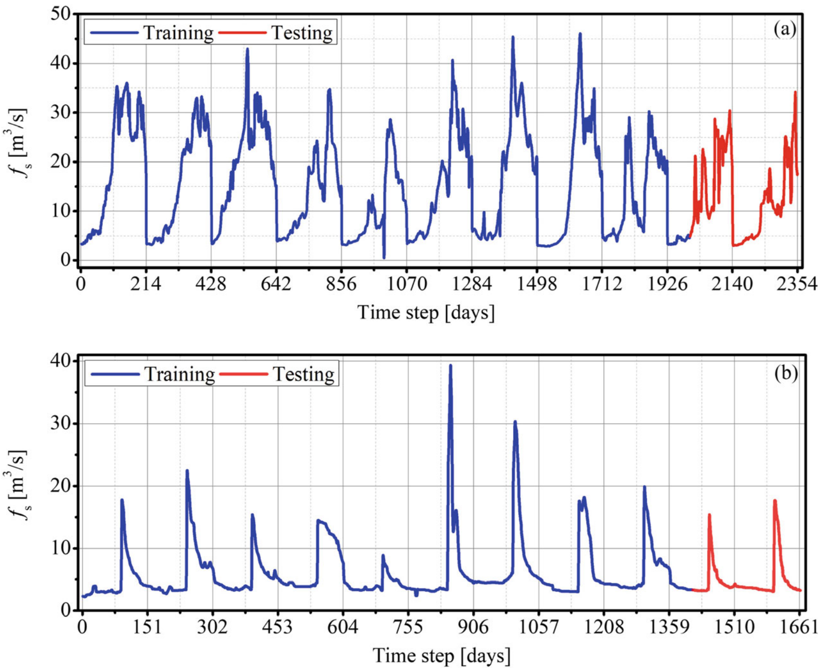


Fig. 3 (a) Rainy and (b) Dry season daily streamflow data partitioning using OriginPro 8.5 (© Victor Eniola)

3 Methodology

The streamflow simulation data, measured in m^3/s, was acquired from BORBDA, Nigeria. After the DPA expounded in the preceding section has been applied to both the rainy and dry season streamflow dataset, the standardized streamflow data is loaded one at a time into the simulation tool; beginning with the rainy season streamflow data, then reshaped to a row vector, and the 1-D time-series data is partitioned into two quotas. Illustratively, the streamflow data is a single time series with values equivalent to flow rate and timestamp equal to 24 hours. In this study, the criterion for data partitioning is based on a division ratio preset at 85:15 as graphically illustrated in Fig. 3. It is convenient to assign the input standardization structure to a variable, so as to directly apply it to the out-of-sample testing data that will later be utilized.

Firstly, the LSTM neural network is constructed by creating an input layer with one feature, LSTM regression layers with 40 hidden units, a dropout layer with a probability value of 50%, a fully connected layer with one response, and a regression layer. The LSTM neural network incorporates a dropout technology so as to enhance model performance. When a dropout layer accompanies every LSTM layer, it helps to circumvent overfitting. The next step is to specify the training options. We set the gradient threshold to one, to prevent gradients from exploding. As there is no final rule of thumb for choosing and tweaking hyperparameters, e.g. the number of LSTM layers and the number of hidden units, a trial-and-error procedure is often considered to achieve the best forecasts. The hyperparameters of the proposed model, given in Table 1, are selected based on the trial-and-error approach.[44] For example, the proposed model used a mini-batch with 128 observations at each iteration.

Upon stating the complete model requirements, the LSTM neural network is trained with the specified training options; thus preparing it for future streamflow forecasting. Monitoring the training progress and accuracy of LSTM neural network is beneficial. As the training process progresses, statistical errors during training are plotted and an observer can see if the network training process is over-fitting the training. The LSTM neural network weights and gradient are updated by each iteration per epoch. For the trained sequence-to-sequence regression LSTM neural network, the responses are the training sequences with values shifted by single time step. This simply means that at each time step of the input sequence, the LSTM neural network learns to predict the next time-step

Table 1 Hyperparameters of the LSTM neural network

S/N	*Hyper-parameter*	*Specification*
1	Gradient threshold	1
2	Mini-batch size	128
3	Initial learning rate	0.05
4	Learning rate drop period	100
5	Learning rate drop factor	0.2
6	Drop out probability	0.5
7	L2–regularization factor	0.0001
8	Learning rate schedule	Piecewise

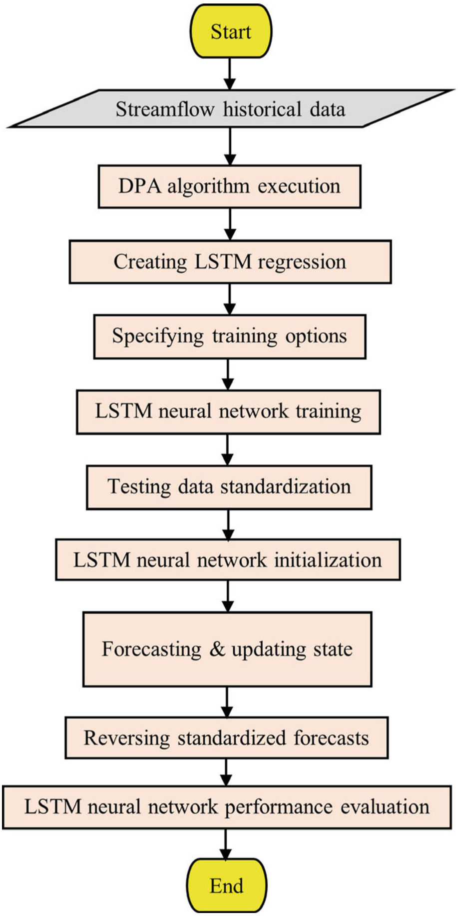
44 Ni et al. (2020).

streamflow. We trained different LSTM neural networks using stochastic gradient descent with momentum (SGDM) optimization algorithm with 0.05 initial learning rate (n_r) scheduled as piecewise and maximum epochs of 150. It is indispensable to experiment with n_r that falls within range, as too high n_r may cause the training to reach a suboptimum or even diverge while too low n_r may make the training process take longer time than expected. The experimented n_r range is between 0.001 and 0.1 with the optimum performing the best streamflow forecast at $n_r = 0.05$. After the specified number of epochs, the optimum $\mathrm{n_r}$ is multiplied by a drop factor as long as the learning rate schedule is preset as piecewise. Mean square error (MSE) is used as loss function in the training process. The output-input vector relationship of the streamflow forecast model can be expressed as follows:

$$Y = \varphi(X) \tag{11}$$

where $X = [x_1, x_2, x_3, \ldots, x_n]^T$ represents the input vector and $Y = [y_1, y_2, y_3, \ldots, y_n]^T$ is the output vector, n is the number of observations, and $\varphi(\cdot)$ characterizes the complex relationship between X and Υ, which is approximated by the proposed LSTM neural network. After the forecast model has been trained, the next step is to standardize the testing data, which the model has no prior knowledge of. This is achieved using the standardization structure variable already determined. The LSTM neural network model is then initialized with the standardized training input. Thereafter, the model can then be utilized for streamflow forecasting and its state updated directly using the testing data at time $t-1$, with the execution environment option set to central processing unit (CPU). The CPU execution environment is preferred because predictions on moderately sized single time-step data are typically faster to compute. When training input is standardized for prediction purpose, it is customary to get the forecast outputs unstandardized for actual data recovery. The unstandardized streamflow predictions are achieved by reapplying the input standardization structure variable established initially. It is sensible to state that the same standardization structure is employed because the LSTM neural network model uses a single time-series data. Figure 4 illustrates the LSTM neural network-based streamflow forecasting algorithm. The entire streamflow forecasting procedures described above are repeated using the streamflow data for the dry season.

Fig. 4 Flowchart of the LSTM neural network-based streamflow prediction method



In the experimental simulations, different scenarios were tested by considering different optimization algorithms such as adaptive moment estimation (ADAM), SGDM, and root mean square propagation (RMSprop), number of hidden units and LSTM layers. Since the proposed technique is modelled by trial-and-error process, hyperparameters were tweaked until the lowest RMSE and MAPE and best CoC/ R^2 and NSME are obtained. These error metrics and model efficiency measures are defined in Sect. 4.

4 Performance Evaluation

Forecast models based on ANN can be designed with different kinds of topology and architecture. Their ability to promptly adapt their forecast results comparably with measured values is essential. To evaluate the performance of forecast models, it is traditional to compute error metrics. In this study, the RMSE and MAPE error indices are calculated as they are frequently used by researchers in the field of forecasting. Predominantly for streamflow forecasting, the NSME is calculated.[45] To analytically ascertain underestimation and/or overestimation of a model, NSME is commonly defined in flow rate prediction as it accounts for model errors in the estimation of mean and standard deviation of the observed dataset.[46]

Sometimes, the CoC is also computed to demonstrate the regression degree. It defines the percentage of the total variation in streamflow that can be explained by the model. CoC values range between 0 and 1. When its value approaches 1, it means that the forecast model is practically good for all the sets of data. But the CoC only is inadequate to describe the forecast model as it fails to reflect deviation between data. On the other hand, it is reasonable when CoC is calculated alongside other model performance indices that consider deviation between data. The RMSE, MAPE, NSME, and CoC utilized in this study are defined below:

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(f_{s_{a,i}} - f_{s_{f,i}}\right)^2} \tag{12}$$

$$\text{MAPE} = \frac{1}{N}\sum_{i=1}^{N}\frac{\left| f_{s_{a,i}} - f_{s_{f,i}}\right|}{f_{s_{a,i}}} \tag{13}$$

$$\text{NSME} = 1 - \frac{\sum_{i=1}^{N}\left(f_{s_{a,i}} - f_{s_{f,i}}\right)^2}{\sum_{i=1}^{N}\left(f_{s_{a,i}} - \overline{f_{s_a}}\right)^2},\ 0 \le \text{NSME} \le 1 \tag{14}$$

$$\text{CoC} = \frac{\frac{1}{N}\sum_{i=1}^{N}\left(f_{s_{a,i}} - \overline{f_{s_a}}\right)\left(f_{s_{f,i}} - \overline{f_{s_f}}\right)}{\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(f_{s_{a,i}} - \overline{f_{s_a}}\right)^2}\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(f_{s_{f,i}} - \overline{f_{s_f}}\right)^2}} \tag{15}$$

[45] Cai et al. (2020), Niu and Feng (2021), Zuo et al. (2020), Ni et al. (2020), and Ali et al. (2020).

[46] Uysal and Şorman (2017).

where, f_{s_a} is the actual f_s, f_{s_f} is the forecasted f_s, $\overline{f_{s_a}}$ is the average f_{s_a}, $\overline{f_{s_f}}$ is the average f_{s_f}, all measured in m^3/s, and N is the number of observations. The lower the RMSE and MAPE and the higher the NSME and CoC, the better the forecast model with the proposed technique presenting the lowest RMSE and RMSE and best NSME and CoC. Besides the performance indices defined above, the extent to which the best forecast model outperforms baseline approaches can be demonstrated by the accuracy gain percentage (g_{ap}) on RMSE, MAPE, NSME, and CoC. The gain percentage is as expressed in Eq. (16), where the index can be RMSE, MAPE, NSME, or CoC.

$$g_{ap} = \frac{\left|\text{Index}_{\text{proposed model}} - \text{Index}_{\text{baseline model}}\right|}{\text{Index}_{\text{baseline model}}} \tag{16}$$

5 Simulations and Discussion

The experimental simulations were carried out on an Intel core (TM) i3 CPU @ 2.4 GHz and 4 GB RAM personal computer system with the execution environment for the modelling preset to CPU. A number of trial-and-error procedures were implemented to achieve optimum model performance for the neural network-based models. Table 2 compares the performance of the proposed technique with those of the baseline models. The LSTM neural network used $n_r = 0.05$ and the ADALINE-NN as well forecasted f_s using the same learning rate, as this is the optimum value that presents the lowest error metrics and shortest training and adaption time. The f_s simulation results of the rainy season are represented by Fig. 5(a), (b), and (c) which respectively illustrate the daily f_s forecasts, relative error (ε_r), and scatter plots of forecasted and actual f_s. In the rainy season, nearly one year of data is used for testing the models. Figure 5(a) shows the actual f_s the f_s forecasted by all models under consideration. It can be observed that the LinReg overestimated the f_s while the underestimation of the ADALINE-NN is indicated by its f_s curve appearing under the curve of the actual f_s. In contrast, the proposed LSTM neural network model forecasted f_s values that nearly match the observed f_s. The actual f_s follows a trend that can be described as having a short moderate rise at the beginning, undulations for up to the next one hundred and thirty days, and a gradual rise for nearly ninety days, succeeded by another wave of f_s. Regardless of the f_s profile

Table 2 Forecast model performance comparisons

S/N	*Model*	*Seasonal results*							
		RMSE (m^3/s)		*MAPE (%)*		*NSME*		*CoC*	
		Rainy	*Dry*	*Rainy*	*Dry*	*Rainy*	*Dry*	*Rainy*	*Dry*
1	LinReg	3.13	2.00	28.15	41.04	0.85	0.59	0.93	0.91
2	ADALINE-NN	3.81	1.63	22.34	19.42	0.78	0.73	0.95	0.93
3	**LSTM**	**2.37**	**1.28**	**11.16**	**8.16**	**0.91**	**0.83**	**0.97**	**0.95**

described above, the proposed model possesses the best capability to fit its values somewhere very close to the trend path of the actual f_s. Model performances are also compared based on ε_r which is computed as the ratio of absolute error to observed f_s. According to Fig. 5(b), the ε_r of the LSTM neural network model presents some spikes though; however, the curve is situated below that of the ADALINE-NN and LinReg model. Additionally, the hypothetical line of average ε_r for LSTM neural network will also be located well below that of the baseline models. To further evaluate the capability of the forecast models, scatter plots of the forecasted and actual f_s have also been considered (Fig. 5(c)). The ideal line is a 1:1 line of the actual f_s used as a benchmark. It can be observed that the linear fit of the LSTM neural network model is the best, as the linear fit of the f_s LinReg model is overestimated whereas that of ADALINE-NN is underestimated.

To consider the performance results of dry season streamflow simulations, Fig. 6(a), (b), and (c) are presented. With two hundred and fifty days used in the simulation, Fig. 6(a) shows the observed and forecasted f_s based on the proposed models and the baseline method. As for the rainy season, the ADALINE-NN model underestimated the f_s while the LinReg model presents overestimated f_s. But the LSTM neural network model gives f_s forecasts that are comparable with actual values. The actual f_s curve is approximately symmetrical about half of the total time steps, although the baseline models tend to maintain a profile analogous to that of the actual f_s, with acceptable CoC. Be that as it may, the proposed LSTM neural network model presents the best profile match. Even with two major spikes, the hypothetical line of average ε_r for the proposed f_s forecast model lies well below the hypothetical average ε_r of the LinReg and ADALINE-NN models (Fig. 6(b)). Moreover, the scatter

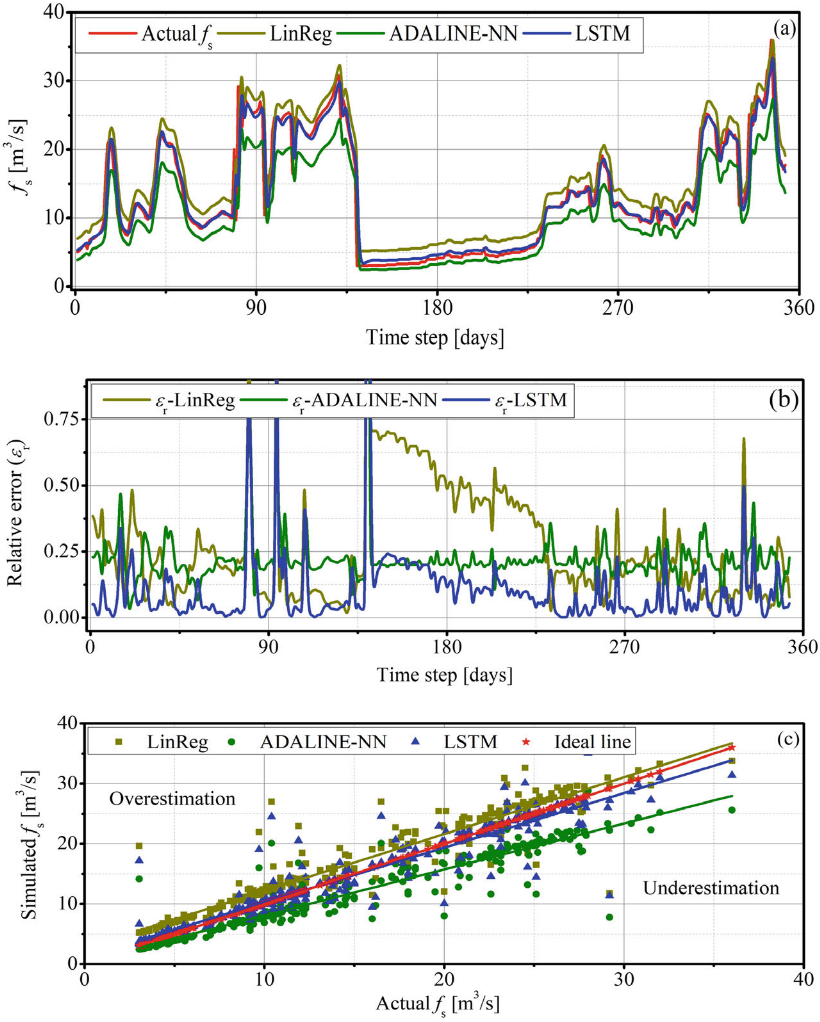


Fig. 5 (a) Simulated f_s (b) ε_r and (c) f_s scatter plots for the rainy season (© Victor Eniola)

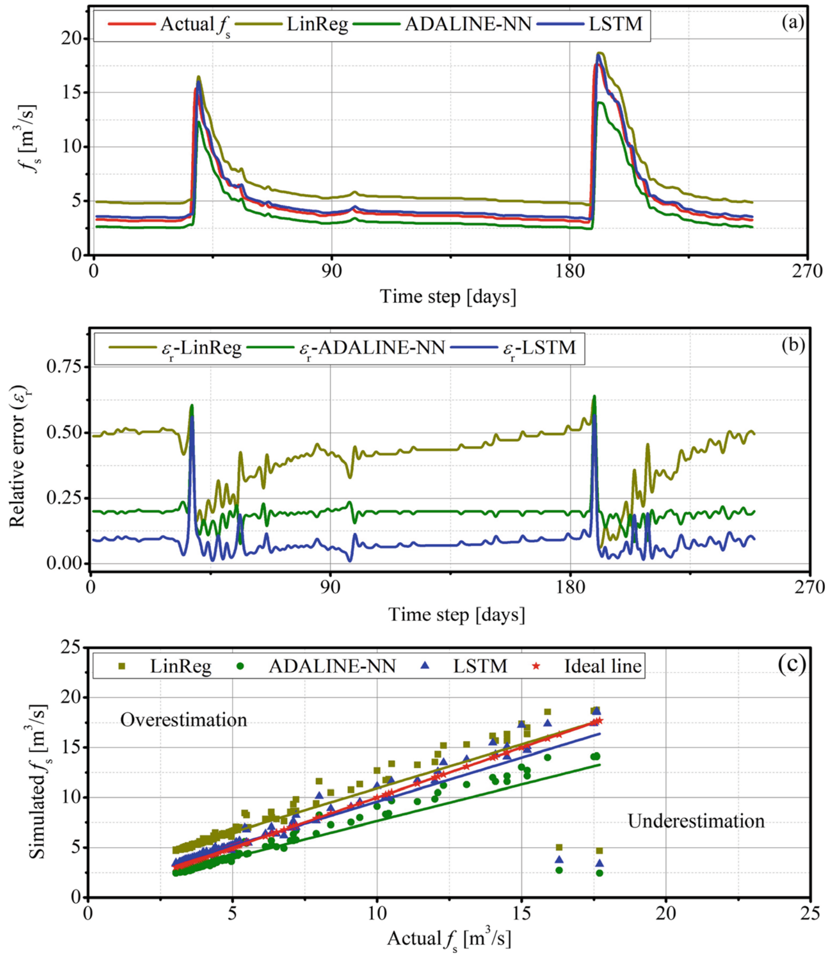


Fig. 6 (a) Simulated f_s (b) ε_r and (c) f_s scatter plots for the dry season (© Victor Eniola)

plots shown in Fig. 6(c) further buttress the fact that the linear fit of the f_s ADALINE-NN model is underestimated while that of the LinReg model is overestimated. The f_s forecasts of the LSTM neural network model are, nevertheless, more satisfactory especially considering the proximity of their linear fit to the ideal 1:1 line. With the performance indices

Table 3 Comparison of accuracy gain percentages

S/N	*Model Comparison*	g_{ap} *(%)*							
		RMSE (m^3/s)		*MAPE (%)*		*NSME*		*CoC*	
		Rainy	*Dry*	*Rainy*	*Dry*	*Rainy*	*Dry*	*Rainy*	*Dry*
1	**LSTM** vs. LinReg	24.28	36.00	60.36	80.12	7.06	40.68	4.30	4.40
2	**LSTM** vs. ADALINE-NN	37.80	21.47	50.04	57.98	16.67	13.70	2.11	2.15
3	**LSTM** vs. LSTM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

presented in Tables 2 and 3 for both seasons, the f_s forecast results of the ADALINE-NN model are better than those of the LinReg model.

The proposed LSTM neural network model employs SGDM optimization algorithm and at the testing phase of both seasons, the model gives a CoC that is larger than 0.94 with the best testing performance at 40 epochs. The statistical significance of CoC approaching unity is that there is a precise linear connection between model outputs and the actual streamflow values, as seen in Figs. 5(c) and 6(c). The LSTM-NN model, in comparison with the LinReg and ADALINE-NN method, presents more reasonable f_s forecasts. It is worth noting that the discrepancies between the results of the LSTM neural network model and those obtained using LinReg and ADALINE-NN technique indicate the incapability of shallow learning models to approximate temporal data. The superior daily f_s forecasting technique with its performance metrics in the testing phase of both seasons is tinted in bold fonts in Table 2. The performance assessment of the superior model for the rainy and dry season demonstrates that over-fitting did not occur. For both seasons, our results indicated that the daily f_s simulated by the LSTM neural network model, in comparison with other baseline approaches, are more ideally fitted to the points decorated with asterisks demonstrating 1:1 equality. Moreover, the LSTM neural network model results are very stable implying the network seldom has the problem of an exploding or varnishing gradient.

Following the development and implementation of the LinReg, ADALINE-NN and LSTM neural network models, the superior technique is chosen based on the model that achieved the lowest MAPE, RMSE and the best NSME and CoC. The LSTM neural network model outpaced both baseline approaches as model comparisons showed that it possesses the greatest predictive accuracy. It has the lowest RMSE and MAPE, and the best NSME and CoC of [2.73, 1.28] m^3/s, [11.16, 8.16] %, [0.91, 0.83], and [0.97, 0.95] for the rainy and dry season, respectively. To further substantiate and contrast the forecasting proficiency of our proposed model with those of baseline approaches, the g_{ap} on RMSE, MAPE, NSME, and CoC are given in Table 3. Positive g_{ap} implies that the proposed model outpaced the baseline model under consideration. Mathematically, the comparison in which the g_{ap} is minimum implies that the baseline model involved is ranked second in terms of extrapolative ability and performance. It is important to note that f_s forecast error is a major issue for water resources managers, engineers, etc., as inconsequential error is suggestive of improved system planning and operation. Consistent with the results presented in this study, the proposed LSTM neural network model distinctly outperforms the two baseline models as indicated by its performance indices, thus promoting it as an adaptable technique for seasonal f_s forecasting over 24-hours' time steps.

6 Conclusion

This study proposed an innovative seasonal f_s forecasting technique based on the LSTM neural network model adapted with DPA. The f_s predictions are made 24 hours ahead and the forecast results are comparatively evaluated with those of the two baseline approaches, namely the LinReg and ADALINE-NN model. To achieve optimal results, the trial-and-error procedure is deployed in the construction of the ADALINE-NN and the proposed LSTM neural network model. The results of f_s simulation indicated that the proposed LSTM neural network model has the capability to handle varnishing or exploding gradient conundrum. It is highly robust and steady with better accuracy when configured for 24-hour ahead f_s forecasting. The LSTM neural network model outpaced both baseline approaches as model comparisons showed that it has the highest extrapolative accuracy. It presents the lowest RMSE and MAPE, and the best NSME and CoC of [2.73, 1.28] m^3/s, [11.16, 8.16] %, [0.91, 0.83], and [0.97, 0.95] for the rainy and dry season respectively. To further demonstrate the forecasting ability of the proposed LSTM neural network model, the g_{ap} results are given in Table 3. From Tables 2 and 3, it can be perceived that ADALINE-NN model results are better, to a greater degree; than those of the LinReg model, presumably because ANNs usually are capable of mapping nonlinear relationship. As the results of the LSTM neural network approach are observed to be more stable generally, it can be established that the proposed model is a practical daily f_s forecasting technique for both the rainy and the dry season.

Since the f_s time-series data used in this study is standardized to have $[\mu, \sigma]$ of [0, 1], future work would investigate the effect of other data standardization methods on the performance and versatility of the proposed LSTM neural network model.

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Open Models Are Not Enough. Advancing Energy System Modelling Towards Practical Usefulness

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1 Introduction

Energy system models are tools used to support deliberation around energy transition strategies. For instance, they are used to explore the economic and environmental impact of alternate energy policies[1] or to

[1] Rodrigues et al. (2022).

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reveal trade-offs between equally feasible carbon–neutral energy system configurations.[2] In the last decade, models have experienced major developments, reaching unprecedented spatial and temporal resolution and technical detail.[3] Increasingly, modellers make the underlying code and data publicly available[4] to foster transparency, reproducibility and trust.[5] Nonetheless, disagreements persist about where the usefulness and real-world relevance of energy system models lies,[6] for a number of reasons.

First, models still tend to represent only one specific (techno-economic) worldview and ignore other possibilities.[7] In other words, models make strong assumptions on what is useful or important to consider and what is not.[8] Such normative assumptions are commonly hidden from view, even though they affect model outputs and their meaning.[9] A prominent example is that sufficiency options to achieve the energy transition are largely underrepresented in the energy modelling literature[10] compared to efficiency measures and deployment of renewable energy technologies.[11]

Second, even models whose data and code are made publicly available with an open licence are not necessarily transparent and perceived as trustworthy by users. The effort for ever-higher realism and complexity can make models and the underlying assumptions too complicated to understand, even when they are open.[12]

Third, models are still too often used as a tool by which modellers, as 'holders of the truth,' provide answers, rather than as a platform for a broader societal debate.[13] In other words, models are mainly used

[2] Tröndle et al. (2020).

[3] Prina et al. (2020).

[4] Pfenninger et al. (2018).

[5] Pfenninger et al. (2017).

[6] Süsser et al. (2022a).

[7] Lombardi et al. (2020).

[8] Braunreiter et al. (2021).

[9] Ellenbeck and Lilliestam (2019).

[10] Zell-Ziegler et al. (2021).

[11] Wiese et al. (2022).

[12] Süsser et al. (2022a).

[13] Ibid.

unidirectionally, for modellers to provide 'solutions,' without suitable mechanisms to bring stakeholder knowledge into the modelling process. Yet, this currently lacking co-creation may be key to generate model-based insights that align with real-world needs and questions.[14]

Increasingly, those who use such models or the modelling outputs for decision-making, perceive these shortcomings.[15] It is thus urgent to discuss these problems in depth and provide new perspectives on how to improve the quality and usefulness of modelling approaches.

The remainder of the article is structured as follows. In Sect. 2, we review and discuss each of the shortcomings identified above, providing practical examples from the most recent literature. In Sect. 3, we move on to proposing possible solutions to mitigate these shortcomings and discuss how to implement them in practice. We conclude the text with a reflection on the implications of our findings for the broader energy modelling community and policymakers.

2 Shortcomings of State-of-the-Art Modelling Approaches

Strong, Hidden Assumptions Arbitrarily Restrict the Window of Possibilities

Energy system models are grounded in a positivist, techno-economic worldview. Most of them seek cost-minimal energy system configurations that fulfil exogenously determined boundary conditions.[16] In energy transition research, these boundary conditions are typically: a greenhouse gas emissions target, e.g. net-zero emissions by 2050; a spatial scope, such as the borders of a country or the EU; and the engineering or physics constraints of the system components. Only occasionally do models consider further objectives[17] or limits.[18]

Because of this techno-economic, optimisation-centred nature of energy models, modellers often struggle with the handling of 'political' or

[14] Pickering et al. (2022).

[15] Süsser et al. (2022a).

[16] Chang et al. (2021).

[17] Lombardi et al. (2020), Sasse and Trutnevyte (2020).

[18] McKenna et al. (2021), Koecklin et al. (2021).

'normative' issues.[19] As they try to unravel techno-economically optimal energy transition strategies, modellers often leave non-techno-economic matters aside. Consequently, although such models generate technically consistent scenarios, the window of possibilities these scenarios explore is significantly constrained. Many alternative options to achieve carbon neutrality remain entirely uninvestigated[20] because modellers disregard socially relevant factors as 'political' or 'normative'. In other words, when relying on the results of most state-of-the-art modelling analyses, we look at an implicitly but strongly limited option space, which hides from view many feasible ways to attain carbon neutrality. And possibly, we never realise that and why it happened.

In practical terms, every addition of a constraint to a (cost-) optimisation model, such as limiting transmission interconnection capacities, increases the cost of the modelled system because it reduces the model's degrees of freedom. Hence, up to a point,[21] a larger and more interconnected energy system design is cheaper and hence results generated under the cost-optimisation paradigm suggest that large, continentally integrated systems are the *best* option. However, this is the necessary outcome—rather than an actual finding—of the decision to optimise costs under the only constraint of carbon neutrality, in disregard, for instance, of the social acceptability of the infrastructure entailed by such a large, interconnected system design.[22] This hidden normative assumption has significant real-world consequences, since it prevents other, more expensive but equally viable options in the model from being considered in policy discussions.[23] In current European energy policy debates, energy system strategies based on large, Europe-wide interconnection are indeed dominant, supported by model results exploring such options in detail.[24] And yet, policymakers, citizens and other stakeholders also discuss entirely different options,[25] corroborating the fact that cost-optimality is not the only driver of energy and climate policy. Some such alternative

[19] Ellenbeck (2017).

[20] Lombardi et al. (2020), Trutnevyte (2016).

[21] Reichenberg et al. (2022).

[22] McKenna et al. (2021).

[23] Ellenbeck and Lilliestam (2019).

[24] Tröndle et al. (2020).

[25] Xexakis and Trutnevyte (2021).

options depart strongly from the cost-optimisation paradigm, which is why modellers rarely consider them, despite their societal prominence.[26] Two examples are degrowth-leaning strategies, such as sufficiency ones, and the reliance on more decentralised system designs.

Sufficiency limits production and consumption to a sustainable level by changes in social practices and societal organisation.[27] As this would reduce the energy demand, it may be a supportive option for reaching climate neutrality.[28] Moreover, Creutzig et al. find that demand-side solutions to climate change mitigation are consistent with high levels of well-being.[29] Despite its benefits and potential, sufficiency options are rarely captured by current quantitative tools or process indicators,[30] although many and diverse sufficiency policy options exist.[31] One reason for that is that demand reduction by policy interventions and behavioural change does not fit into the rigid structure of cost-optimisation models, and that reducing GDP does not match energy-economic models' search for reducing emissions while maximising economic growth.

A decentralised system would likely be more expensive than a continental, centralised system as it lacks the economies of scale brought about by larger units and the sharing of flexibility options across regions and countries.[32] And yet, it may still be attractive in practice, for example, due to higher regional value creation and energy independence, and because of the lower institutional and political complexity. A standard cost-optimising model is unlikely to deliver such an option due to the higher overall cost, regardless of any benefits (including economic ones) that may play out on a more local, policy-relevant scale.[33]

Decentralised and sufficiency-centred strategies for carbon neutrality are just two examples of the many options that implicit normative model assumptions hide from view. As modellers tend not to communicate their implicit normative assumptions, and by extension, which options they

[26] Zell-Ziegler et al. (2021).

[27] Jungell-Michelsson and Heikkurinen (2022).

[28] Grubler et al. (2018).

[29] Creutzig et al. (2022).

[30] Mundaca (2019).

[31] Best et al. (2022).

[32] Tröndle et al. (2020).

[33] Sasse and Trutnevyte (2019).

arbitrarily exclude, users of model results are left with the misleading impression that such alternative options simply do not exist.

Open Data and Code Do Not Automatically Entail Understandability

Many modellers and model users agree that model transparency, data reliability, reproducibility of the modelling results, and open-source licencing of models are important conditions for and improve the quality of the modelling process.[34] And indeed, the open release of model code and data and the open-access publication of the related studies have increasingly become standard practice.[35] Simultaneously, we also increasingly see that they alone are not enough to address the opacity of energy modelling processes.[36]

First, recent work[37] has shown that the mere release of code and data on public repositories is often not enough to ensure understanding and re-usability of those across different modelling teams, let alone non-expert users. Without proper documentation tailored to specific target user groups, also an open model will remain largely non-understandable.[38] This is particularly true for models that are becoming increasingly large and complex as they seek to cover as many energy transition challenges as possible at once.

Second, numbers and equations do not provide all the critical pieces of information. For instance, the normative assumptions discussed in subsection 2.1 are not explicit because they are omitted already at the model design stage. Therefore, an inspection of data and code is unlikely to reveal them. This represents a critical issue. On the one hand, every model is designed to explore specific research questions under specific assumptions. There is no guarantee that the same model can meaningfully explore and answer an entirely different set of questions and assumptions.[39] On the other hand, open models are intended to foster re-usability by many users, including users with no relationship

[34] Chatterjee et al. (2022).

[35] Pfenninger et al. (2018).

[36] Pfenninger (2023).

[37] Chang et al. (2021).

[38] Pfenninger (2023).

[39] Ellenbeck and Lilliestam (2019).

with the original developers.[40] If the assumptions under which a given model design is sensible and useful are not explicitly communicated, as is typically the case, there is a high risk that the model is improperly applied outside of the initially conceived scope, affecting the quality and legitimacy of the results.[41]

In summary, while open data and code are necessary conditions to ensure transparency and understandability of an energy modelling process, they are not sufficient. There is a need for further advancements to strengthen the translation of the theoretical benefits of openness into practical ones and extend the concept of openness to also include 'open assumptions.'

Models are Used Unidirectionally, Overlooking Stakeholder Needs

Ideally, energy system models are 'thought experiments' by which users can explore energy transition options and understand the trade-offs as a starting point for further discussion.[42] And ideally, modellers aim for such a discussion to support real-world policy decisions.[43] But for this to occur in practice, model outputs and user-interaction options should match real-world stakeholder questions and needs.[44] Instead, modelling analyses are often perceived as unidirectional 'exercises' in which modellers use their 'truth machines' to provide precise answers to the questions that they themselves deem relevant,[45] disregarding the subjectivity inherent to the modelling process and the plurality of stakeholder information needs.[46]

The importance for users to be able to contribute to the modelling process actively is closely related to our previous discussion on the issue of hidden assumptions and worldviews (see Sect. 2.1). Different worldviews are a prominent example of aspects that different users or stakeholders may want to include in the analysis of alternate options for the resulting insights to be relevant. Professional networks typically share

[40] Pfenninger et al. (2018).

[41] Pfenninger (2023).

[42] Pickering et al. (2022).

[43] Silvast et al. (2020).

[44] Süsser et al. (2022a), Xexakis and Trutnevyte (2021).

[45] Braunreiter et al. (2021).

[46] Süsser et al. (2022a).

a common perception of the energy system and its future, leading to 'cognitive monopolies.' Other worldviews are difficult to integrate until such networks are expanded to a broad range of stakeholders.[47] Furthermore, stakeholders may help quantify the value of some parameters, suggest which metrics to explore across alternate system configurations or inform on which variations to scenarios are most relevant.[48] In other words, they have the potential to enrich the process with pieces of knowledge that modellers cannot access by themselves. For instance, recent work by McGookin et al. showed that 'authentic' involvement of stakeholders in the modelling process facilitates understanding the 'messy reality' within which energy systems operate.[49] Such an understanding allows for better defining modelling approaches and aligning modelling tools to local needs and developments. Similarly, McKenna et al. showed that crowd-sourced stakeholder considerations about which landscapes are scenic, and thus more worth protecting, can be used to adjust the values assumed for the socially acceptable wind generation deployment potential across the regions of a country.[50] When accounting for real-world stakeholder input, the optimal configuration of wind generation capacity deployment may change dramatically compared to when running the analysis only based on state-of-the-art techno-economic parameters. Moreover, recent work[51] has shown that, even when explicitly generating multiple energy transition alternatives for societal discussion instead of a single 'solution', integrating stakeholder views in the process is highly advisable. In fact, although the decision alternatives that models can generate are virtually infinite, modellers tend to provide only a tiny subset of options for the sake of computational tractability. Only iterations with stakeholders can ensure that the generated option space reflects real-world stakeholder and decision makers' needs.

[47] Midttun and Baumgartner (1986).

[48] Campos et al. (2022), Xexakis and Trutnevyte (2021).

[49] McGookin et al. (2022).

[50] McKenna et al. (2021).

[51] Pickering et al. (2022), Lombardi et al. (2023).

Modellers often claim to value stakeholder engagement.[52] In most cases, however, such engagement is limited to feedback at the beginning or the end of the modelling process.[53] Moreover, engagement is often circumscribed to policymakers or to a small community of high-level stakeholders that, rather than helping challenge the status quo and the 'cognitive monopolies' mentioned above, lead to technology-policy-reinforcement feedback.[54] This reinforces the status quo rather than seeking new solutions. Recent analyses[55] argued that failing to include inputs from a broader range of stakeholders in the modelling process is among the main reasons for user distrust and lack of relevance in the outcomes of the process. In fact, planning for the energy transition is a typical post-normal science issue[56]: beyond policymakers and system operators, a multitude of actors—virtually every citizen—is affected by and potentially interested in the outcomes of the process.[57] If only modellers or a few high-level stakeholders lead the process, the energy transition options they explore are based solely on parameters, constraints and scenarios that they deem relevant. With such a limited 'elite' stakeholder involvement, results fail to inform and support deliberation on the aspects that are important to most stakeholders and decision makers.

3 Possible Solutions to Improve the Quality of Modelling Approaches

Previous work and efforts to improve the quality and usefulness of energy modelling particularly emphasised the need to advance from 'black-box' to open and transparent models.[58] Some have referred to this first wave of efforts and advancements as 'energy modelling 2.0'.[59] Here, we argue that a number of further advancements are essential in light of the above-mentioned shortcomings, if the aim is to make models fit as advice tools

52 Süsser et al. (2022a).

53 Süsser et al. (2022a).

54 Sgouridis et al. (2022).

55 Braunreiter et al. (2021)Sgouridis et al. (2022).

56 Sgouridis et al. 2022.

57 Lombardi et al. (2020).

58 Pfenninger et al. (2017), Pfenninger et al. (2018).

59 Müller et al. (2018).

for societal and political processes. First, the standard provision of a list of assumptions and deficiencies alongside each publication. Second, the preference for modular, multi-model approaches—a *cosmos of models*—in opposition to the growing 'one-size-fits-all' trend to face the complexity of energy transition questions. Third and most important, a concerted effort towards co-creative, participatory modelling approaches that integrate stakeholders in an extended peer community. We call this set of advancements 'energy modelling 3.0', building on previous work that tentatively proposed the same terminology with a focus on stakeholder engagement alone.[60] In the next subsections, we discuss in depth each of the proposed advancements.

Standardising Explicit and Understandable Lists of Assumptions and Deficiencies

In subsection 2.2, we argued that open data and model code are necessary preconditions for transparent and understandable models, but also that providing all data and code along with a scenario study is not sufficient. The overwhelming amount of data and code that characterises state-of-the-art energy system models makes it difficult or impossible to get a clear overview of a given study's most relevant drivers and potential shortcomings. This is not only true for people outside the respective modelling team: modellers themselves are in danger of becoming unaware of the deficits of their models as the models' scope and complexity increase through time.[61] Further, data and code do not provide an immediate understanding of the normative assumptions underlying a given study. As discussed in subsection 2.1, understanding these implicit normative assumptions is critical for evaluating the usefulness of results.

We thus propose to standardise the practice of publishing an 'assumptions and deficiencies statement' along with each model or scenario publication. Such a statement would include a list of the model assumptions that are most impactful on the results, with a particular reflection on normative assumptions. It would also list the main deficiencies and how they restrict the scope for which the results are valid. In other words, it would summarise what the resulting numbers can tell us and what they

[60] Müller et al. (2018).

[61] Pfenninger (2023).

cannot, which normative assumptions underlie the input (and hence the output), and what key factors may have been excluded from the model despite being potentially relevant for the research question.

Some of the elements above do occasionally appear in the discussion section[62] or even in a dedicated 'limitations'[63] or 'critical appraisal' (sub)section[64] of energy modelling publications. Yet, even when authors provide such reflections, a more structured statement at a prominent spot of the article could significantly improve the outreach of such critical information, for at least three reasons. First, it would allow modellers to think about the deficits of their work in a systematic, structured way. Second, it would provide the readers and recipients of the results with an overview of what the results can be helpful for. Third, it would help establish a 'deficiency-discussion' culture among the energy systems modelling community. Making an 'assumptions and deficiencies statement' a standardised and harmonised practice would make the open communication of a modelling exercise's limitations a less daunting task and help the modelling community identify the open research gaps in their work.

Moving Away from One-size-fits-all Models Towards a Cosmos of Models

The scope and size of models are constantly increasing. This is not only due to increasing advances in computational power but also to the need to deal with complex, systemic challenges of the energy transition. For instance, taking into account sector coupling, high temporal and spatial resolutions,[65] environmental implications[66] or social drivers and constraints[67] that affect the potential and speed of the transition is necessarily both code- and data-intensive. However, the need to move beyond single-sector or purely techno-economic modelling carries the risk of models becoming too complex: too complicated for modellers to be

[62] Pickering et al. (2022), Lombardi et al. (2020).

[63] Sasse and Trutnevyte (2019), Victoria et al. (2022), Schwenk-Nebbe et al. (2022), Sepulveda et al. (2021).

[64] Neumann (2021), Parzen et al. (2022).

[65] Chang et al. (2021).

[66] Süsser et al. (2022b).

[67] Krumm et al. (2022).

aware of all the implicit assumptions, or too intransparent for users to understand where the modelling results come from.

To mitigate such problems, we argue that it is advisable to move away from trying to cover as many aspects of a problem as possible with large, individual models. A better approach would be to create and use a 'cosmos of models' that interact in a modular and adaptable way. For example, some models could deal with the details and maximise technical complexity. Others may look at the 'bigger picture', including potential societal disruptive events such as pandemics and wars, or at non-mainstream worldviews, such as those focusing on sufficiency, autarky or grassroots-driven futures. These models would need to be interoperable, with interlinkages across models either existing from the onset or easy to set up at need.[68]

Another advantage of such a cosmos of energy models would be that smaller models within the cosmos may allow for a first, quick response to unforeseen real-world issues and challenges that impact energy policy. Let us consider the current challenge of rapidly rising gas prices in Europe following the reduction of gas supplies from Russia amid the Russian invasion of Ukraine. European countries are faced with an unforeseen trade-off between pursuing their pathways to carbon neutrality, building on gas as a bridging fuel and ensuring energy security and affordability in the short term. Each country is reacting differently, for instance, discussing changes to nuclear power plans, building new re-gasification terminals or reactivating retired coal power plants. At the same time, the European Commission quickly designed the REpowerEU plan, which sets out the need to reduce energy consumption, expand renewable energy and diversify fossil fuel resources for all member states.[69] Large, monolithic models take time to set up in such a way to analyse all these issues at once, and may be unable to find radically new solutions, also because of their built-in assumptions. Instead, a modelling cosmos could allow for a quick but robust investigation of specific issues in depth, for instance, looking at options for avoiding blackouts, replacing natural gas or reducing energy poverty. Such specific insights could be then harmonised to provide a comprehensive picture.

[68] Bollinger et al. (2018).

[69] European Commission (2022).

For example, the Horizon 2020 project 'Sustainable Energy Transitions Laboratory' (SENTINEL) is one recent effort to start building such a modelling cosmos. The project connects modelling tools from across different modelling communities and paradigms. The experiments performed during the SENTINEL project demonstrate the value of smaller, interlinked modelling tools. The project has successfully soft-linked various tools and used them to answer research questions co-created with stakeholders, including questions related to an energy transition without Russian gas.[70]

It is worth noting, however, that this project encountered a higher-than-anticipated difficulty of achieving such interlinkages in practice: the involved modellers found it difficult to align model assumptions and scenario runs to truly link existing modelling tools.[71] One key reason: the difficulty for teams to understand implicit assumptions embedded within a model coming from a different discipline. So our first recommendation could also make our second recommendation more possible and doable. Albeit beneficial in terms of quickness, flexibility and comprehensiveness of the response to real-world challenges, setting up a frictionless modelling cosmos entails a more substantial collaboration effort between different modelling teams.

Co-Creative, Participatory Modelling with Stakeholders in Extended Peer Communities

In Sect. 2.3, we discussed the pitfalls of unidirectional modelling approaches that fail to integrate stakeholder knowledge and perspectives. Today, there is growing demand for stakeholder involvement in research as a new way of knowledge production and decision-making[72]—so much that it is now even a requirement for many research projects.[73] Nonetheless, there are different types of stakeholders that can be involved and different ways to do so, with different degrees of impact on the produced knowledge.

[70] Stavrakas et al. (2021), Michas et al. (2022).

[71] Michas et al. (2022).

[72] Lang et al. (2012).

[73] European Commission. Horizon (2020).

Stakeholders can represent different groups who are affected by the research results or have a concrete interest in the research outcomes, ranging from citizens, civil society organisations, industry and policymakers to consulting and academia, from local to international level. Stakeholder engagement can come in many different forms and intensities, such as information sharing, consultation, cooperation, collaboration and empowerment.[74] As we argued in Sect. 2.3, an ideal involvement of stakeholders includes a broad base of stakeholders rather than a few high-level ones, and involves these stakeholders repeatedly throughout multiple phases of the modelling process. When this occurs, there is the potential for co-creation to happen.

Co-creative or participatory approaches[75] have been successfully applied in many fields to integrate the available knowledge,[76] create ownership for problems and solutions and a consensus about paths forward,[77] develop practically relevant and actionable solutions to complex, real-world problems[78] and increase policy impact.[79] And yet, co-creative approaches in energy modelling and planning are still rare.[80] The common practice remains for modellers to unidirectionally inform a specific target group about their modelling outcomes.

To foster a wider adoption of co-creative approaches in the energy modelling community, there are several possibilities for involving stakeholders along the modelling process to tailor models and model runs to the specific needs of specific cases and contexts:

1. *Research design*. Co-defining the problem, the modelling needs (including which models to use and which not) and the research questions.
2. *Model assumptions*. Discussing and co-defining qualitative storylines, quantitative assumptions and input data.

[74] Schneider and Buser (2018).

[75] Lawrence et al. (2022).

[76] Lang et al. (2012).

[77] Waisman et al. (2019), Cuppen et al. (2021).

[78] Fazey et al. (2018).

[79] Süsser et al. (2021).

[80] McGookin et al. (2021).

3. *Model development*. Jointly developing a model's (new) features and constraints. Or directly shaping the criteria or numbers in the model's objective.
4. *Model results*. Discussing modelling results and their meanings (what they do and do not mean) in the on-the-ground context.
5. *Model communication*. Leveraging stakeholder knowledge in the co-design of communication materials and in the communication of the research outcomes. Involving stakeholders in publications and in advocating for the open-access release of models, data and results.

Involving stakeholders along these five steps (Fig. 1) enables a two-way, interactive exchange of knowledge and a joint exploration of the solution space for future energy systems. Establishing feedback loops between the various stages of the modelling process is also possible, which may lead to a re-designing of model assumptions and mathematical formulation.[81] Such deep stakeholder involvement allows moving away from the idea of modellers as holders of the truth that provide answers to society, towards the opposite concept of 'extended peer communities' in which modellers and stakeholders, or society more generally, co-create knowledge to solve societal problems. Furthermore, it is a practical way to ensure that the modelling results are useful to the users and eventually more policy relevant. For instance, co-creating models with stakeholders allows assessing if, for a given research question, it makes more sense to push for technical detail at the expense of higher diversity of worldviews and larger solution space, or vice versa.

[81] Lombardi et al. (2023).

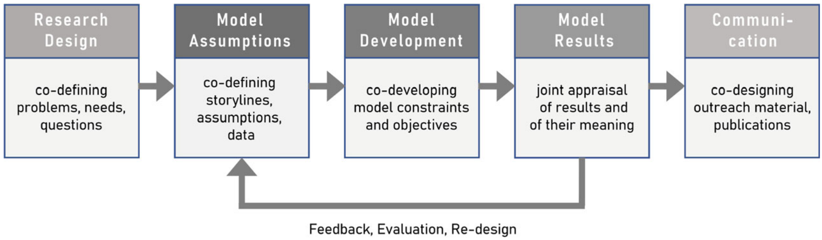

Fig. 1 Graphical summary of the ways and stages in which stakeholder involvement can occur along the whole modelling process chain (© Francesco Lombardi)

4 Conclusion

We have discussed how, despite valuable efforts in the last decade to bring the energy system modelling community into a more open and transparent 'modelling 2.0' state, a number of critical shortcomings remain to be addressed to strengthen the quality, usefulness and real-world relevance of energy modelling processes. These include the presence of hidden normative assumptions; the discrepancy between openness and understandability; and the unidirectional use of models that reinforces cognitive monopolies and biases.

To address these problems, we propose the following advancements:

- The focus on openness and transparency should go beyond code and data to include 'open assumptions', prioritising the understandability of the released material. As regards open assumptions, we propose that every modelling analysis be accompanied by an explicit, visible list of both assumptions and aspects left outside of the model despite potentially relevant for a given research question.
- Instead of trying to fit all the challenges of the energy transition into all-encompassing, monolithic models, modellers should strive to work with a cosmos of modular models. Technically detailed, complex models should be combined at need with simpler models that can allow for a clearer understanding of the interdependencies between inputs and outputs and can explore other practically relevant questions, such as the impact of different worldviews or disruptive events.

- Modelling should be, to the extent possible, a co-creative, participatory approach involving many stakeholders. Stakeholder knowledge can add value across several stages of a modelling process and is key to choosing the right (combination of) models for the right research questions, maximising the benefits of openness and transparency.

Although they are far from effortless, we argue that such advancements are key to achieve the next step in the quality and usefulness of energy modelling analyses. Bringing the energy modelling community into such a 'modelling 3.0' phase is critical for it to be able to adequately support the urgent task of planning for the energy transition.

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Modelling the Energy Transition 2: Societal and Cultural Futures

Backcasting. Prototyping Future Ontologies by Backward Chaining Possible Futures

Gabriele Gramelsberger

1 Introduction

The case of the Antarctic ozone hole is of particular interest for exploring computational models as scientific tools for prototyping future ontologies. While scientists in the 1970s theoretically predicted[1] and later measured the Antarctic ozone hole,[2] thus increasingly learning about the photochemical reactions caused by chlorofluorocarbons (CFCs) leading to the depletion of ozone, the models at that time showed no indication of depilation. In fact, as Joseph C. Farman et al. reported in 1985,

> recent attempts to consolidate assessments of the effect of human activities on stratospheric ozone (0_3) using one-dimensional models for 30° N have suggested that perturbations of total O_3 will remain small for at least the next decade. [...] The inadequacy of this approach is here made evident by observations that the spring values of total O_3 in Antarctica have now fallen considerably.[3]

[1] Molina and Rowland (1974).

[2] Farman et al. (1985).

[3] Farman et al. (1985, p. 207).

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In contrast to the general, but misleading assumption that due to lower temperatures photochemical reactions can only take place extremely slowly during winter half-years, observational data indicated a significant decrease of ozone since 1982.[4] Although initially interpreted as a measurement error by Farman himself, it quickly became apparent that something was wrong with the Antarctic ozone layer. Ironically, not only early models, but also remote data of NASA's Nimbus 7 satellite did not immediately confirm Farman's dramatic in-situ measurements, a failure caused by incorrect data analysis algorithms.

The ozone layer is vital to survival because it absorbs solar ultraviolet light. Decrease in ozone can affect the health of organisms and plants substantially. While early models failed in predicting the Antarctic ozone depilation, later models impressively demonstrated what an unregulated emission of CFCs would spell for mankind in 2020: an additional, lasting and growing ozone hole "over the Arctic, an area with a substantial human population and vibrant ecosystem."[5] By 2065, nearly two-thirds of the Earth's ozone would have vanished. In the computer models, a bluish world would show with a "UV index in mid-latitude cities" of "15 around noon on a clear summer day (10 is considered extreme today)."[6] Being exposed to such a high UV index would raise the risk for skin cancer dramatically within minutes. Such a bluish world would require permanent indoor life and constant UV protection.

However, this bluish has been avoided by international negations on a global ban of chlorofluorocarbons starting in the 1980s and culminating in the Montreal Protocol on Substances that Deplete the Ozone Layer in 1987. The ban came into effect in 1989 with a complete CFC phase-out in 2030. The Copenhagen Amendment to the Montreal Protocol in 1992 accelerated the phase-out to 1996, and model results, again, confirmed that "the future not taken [would have been] much worse than that expected in the Copenhagen '92 scenario."[7] Ever since, the Montreal Protocol is regarded as a landmark multilateral environmental agreement and has become the role model for global climate politics. As analyzed by researchers retrospectively, the success of global politics resulted from

[4] Farman et al. (1985).

[5] Wilka et al. (2021, p. 12).

[6] NASA (2023).

[7] Prather et al. (1996, p. 554).

three factors: "(1) the evolving scientific understanding of the problem, (2) increasing public concern over the problem based on the threat of skin cancer and the discovery of the Antarctic ozone hole, and (3) the availability of acceptable substitutes for CFCs."[8]

Usually, models are seen as mediators,[9] as the basis for scientific reasoning,[10] and as the driver of today's cultures of prediction.[11] Philosophy of science, in particular, discusses the intricate relation between scientific laws and models[12] and the explanatory power of models,[13] while situating models ontologically in different domains: as set-theoretic structures,[14] as physical entities,[15] as representations,[16] but also as fictional objects.[17] However, besides the enormous diversity in the constitution and use of models, computational models do not only develop explanatory, projective, and predictive power. From a historical view on models, the following epistemic turning points can be observed: Mathematical models were originally used for heuristic purposes, but turned into predictive tools by the introduction of computers in the 1950s, and increasingly in the 1970s when supercomputers entered the stage.[18] However, what can be experienced today is the increase of an instructive use of computational models starting in the 1970s, but accelerating in the 1990s, when models became more complex, e.g., as integrated assessment models informing environmental policy making and technology assessment.[19]

The main hypothesis of this paper is that models also support prototyping future ontologies in an increasingly technological world; e.g., in case of CFC production a green world against a bluish world. "Ontology"

[8] Morrisette (1989, p. 793); see also about today's situation Solomon et al. (2016).

[9] Morgan and Morrison (1999).

[10] Magnani et al. (1999).

[11] Heymann et al. (2017).

[12] Cartwright (1999); Giere (1999).

[13] Bokulich (2011).

[14] Suppes (1960).

[15] Schaffner (1969).

[16] Knuuttila (2011).

[17] Godfrey-Smith (2007), for an overview of the philosophical debate see Gelfert (2016), Frigg (2020).

[18] Dahan-Dalmedico (2001).

[19] Feichter and Quante (2017); Kaminski et al. (2023).

here refers to the philosophical understanding of the study of being and, in particular, of becoming; or, more precisely, it refers to shifts in boundary conditions leading to alternative worlds. The main research question of this paper is how models prototype future ontologies. In other words: What are the main epistemic strategies involved in this capacity? Exploring the case of anthropogenic climate change, the focus is on epistemic strategies of backward chaining possible futures by gradually transgressing into backcasting. While forecasting poses a "what will happen"-question, backcasting transforms this question into a more proactive one: "If we want to achieve a particular goal, what actions must we take to get there?"[20] Introduced by John Robinson (1982, 1990), backcasting became a dominant epistemic strategy in environmental sciences "for people who hate to predict."[21] Thus, backward chaining possible futures and backcasting became the dominant epistemic strategy of the instructive power of models informing policy actions.

2 Hybrid Ontologies of a Technological World

In philosophy, ontology refers to the study of being and related concepts, such as existence, categories, reality, and becoming. In ancient philosophy, ontology was linked to the various and incommensurable spheres of being posing the question of what the basic categories were. Aristotle defined ten categories: "Of things said without any combination, each signifies either substance or quantity or qualification or a relative or where or when or being-in-a-position or having or doing or being-affected"[22] of which substance (quality) was the prime category.[23] Later Immanuel Kant in his *Critique of Pure Reason* called Aristotle's list of categories rhapsodic and developed a new scheme related to the transformations of modern science.[24] He removed substance by quantity as

[20] Tinker (1996, p. xi).

[21] Robinson (1990, p. 820).

[22] Aristotle (1963, 1b25–2a4).

[23] "To give a rough idea, examples of substance are man, horse; of quantity: four-foot, five-foot; of qualification: white, grammatical; of a relative: double, half, larger; of where: in the Lyceum, in the market-place; of when: yesterday, last-year; of being-in-a-position: is-lying, is-sitting; of having: has-shoes-on, has-armour-on; of doing: cutting, burning; of being-affected: being-cut, being-burned." (Aristotle (1963, 1b25–2a4).

[24] Cf. Kant (1922).

a prime category reflecting the focus of empirical science on the world as a measurable given and experimentally accessible one. Kant's table of categories was not only more systematically derived than Aristotle's, but also marked a transition in ontology from analyzing and categorizing the world as a given into conceiving the world as a construction—constructed by human's pure intuition (Anschauung) and the mind. In fact, Kant's categories outline the various abilities to organize the world impressions, indicating the existence of things but not denoting their meaning. This changed the notion and function of categories as well as of ontology and turned them into operative entities resulting from apperception, i.e., in "an active power for the synthesis of the manifold."[25] Categories in Kant's sense turned into formal organizational concepts of experience. The various modes of synthesis then define the categories of the mind, such as quantity, quality, relation, and modality, ordering and integrating sensory impressions in terms of various modes of temporality. The procedure of transcendental schematism is the decisive link. It is a rule-based procedure for ordering sensory data simultaneously (space) and successively (time) and subordinating them to the temporal modes of the categories.[26]

However, if the world is not a given one, but a constructed one—although not arbitrarily, but transcendentally organized by pure intuition and mind—the operative mode of these organizational concepts of experience can be used for exploring possible instances of organizational concepts, and thus of experience. In this regard, computational models can be seen as rule-based instruments for ordering data spatially and temporally, exploring orders beyond classical, i.e., Newtonian uniform and linear orders, and thus beyond Kantian categories.[27] The hypothesis is that we currently experience the perfection of this development toward a plurality of ontologies, because exploring possible instances of organizational concepts of experience can be materialized by technology today. Thus, modelling, on the one hand, is the domain for prototyping different ontologies by designing computational environments for testing the trajectories of these ontologies and the life world conditions they would create, usually called 'boundary conditions.' Technology, on the

[25] Kant (1922, p. 98).

[26] Cf. Gramelsberger (2020).

[27] Cf. Gramelsberger (2022).

other hand, is mankind's instrument to pragmatically arrive at different ontologies and worlds by realizing these boundary conditions. Thus, modelling increasingly helps to inform technological developments. In this ontological view, modelling can be characterized by the merging of Aristotle's categories of 'quantity' and 'doing.' Obviously, we experience today the replacement of 'quantity' as prime category by a hybrid version of 'quantity and doing' constituting the operative realm of what we can call 'programming': programming these possible prototypes as well as re-programming the boundary conditions of the actual world.

Therefore, it is not by chance that ontologies experience a revival in many scientific disciplines—in genetics, medicine, information science, and others. For instance, in biology, we have experienced the introduction of genetic categories of life forms increasingly replacing and often falsifying the older, phenomenological ones. Furthermore, the three domains of life forms (bacteria, archaea, eukarya) have been expanded by the new domain of "synthetica"—not only genetically designed organisms in the laboratories by using Computer-aided Design (CAD) methods and DNA-printers,[28] but also hybrid entities of "biofacts."[29] Chlorofluorocarbons (CFCs) are further examples, in this case, "chemicofacts," which were first synthesized in 1929 by Thomas Midgley as a refrigerant, called Freon, to replace toxic chemicals in refrigerators. Freon was regarded as a "miracle compound" with a low boiling point, low toxicity, and considered to be non-reactive.[30] Nevertheless, Freon was the beginning of the end of the Antarctic ozone layer gradually introducing new boundary conditions of ozone depilation, which will be—hopefully—completely reversed in the year 2066. However, this ontological hybridity of natural-technical entities emigrating from the laboratories to the lifeworld is typical for today's scientific setting with myriads of newly synthesized chemicals, materials, and genetic strings, but not for ancient and modern times. It is evident that such unprecedented entities not only change the boundary conditions of the existing world and reality, but also require an epistemic shift in the use of models.

[28] Cf. Gramelsberger et al. (2013).

[29] Karafyllis (2007).

[30] Bellis (2016).

3 Backcasting, Backward Chaining Possible Futures, and Forecasting

This epistemic shift in the use of models is a shift from "predictive" to "instructive," mirrored by the shift from "what will happen?" questions to questions like "if we want to achieve a particular goal, what actions must we take to get there?"[31] Backcasting started in the realm of energy assessment, when Amory C. Lovins explored two energy paths in 1976; the first one is forecasting, the second one, "in contrast, works backward from a strategic goal, asks what we must do in order to get there, and thus reveals the potential for a radically different path."[32] This "backward-looking analysis" inspired John B. Robinson to call such an epistemic strategy "backcasting;" while "the major distinguishing characteristic of backcasting analysis is the concern, not with likely energy futures, but with how desirable futures can be attained. It is thus explicitly normative, involving 'working backwards' from a particular future end-point to the present to determine what policy measures would be required to reach this future."[33] Of course, forecasting and backcasting strategies differ epistemically. First, because backcasting is normative. Second, because backcasting is, at the same time, more flexible: "while the value of an energy forecast as conventionally used by decision makers depends on its accuracy […], this is not the case with backcasting."[34] Third, because backcasting shifts studying the likelihood of a projected future to analyzing alternative futures. And finally, because forecasts "are not inherently connected to the purposes of policy," while backcasts are[35]; which points to the instructive use of models. In brief, backcasting is "a method in which the future desired conditions are envisioned and steps are then defined to attain those conditions, rather than taking steps that are merely a continuation of present methods extrapolated into the future."[36] From a computational modelling point of view, forecasting and backcasting could not be more different. While forecasting usually involves spatial

[31] Tinker (1996, p. xi).

[32] Lovins (1976, pp. 86–87).

[33] Robinson (1982, p. 337).

[34] Robinson (1982, p. 337).

[35] Robinson (1982, p. 338).

[36] Holmberg and Robèrt (2000, p. 294).

and temporal change mainly expressed through partial differential equations, e.g., anthropogenic climate change in 2050 driven by atmosphere and ocean models which are based on thermo- and hydrodynamics,[37] backcasting is scenario- and decision-driven and thus can involve user participation—"a 'second generation' form of backcasting […] as a form of social learning about desired futures."[38]

Compared to backcasting, backward chaining possible futures interconnects forecasting with some backcasting elements. In the context of global climate change policy, backward chaining possible futures gradually entered the forecasting strategies at a time when climate models not only projected the rise of annual global temperatures based on the artificial assumption of a doubling of atmospheric carbon dioxide (CO_2) to 560 parts per million (ppm) compared to 280 ppm of the pre-industrial age (firstly posed by Syukuro Manabe and Richard Wetherald in 1967 as the famous 'climate sensitivity' question), but also considered the influence of climate policy measures on forecasting results. This gradual mix of forecasting and backcasting elements, called 'projecting' in the context of climate change, informed the Assessment Reports of UN's Intergovernmental Panel on Climate Change (IPCC) since the 1990s. The so-called SA90 scenarios for the first IPCC report in 1990 already used four scenarios: a 'business-as-usual' scenario (A), the 'Montreal Protocol' scenario referring to the emission reductions agreed upon in Montreal in 1987 (B), two scenarios about the impact of mitigation (C), but also a scenario on energy transition measures after 2050 (D)—scenario C being more optimistic than scenario D. Although, these emission scenarios informed climate projections, the strategy to use alternative scenarios indirectly allowed backward chaining possible futures to today's and near-future behavior. In this case, forecasting can be reversed into backcasting to some extent. It became clear, that no action and "business-as-usual", respectively, would be no policy options if dramatic climate change in 2030 and beyond should be avoided.

The SA90 scenarios were massively improved and expanded by the IS92 emission scenarios, considering more socioeconomic factors, because since the completion of the 1990 SA90 scenarios

[37] Cf. Gramelsberger and Feichter (2011).

[38] Robinson (2003, p. 854).

> events and new information have emerged which relate to that scenario's underlying assumptions. These developments include: the London Amendments to the Montreal Protocol; revision of population forecasts by the World Bank and the United Nations; publication of the IPCC Energy and Industry Sub-group scenario of greenhouse gas emissions to 2025; political events and economic changes in the former USSR, Eastern Europe and the Middle East; re-estimation of sources and sinks of greenhouse gases (reviewed in this Assessment); revision of preliminary FAO data on tropical deforestation; and new scientific studies on forest biomass.[39]

The important change in these new scenarios consisted of the strategy to translate the underlying assumptions into projections of emission releases. The scenarios outlined different narrations of how mankind would develop and how much greenhouse gas emissions would result from the various developments. This conceptual shift from atmospheric carbon dioxide to specific greenhouse gas emissions gradually supported backward chaining possible futures to policy measures.

After the release of the second Assessment Report in 1995, the IPCC decided to develop new scenarios for the third Assessment Report in 2007 (The Special Report on Emissions Scenarios [SRES] introducing four sets of scenarios called 'families' which formed forty scenarios), as well as for the fourth Assessment Report in 2013 (The Representative Concentration Pathways [RCPs]). The RCPs, in particular, introduced two new aspects: First, the RCPs were "named according to radiative forcing target level for 2100. The radiative forcing estimates are based on the forcing of greenhouse gases and other forcing agents."[40] The different climate futures described by the pathways depend on the volume of greenhouse gases (GHG) emitted in the years to come. Second, a distinction between near-term (2035) and long-term (2100) scenarios was made "because the nature of policy- and decisionmaking changes with time scale."[41] Long-term simulations are necessary "to assess the risk that actions taken during the twenty-first century might set in motion irreversible processes leading to major geophysical changes such as large reductions in the

[39] Leggett et al. (1992, p. 73).

[40] Van Vuuren et al. (2011, p. 11).

[41] Moss et al. (2008, p. 7).

Greenland Ice Sheet."[42] The distinction between near-term and long-term scenarios resulted from a shift in epistemic strategy for scenario development. "Past scenario development has been conducted in a mainly sequential form, with socioeconomic and emissions scenarios developed first and climate change projections based on those scenarios carried out next."[43] This "sequential process" for scenario development generates a long time lag between developing scenarios and projections, it slows the integration of information and impedes the development of truly integrated scenarios, but, in particular, "hard-wires" the simulation to the scenarios. "When the socioeconomic scenarios are modified, the model simulations have to be run again."[44] In contrast, the "parallel process" for scenario development should allow to update scenarios in less time while already computing projections with full 3D climate models. Pathways can be updated by scaling up the projections based on simpler models. This new approach is the reason why the scenarios have been called "pathways": "their primary purpose is to provide time dependent projections of atmospheric greenhouse gas (GHG) concentrations," and the "trajectory that is taken over time to reach that outcome" is of interest.[45] Therefore, all RCP scenarios consider time paths for emissions and concentrations, and they consider anticipated (or backcasted) changes in technological development as well as in policies. The projections show that changes in climate policy are very "meaningful (i.e., detectable) alterations to the modeled future climates."[46]

Finally, the Shared Socioeconomic Pathways (SSPs) used for the current IPCC Assessment Report combine SSPs and RCPs in a scenario matrix architecture with many different scenarios. However, within this framework, five "marker" scenarios are highlighted which represent the best distinct characteristics of the storylines: SSP1: Sustainability, SSP2: Middle of the road, SSP3: Regional rivalry, SSP4: Inequality, SSP5: Fossile-fuel development.[47] Nevertheless, "the 'non-marker' scenarios are important," too, "since they provide insights into possible alternative

[42] Moss et al. (2008, p. 10).

[43] Moss et al. (2008, p. 11).

[44] Moss et al. (2008, p. 11).

[45] Moss et al. (2008, p. 12).

[46] Moss et al. (2008, p. 11).

[47] Meinshausen et al. (2020).

scenario interpretations of the same basic SSP elements and storylines."[48] SSP1, the best of all possible worlds, is also called the "UN world;" a world in which all states respect the Sustainable Development Goals (SDGs). Of course, such a prototype of a future world is to be regarded ontologically as fiction rather than reality. The same is hopefully true for the SSP5 scenario. "In essence, the long-term historical developments (~20–30 years) suggest that the world has followed an emission pathway in the middle of IS92, SRES, RCP, and SSP scenario ranges."[49]

4 Conclusion—Backward Chaining Possible Futures, Prototyping Future Ontologies

Today's climate projections consider future climate policies. They include narrations of successful and failed actions today, in near-future, and in long-term. These narrations of the various scenarios indirectly tell us about the actions we must take to achieve a particular goal. They are backward chaining possible futures; some to be avoided, some hardly to accept, only one to bring about. However, these narrations are usually not read and understood in this way, because we stare mesmerized at the projections of 2030, 2050, and 2100. And what is even worse, the history of emission scenarios shows that actions are postponed to the future and thus to the next generations. Even 'business-as-usual' in 1990 and today are not the same, as "global CO_2 emissions have increased by 40% [between 1990 and 2018 …], with an average annual growth rate of 1.7%."[50] In 1900 1.95 billion tons of CO_2 were emitted, in 1950 6 billion tons, in 2000 25 billion tons and today more than 37 billion tons per year.[51] The CO_2-budget for staying below the 1.5 °C threshold would be exhausted by 'business-as-usual' in about 8 years and for staying below the 2 °C threshold in 25 years. A world of tremendous climate change is a reddish world heated up. Unlike the bluish world of the ozone depilation, success is much harder to achieve, although we have an "evolving scientific understanding of the problem," experience an

[48] Riahi et al. (2017, p. 154).

[49] Pedersen et al. (2020, p. 2).

[50] Pedersen et al. (2020, p. 2).

[51] Cf. Global Carbon Project (2023).

"increasing public concern over the problem," but miss "the availability of acceptable substitutes."[52]

What the scenarios show is that there will be a point of no return, i.e., no possibility in altering the pathways anymore in reality. In other words: Postponing climate actions to the next generations will leave no alternative pathways for them, because the boundary conditions of the future world, and thus its ontology, have been already decided. Prototyping has been turned into reality. This is the downside of the hybrid category of 'quantity and doing' as a strategy both programming possible prototypes and re-programming the boundary conditions of the actual world. Models for prototyping future ontologies by backward chaining possible futures can be permanently updated and fitted to the actual path while illusively suggesting there is still a choice. Thus, the epistemic strategy of backward chaining possible futures will lose its instructive power. This is the motivation to turn to backcasting as a normative-epistemic strategy; yet, this does not mean that "the normative conditions [are imposed] in advance (first generation backcasting) but allows the emergence of desired futures as a product of the process of analysis and engagement."[53] Social learning and involvement are required in order to "combine expert understanding with the knowledge, values, and preferences of citizens and stakeholders."[54] For in case of anthropogenic climate change, the problem is not only that acceptable substitutes are not easily available, but that changing anthropogenic behavior is less a matter of instructions of policy actions than of social learning. Therefore, we actually experience a further epistemic turning point in the use of models from the instructive to the participative use.

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52 Morrisette (1989, p. 793).

53 Robinson (2003, p. 854).

54 Robinson (2003, p. 854).

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Indicator Politics: Modelling Societal Problems Under Real-World Conditions

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1 Introduction: Societal Problem-Solving as Modelling

Societal problem-solving as an overarching term links different social spheres such as politics, culture, economics and the public sphere with epistemic and technical questions in experimental processes. Such processes open up opportunities for the organization of collective order, whether as confirmation or change, in order not only to grasp the world adequately in terms of reality, but also to identify design possibilities for improving interaction opportunities with the world. Models play a key role in this.[1] Models bundle specific states of aspects of the social or natural world in order to enable learning processes in this way. "[Via] these models we reconstruct our world as an external world of means under our ends." But at the same time, "we give the world a chance for us to change (and our models) in the course of the change we make in the world for experimentation. After the experiment as 'event,' not merely

[1] On the concept of models, see Tondl (2003, pp. 122ff.) and Hubig (2006, pp. 198ff.).

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nature but we ourselves are 'transformed'."[2] A further specification can be made by looking at models as scenarios.[3] Prototype scenarios play a formative role here.[4] In contrast to narrative scenarios, which capture socio-technical settings as a narrative, prototype scenarios form a material arrangement. The FabLab movement[5] ultimately opens up real labs for the development of very different prototype scenarios, making them accessible to experimental testing.

Now, it is fair to argue that the modelling of societal problems is by no means identical to the formulation of prototype scenarios. This brings into play an important idea, namely the question of the structure of societal problems. Here we can identify different forms.[6] A simple case are well-structured problems like those where the knowledge and value bases are more or less consensual and where there are, if any, only challenges to more effective modellings of the problem. Here, the focus on outstanding factual issues is functional. The situation is different, though, for partially structured problems like those where knowledge bases are not yet consensual and where the normative standards of evaluation diverge. Finally, we are dealing with unstructured problems when knowledge bases as well as normative standards differ.[7] The debate on sustainable development represents the paradigmatic case of a discourse in which the construction of the problem involves a mixture of social, economic, political and epidemic issues. At the same time, this case is challenging in contrast to well-known well-structured problems, such as the regulation of industrial chemicals. There are no simple, clear standards for the construction of such a problem, as the forms of implementing sustainability are simply too multifaceted. For this reason, it is the construction of societal problems, their concrete modelling as well as their institutional framework conditions that are essential in order to arrive at adequate problem descriptions and means of problem-solving that are as effective as they are legitimate. Societal problems do not simply exist.

[2] Hubig (2006, p. 199); translation S. B.

[3] Schulz-Schaeffer and Meister (2017).

[4] Dickel (2019).

[5] Schneider (2018).

[6] Hurlbert and Gupta (2015).

[7] Cf. Hurlbert and Gupta (2015, p. 102).

Against this background, the following line of argumentation will be pursued in this paper. First, the interplay of epistemic-technical and societal processes will be reconstructed as an emergence of civic epistemologies. Here, the dynamics of contextual references play a decisive role (Sect. 2). Secondly, the knowledge relations of societal problems are analytically separated as an interplay of indicators, criteria and observables. The argument will be made that there are basically two ways of dealing with indicators: Indicator work and indicator politics (Sect. 3). This difference is further outlined by an analysis of political discourses distinguishing between political ability ("politisches Können"), political will ("politisches Wollen") and political obligation ("politisches Sollen"). Indicator politics, in contrast to indicator work, which focuses on political ability, places political will and obligation above political ability (Sect. 4). Thus equipped, we take a look at a selected site for defining and solving societal problems: Real-world laboratories (Sect. 5). A summary and outlook conclude these reflections (Sect. 6).

2 Civic Epistemologies: Processing Context-Neutrality and Context-Openness

In societal problem-solving, the structure of institutionalized spaces in which the development of problem descriptions as well as problem solutions can be addressed plays a decisive role. The effectiveness and legitimacy of this procedure depends on whether the problem construction takes place in a way that is perceived as relevant and appropriate by the participants. For the institutional framing of processes of risk regulation, Sheila Jasanoff proposed the concept of "civic epistemologies," which generally can be applied to considerations such as those developed here. As Jasanoff wrote in her seminal book *Designs on Nature*: "Civic epistemology [...] refers to the institutionalized practices by which members of a given society test and deploy knowledge claims used as a basis for making collective choices."[8] In this definition, the focus is on the institutional aspects of knowledge processing. Clark Miller emphasizes another aspect of civic epistemology, namely "practices, methods, and institutional processes by which the community identifies new policy issues, generates knowledge relevant to their resolution, and puts that

[8] Jasanoff (2005, p. 255).

knowledge to use in making decisions."[9] Miller mainly addresses the openness of the situation with respect to practices. The social, cognitive and temporal dynamics in civic epistemologies enable processes that open black boxes. Thus, the heterogeneity resulting from different knowledge resources can be ordered and institutional environments for processing different forms of expertise can be created.

Conceptually, the formation of civic epistemologies can be contoured even more precisely if one looks more specifically into strategies of structuring the problem situations. Basically, we are dealing with fundamentally different strategies of problem construction. Rather simplifying, yet in an instructive way, it has been claimed that such a difference in strategies can be described by a distinction between context-neutralizing and context-open forms of risk communication.[10] Although originating from a different debate, this distinction nevertheless represents a form-theoretical argument that can be made fruitful for other problems, including strategies for analyzing complex problems.

According to Giegel, the first form of risk communication is characterized by the fact that it follows a mode of operation similar to that of differentiated subsystems: context-neutralizing operations "are characterized by the fact that they establish a strict boundary between an inner area, in which complexity is drastically reduced, and an outer area, which in its over-complexity cannot be understood and certainly not practically mastered."[11] However, this gain in rationalization in the inner area demands stability of social and natural factors in the then separated outer area. For it is quite obvious that operations such as those initiated in large power plants cannot themselves produce the socio-material environment they require (i.e. for example: the necessary standards, infrastructures, human capital, legal basis for operation and much more). Context-neutralizing operations work while they somehow ignore environmental complexity.

In contrast, with context-open operations, "the attempt to draw a strict boundary between system-internally regulated and system-external communication of the lifeworld […] remains inherently contradictory."[12]

[9] Miller (2005, p. 406).

[10] Giegel (1993).

[11] Giegel (1993, p. 107); translation S. B.

[12] Giegel (1993, p. 108); translation S. B.

We encounter this form of operations especially in those areas where the integration of environmental complexity is of great importance and narrow system boundaries are to be broken down, for example in medicine, nursing, education or even in pastoral care. Therefore, "in context-open operations, it can no longer be a matter of carrying out an internal system operation alone and leaving everything else to the environment; rather, the processing of the environment itself must still be included in the internal operation."[13] What is crucial here is that despite the creation of an internal area capable of being processed, which allows complexity to be reduced, "the established boundaries between the inside and the outside of the system under consideration are repeatedly breached."[14] Thus, the difference between these two modes of operation is not found in the creation of internal areas that are relieved of complexity, but in the sensitive handling of the boundaries that are created at the same time. Ultimately, the difference between context neutrality and context-openness can be found in different variations in the literature. Of particular importance is the argument of how the dynamics of participatory opening and closing can and should be dealt with.[15]

In the societal construction of problems, both forms of operation are typically present. Context-neutralizing operations are obvious in cases where there is already a clear system definition for the problem to be addressed. Context-open operations are helpful when the contours of the problem are not conclusively defined and the exploration of the problem is part of the discussion. In principle, a selection of analytical strategies appropriate to the subject matter is a challenge for any type of formation of civic epistemologies, yet a tendency towards context-neutralizing analysis strategies can be observed. The sheer complexity of societal problems can be mirrored in the difficulties of meaningfully configuring context-neutralizing and context-opening analysis strategies via institutionalized procedures of problem-solving.

[13] Giegel (1993, p. 108); translation S. B.

[14] Giegel (1993, p. 108); translation S. B.

[15] Stirling (2008).

3 Social-Epistemical Construction of Problems by Indicators

While looking at emerging civic epistemologies, it is important to take into account a wide variety of features. One aspect focuses on orders and standards for epistemic quality as well as on positions of epistemic authority during problem-solving processes. This can be observed, for example, in the field of chemicals or genetic engineering technologies, but also during transformation processes like the energy or mobility transition. In all these cases, societies are not only taking problem-solving actions, but, at the same time, these actions are changing the existing collective and the epistemic order. Some aspects that are strongly influencing the structure of such civic epistemologies are the complexity of the infrastructures related to these solutions, the multifaceted history of problem-solving, the possibility of multiple futures and development pathways,[16] the landscapes of multiple knowledges and non-knowledges[17] and the specific social challenges like building trust or confidence. Within such processes of emerging civic epistemologies, the standards for the form and relevance of knowledge and the hierarchy of epistemic agents are (more or less explicitly) formulated and fixed. Thus, the boundary conditions as well as the objects of problem-solving are constituted within civic epistemologies, understood as regimes of specifying and ignoring problem-solving while processing problems. Roughly speaking, there are three heuristically distinguishable dynamics of articulating, selecting and solving problems. They are typically co-present and related to different actor groups.

The first dynamic is the articulation of a problem; it might be termed ‘problem setting.’ The dynamics of emerging civic epistemologies are fueled by the introduction of a problem and the processes emanating from the ‘affordance’ that lies in the simple fact of presenting a problem. There are numerous examples for these processes; but without the here suggested conceptualisation of such phenomena these processes used to be analyzed within the so-called agnotology studies.[18] The example of the regulation-avoiding strategies of the tobacco industry illustrates that

[16] Lösch and Schneider (2016).

[17] Gross and McGoey (2015).

[18] Oreskes and Conway (2010).

they did not make the claim that cigarettes had no effects on health. The strategy was far more subtle. It claimed that if there were connections between cigarettes and cancer, they would represent a severe health hazard that needed to be regulated. Therefore, these conjectures should be thoroughly studied. And if strict evidence of this causality should be proven then smoking and the purchase of cigarettes should be regulated. The point here is to demand unambiguousness, which seems quasi-impossible. And indeed, it took about fifty years of research to get to this point. So, with the introduction of the problem ('cancerogeneity of tobacco'), also standards for epistemic quality were articulated to frame the problem more specifically. As the tobacco industry succeeded with its epistemic tactic to call for the highest standards of evidence, this problem articulation heavily influenced the dynamic within this epistemic regime.

The second dynamic concerns the choice between different options to articulate a problem. Problem descriptions are changing over time within epistemic regimes. In any case, emerging civic epistemologies regulate which problem descriptions are feasible and legitimate and which ones are not—and which other problems and aspects will therefore be put aside or ignored. The problem dynamic is a story of choosing problems, more specifically, to expect non-knowledge in the context of these problems, and to reduce it. A case in point is the change from damage indicators to hazard indicators in the regulation of chemicals within the EU.[19] The paradigm shift is hidden in the abstract formula 'PBT equals CMR'. PBT represents the indicators "persistency", "bioaccumulation potential" and "toxicity". CMR represents the indicators "carcinogenicity", "mutagenicity" and "reproductive toxicity" of a chemical substance. Equating PBT with CMR substances represents a focus shift from the level of damage to the level of hazard: PBT indicators are indicators of possible harm ("hazard"), whereas CMR indicators are indicators of concrete damages ("risk"). This shift must be seen as a revolution. For many decades, the evidence of a real danger had to be proven to allow regulation. Now, regulation can be implemented when a possible harm is indicated. That way, standards for epistemic quality were redefined as the sources of expertise and their disciplinary background changed. CMR indicators were used by toxicologists and physicians, PBT indicators by environmental chemists.

[19] Cf. Böschen (2014).

The third dynamic is connected to solving or processing a problem. One case in point is how the European Union regulated GMO (genetically modified organisms). A so-called post-release monitoring was established, instituting a time span of ten years to observe possible negative effects of the authorized organism. After this time span, a new approval of the GMO is required. Thus, the permission can be given on the basis of up-to-date knowledge and findings, or it can be denied. Moreover, procedures for testing hypotheses as well as for detecting unforeseen environmental effects were established. The overall strategy of temporalization is highly important to solve problems of non-knowledge. Nevertheless, this strategy depends on whether non-knowledge is seen to be resolvable over time. If the non-knowledge related to the main problems of a regime turns out to be irreducible then the social balance within that regime will become fragile. Against this background, the institutional order of processing the problem of detecting and reducing possible ecological effects of GMO is an advanced mechanism within an epistemic regime. This is why, within this order, standards for epistemic quality were redefined and EFSA (European Food Safety Authority) became the key player for processing epistemic quality.

This brief depiction of the articulation, selection and solving of socio-technical and socio-epistemic problems respectively also points to some specific challenges for societal problem-solving. First, the description of complex problems and the strategies to solve them are heavily influenced by the use of indicators. For example, the use of the indicator ‘security of livelihood’ in a sustainability problem introduces a specific description of a certain problem which is thus positioned as a key problem, with very clear and specific strategies for its solution.[20] In another example, using the indicator of toxicity as a central problem concerning the regulation of chemicals introduces both a specific description of the problem and a strategy to deal with it.[21] The use of indicators to provide a description and the classification of safety or precautionary strategies are interlinked. In many debates, the availability of specific problem-solving strategies organizes the problem context that is addressed through indicators.[22]

[20] Cf. with regard to climate science: Gramelsberger (2018).

[21] Cf. Böschen (2014).

[22] E.g. Garrelts and Flitner (2011).

Second, indicators cannot be seen as normatively neutral instruments for analyzing problems. Although indicators are tools for describing and analyzing a problem methodically, their selection is everything but normatively neutral. It makes an important difference whether we look at the CO_2 footprint of a product or at the whole chain of different risk factors associated with a technology. Thus, any study of a complex problem has to be inherently selective. Claiming comprehensiveness is therefore a form of implicit politics. Moreover, the selection of indicators is not normatively neutral but driven by specific criteria chosen by certain actors to propose a focused description of a problem. Therefore, with regard to the analysis of societal problem-solving, one has to be aware of both the epistemic quality of problem descriptions and its own selectivities.

What seems to be required is a specific knowledge analytics, allowing a more reflective and transparent perspective and offering insights into the normative as well as the empirical dimension of knowledge claims. Thus, it seems to be useful to build an analytical framework to classify the different aspects of knowledge used for the description of problems. A trias of indicators and their empirical and normative qualifiers seems to be helpful.[23] I suggest differentiating knowledge sources and their politicalness by three aspects: criteria, indicators and observables.[24] Criteria evaluate indicators against the background of general cultural values or interests (e.g. 'precautionary principle,' 'low-carbon society' or 'economic welfare'). Indicators represent an effect-related aspect of a problem, which should be considered or solved (e.g. 'toxicity,' 'cancerogenity' or 'CO2 footprint'). Finally, observables apply indicators by providing specified methods for empirical observations or test strategies (e.g. 'LC50 test' for acute toxicity or measurement routines related to industry norms).

Typically, in public-political discourses, statements only address the level of criteria and indicators. This is the level of general classification and normative orientation. The more technical level of observables is rarely addressed. One could argue that the observables are the most implicit part of 'indicator politics.' Let us return to the example of the tobacco industry analyzed within the framework of the agnotology studies. Expressed in terms of the knowledge analytics suggested here, this process can be

[23] Cf. Hubig (2016).

[24] Böschen (2014, pp. 40–41).

reconstructed. Although there was a consensus about the criteria ('protecting humans against health hazards') and indicators ('cancerogenity'), the problem was transformed onto the level of observables. Tests had to be constructed to meet the highest level of evidence. And, as there was a call for 'high evidence,' not only concrete methods for observation had to be constructed (and were contested), but a vast amount of data had to be observed. And that needed time.

We can see that the use of indicators harbours an inherent tension, if not a paradox. On the one hand, the use of indicators is necessary to analyze real-world problems and reduce their complexity to a manageable form. On the other hand, using indicators promotes a political statement as well; their use is in any case related to certain norms and values fueling the relevance of a single indicator or a specific set of indicators. By applying a certain indicator, attention is drawn to a selected aspect of the problem while others are ignored. Whereas in (emerging) civic epistemologies the debate is structured by an ongoing struggle between different knowledge providers claiming to know the 'true' problem description and aiming at maintaining or changing the rules of the civic epistemology. Against this background, we can introduce a distinction between indicator work and indicator politics. Conceptually, indicator work can be understood as the selection and configuration activity of indicators in the area of tension between two strategies of analysis: 'context neutralization' and 'context openness.' In contrast to indicator work, indicator politics tries to reduce the complexity of societal problems by highlighting specific aspects of societal problems while implicitly carrying out a context-neutralizing strategy. This could be observed very well in the debate on the use of nuclear energy. Under the impression of the climate issue, power plants could be presented as climate neutral. The other contexts (risks of the power plants, risks of uranium mining, etc.) then simply no longer carried any weight.

4 Political Discourses: Tensions Between Indicator Work and Indicator Politics

In order to work out the difference between indicator work and indicator politics more precisely, I will resort to a heuristic that comes from political theory. In addition to questions of competent governance based on (technical) expertise, the fundamental democratic concerns of collective decision-making and moral self-understanding are also negotiated.

These basic concerns correspond to three distinguishable semantics of public speaking. Thus, a heuristic should address three layers of political discourse which distinguishes between political ability ('politisches Können'), political will ('politisches Wollen') and political obligation ('politisches Sollen'). To clarify this, I will briefly characterize the three semantics below.

Firstly, democratic discourses have an implementation function according to which democratic politics is primarily about enabling efficient political decision-making and overall societal control,[25] i.e. generating and successfully applying effective forms of governance as a means of realizing the political self-determination of society (political ability). Democratic discourses unfold a specific semantics of political ability primarily in the medium of constituted power, i.e. in the institutionalized forms of democratic politics. In addition to the classic representative, governmental and social mediating institutions, political ability also includes diverse hybrid forms of governance in which networks of non-governmental organizations, business enterprises and individual citizens are also involved as actors. The implementation capacities of democratic discourses generated on this basis encompass the most diverse forms of knowledge,[26] ranging from factual information and technical expertise to the ability to understand the functioning of political processes and institutions as well as to assess which goals are politically feasible and what costs and non-intended side effects their implementation implies. The semantics of political ability thus concentrates on factual problems, which may always include norms, but address them primarily in the sense of coordination rules in processes of problem-solving. Normatively, the orientation towards the "values" of neutrality and objectivity in the context of "good governance"[27] is therefore inscribed in the semantics of political ability. This is about the capacity to determine, understand and handle those objective problems that arise as political tasks independently of the normative targets of collective will formation and moral convictions in the sense of competent and responsible problem-solving.

However, agreement on such normative guidelines is also an essential component of democratic discourse. Therefore, secondly, they represent

[25] Mayntz and Scharpf (1995).

[26] Nullmeier (1993) and Schuppert (2008).

[27] Czada (2010).

the attempt to enable a process of collective will formation through exchange, conflict, but also by bringing together different opinions, interests and ideas about the goals of political shaping (political will). The semantics of political will normatively express the basic democratic idea of collective self-determination and with it an understanding of political power not only as "constituted" but also as "constituting."[28] The power of the public sphere is thus to be understood here as a bottom-up phenomenon, i.e. as the power of a collective body of free and equal citizens.[29] In reality, this 'collective body' or the public as a whole always consists of a multitude of often contradictory positions, and processes of collective will formation take place primarily in the form of ongoing and not completely resolvable conflicts between them. But understood in such a pluralistic-agonal sense, the semantics of political will is nevertheless a real element of democratic politics, articulated in concrete forms of "practical enactment in public life"[30] and having real effects on the agenda of democratic processes. The political will of the public in this sense is factually articulated, for example, in fundamental readjustments of public debates on self-understanding, which can take the form of both fundamental 'additions' and (at least partial) 'interruptions' of previous public debates and corresponding development trends.[31]

However, democratic discourse on the normative basic coordinates of the political process is not exclusively about organizing collective will-forming processes, but—thirdly—also about the attempt to generate categories of moral orientation and to articulate basic principles of public-political morality, which determine, for example, basic rights worthy of protection as indispensable preconditions for the legitimate application of political formative power (political obligation). This moral character of public discourses is expressed above all through the fact that here the question of the fundamental restrictions to which political action should be subject is always a question of negotiation.[32] The corresponding semantics of political speech follow a logic that is objective and universal in its claim, but primarily negative, of determining the moral

[28] Kalyvas (2005, pp. 227ff.).

[29] Rawls (2003, p. 222).

[30] White and Ypi (2017, p. 444).

[31] Wenman (2013).

[32] Rawls (2002, pp. 27f.).

limits not only of what is politically "feasible," but also of the legitimate "arbitrariness" of the democratic sovereign.[33]

Against this background, it can be argued that it is crucial how indicators (as an expression of political skill) are embedded and used. This is because they represent selected aspects of reality that are considered relevant and should be addressed through political action. In situations where there are well-structured problems, the indicators used to describe the social problem are usually indisputable. At most, the question of the most effective observables then plays an important role. Not so, however, with unstructured or highly unstructured problems. For here, in addition to the characterization of sections of reality, the aspects of societal problems that are considered essential are emphasized. These are mostly acts of political will or political obligation. They serve to characterize the problem in a way that corresponds to the respective convictions and problem-solving strategies of the expressing actors. Depending on the institutional structure of civic epistemology, this 'doing problems' leads to a more or less far-reaching selectivity or blockade. In this sense, indicator politics can be understood as the tactical use of indicators to mobilize support for a selective description of problems and a one-sided interpretation and development of rules in civic epistemologies.

5 Real-World Labs: Playing Fields for Indicator Politics

These general considerations regarding the social construction and processing of problems can be further specified very well in the case of the real-world laboratories. In terms of knowledge policy, the establishment of real-world laboratories (living labs) represents the most ambitious form of societal experimentation practices to date. Such practices of experimentation not only display an astonishing diversity, but are also even more ubiquitous in contemporary societies. Under the auspices of a 'Great Transformation' the establishment of real-world labs is accorded special significance. While transformative processes represent highly experimental processes, real-world labs can provide transformative research spaces with a quasi-stable framework. In "real-world labs"[34] actors from

[33] Rawls (2002, p. 31).

[34] E.g. Wanner et al. (2018) and Engels et al. (2019).

different stakeholder groups, in particular from science and civil society, but also from politics and business, should cooperate[35] in order to experimentally produce new approaches to sustainable action and thus shape transformation processes.

Ultimately, a variety of different forms of local experimentation follow this concept. These include living labs, urban labs, transition experiments, social innovation labs and many others.[36] Although there is no lack of attempt to analytically separate the various forms and position them in relation to one another, this conceptual jungle has not yet been truly penetrated, if only because the diversity of the social and cultural contexts of real-world labs is very high. Nevertheless, a defining characteristic of real-world labs that transcends all these activities is that they are intended to experimentally address problems that are positioned as socially relevant and to develop (knowledge) solutions by means of collaborative action. Roughly speaking, three groups of real-world labs can be classified.

Firstly, there is the group of real-world labs that are grouped around individual products, services or otherwise clearly definable objects.[37] Such real-world labs are characterized by a high degree of condensation of the concrete research situation allowing to balance context-neutralization and context-openness and to specify research questions accordingly. It is probably no coincidence that an abundance of real-world labs of this type has been established in the field of digital technologies. Alavi et al. have proposed an instructive grouping of this real-world lab type.[38] These real-world labs differ according to the degree of control over the experimental situation exerted by the participating scientists, and they range from 'Visited Places' with the highest degree of control to 'Innovation Spaces' with a perspective of shared control through co-production processes.

The second group of real-world labs focuses on activities in the field of spatially bound developments. Here, the focus is particularly on neighbourhoods or cities. This type of lab, which is also referred to as Urban Transition Labs, Urban Labs or City Labs,[39] is of particular importance because the associated experimental practices are not only spatially

[35] Cf. e.g. Compagnucci et al. (2021).

[36] Schäpke et al. (2018).

[37] E.g. Hyysalo and Hakkarainen (2014).

[38] Alavi et al. (2020).

[39] Scholl and de Kraker (2021).

assigned, but at the same time the hierarchical coordination of action is facilitated by planning staffs in administrations, and new options can be brought into play via specific milieus of civil society actors.[40] In its 2011 transformation report, the WBGU encouraged municipalities to provide such experiments: “Municipalities should generally show more courage for ambitious experiments with a signal effect.”[41] In a more recent annual report, the WBGU even advocates the idea of “50 global urban real laboratories over 50 years”[42] to provide a stable framework for transformative research. In real-world labs, actors from science, civil society, politics and business should cooperate to experimentally produce new approaches to sustainable action and thus make contributions to the transformation on the ground.

The third group deals with questions of sustainability transformation in different facets. Even if the moment of close spatial coordination (e.g. in neighbourhoods) is often significant here, these activities are not characterized by a specific innovative motivation, but rather attempt to open up a space for diverse experimental testing.[43] At the same time, a rich discourse of reflection has established itself in this field of sustainability and transformation research. For example, Schäpke et al. distinguish real-world labs by five relevant dimensions, which they define as (1) the contribution to transformation processes, (2) the use of experimental methods, (3) the orientation towards a transdisciplinary research mode, (4) the scalability and transferability of results and (5) learning and reflexivity.[44] In other works, specific normative values are accentuated even more, such as the “normative orientation towards sustainability” or “civil society orientation.”[45] In essence, it is about the co-production of model-capable design knowledge, which is elaborated by means of transdisciplinary transformation or sustainability research in a fixed location, in order to solve concrete, hitherto poorly defined or poorly definable societal problems. Nevertheless, such basic characteristics of transformation

[40] WBGU (2016), Evans and Karvonen (2014), and Voytenko et al. (2016).

[41] WBGU (2011, p. 316).

[42] WGBU (2016, p. 36).

[43] E.g. Quartier Zukunft (2020).

[44] Schäpke et al. (2018).

[45] Beecroft and Parodi (2016, p. 7).

real-world labs remain too unspecific to be able to describe their characteristics adequately and at the same time distinguish them from other activities.

Obviously, these three forms of real-world labs correspond in a certain way with the strategies for constructing problems. In the first group of real-world labs, context-neutralizing strategies predominate. The aim is to increase technical functionality. And, with regard to the quest of construction, one can state that constructing is making a functional simplification that continuously transforms inputs into outputs in a stabilizing way. Luhmann defined technology accordingly as a "functioning simplification in the medium of causality."[46] Technology structures specific sections of reality in a simplifying way. It functions by stabilizing pragmatic expectations into reproducible routines. The goals and functionalization desires vary, which is why technology is not used to depict reality, but rather to open it up in a way that is bound to action practice. The second group already has to deal with greater challenges here, because context-opening strategies play a role in the processes of designing on site. They must therefore also be reflected in civic epistemologies. If these demands are ignored, public-political conflicts are unavoidable. Rather, one can generally say that the balance between context neutrality (in order to increase political ability) and context-openness (in order to provide an arena for political will and obligation at the same time) is particularly difficult to achieve here. The third group, on the other hand, is easier to manage, because an open experimental space is actually set up for trying out new problem articulations. During this process, new options for linking political ability, will and obligation can be explored. Moreover, this experimental openness eases the possible sharpness of public-political discourse.

6 Conclusion

Real-world labs as infrastructures for real experimental practices provide a structured space of experience to explore and stabilize innovation or transformation options. Since real-world labs extend expansively into the lifeworlds of many citizens, the institutional design of such real-world labs is all the more important, and the more fundamental questions of order

[46] Luhmann (1991, p. 97).

in the respective lifeworlds are touched upon. Against this background, it is important to examine the democratic implications of participation in such socio-techno-ecological innovations in good time and to determine what kind of real-world laboratory is involved. If one sums up the considerations of this article, then two indications in particular can be derived with regard to the question of modelling social problems in real-world labs.

Firstly, it is important to take into account the sometimes intricate connection between the problems to be constructed and the innovations as well as the dimensions of political discourse expressed in them. Depending on the structuredness of the problem, the specific significance of the dimensions of political ability, political will and political obligation occurs. It should be clear that even if a problem initially presents itself as a purely factual problem, options for opening up to the other two dimensions should also be provided for. As things have politics, they can always become the object of politicization. In the case of poorly structured or even poorly structurable problems, special attention must even be paid to the political will and obligation in order to sensibly delineate the problem-solving space in which the factual questions can be dealt with.

Secondly, it seems essential to understand real-world labs as an emergent civic epistemology, in which questions of an appropriate institutionalization of problem-solving processes are dealt with in addition to epistemic-technical questions. In this way, the interplay of the three political discourses can be disentangled and the real-world labs work as a place for the construction of epistemic-technical solutions to societal problems. The litmus test is the extent to which indicator work can be carried out—or indicator politics dominate.

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Understanding Petromodernity: Oil as a Medium Between Geology, Technology, and Different Types of History

Benjamin Steininger

One crucial difficulty in modelling the necessary transition into a post-fossil world is that so far we did not even come close to understand the full breadth, depth, and complexity of the (pre-post-) fossil world. Whereas even the most complex scenarios in the sphere of natural processes such as the global climate can be modelled by scientists with respect to well-defined natural laws, it is far less obvious which laws, constants, and parameters could be put into models to understand the future of culture and history. There is a big gap between the need to understand global trends of human history and culture in order to practically change or even engineer these trends, and the singularities of concrete events that actually and still appear as the core of historiography. What in retrospect appears as a string of events and causalities, what even might show patterns and large historical trends when analysed with quantitative methods of 'clio-dynamics'[1] can of course inform ways of dealing with decisions for the future. But it cannot predict the contingent constellations of future single

[1] Turchin et al. (2017).

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events. Moreover, even very precise insight into general trends of the past doesn't make the perspectives on single cases and single constellations redundant. It is the very unique constellation of material and abstract facts and perspectives that form what history actually is. And the epoch of petromodernity consists, in fact, of a very unique set of material and abstract constellations, showing complex interactions of fossil fuels and of abstract cultural factors such as the petromodern value and desire system.

Oil connects these very different layers, categories, and forms of agency. In fact, it can be understood in multiple ways as a form of a structural 'medium' of modernity. Oil connects deep-time natural history with the present in an epistemic and energetic sense. Time layers, geographies, and processes are shorted out in an almost cosmic way. Oil works as a chemical storage medium for fossil energy that is consumed today, and through devices and in places where other types of energy simply wouldn't work. In another, somehow more biological sense of the term 'medium,'[2] it defines the economic and cultural 'milieu' (from the Latin *medius locus*) in which modernity could grow. Only by following this substance as a multiple connecting medium-type, the complexity of the epoch can be revealed.

My contribution serves this specific concern. The essay is intended to offer insight into some of the particular complexities and contradictions of the fossil modern world, which we will soon, in one way or another, have to leave behind. However, I am not concerned with modelling concrete post-fossil futures. What I am concerned with is the analysis and reflection of the fossil present and history, as a historian of science and technology, as a cultural theorist, and as a curator. My area of expertise as a historian of science is the role of the fossil chemical industry in modernity and in the Anthropocene, particularly the role of industrial catalysis as one of the main drivers of modern technology and history.[3] This field merges almost seamlessly into petrochemistry and into petroculture research. Beyond that, the contribution makes use of a curatorial interest in arguing not only with textual sources but with pictorial and material findings from various historical and geographical angles of petromodernity.[4] They serve

[2] Berz (2010).

[3] Steininger (2014); Steininger (2021).

[4] Klose and Steininger (2024); Klose et al. (2021).

here—as in some of my other texts—not just as illustrations but as thorough contemporary testimonies of our epoch. By far not all the layers to which these testimonies refer can be interpreted via texts and even less so in the very limited space of this essay. But at least some of the pictorial sources of my work can show the methodological stretch from the first discovery to an exemplary reflection, and maybe they can also provoke a certain interest in the readers to investigate such materials in their own experience environments.

1 The Modern Epoch Read as 'Petromodernity'

An energy transition move towards a state N + 1 should know how the state N has been produced historically and systematically. Thus, to really leave behind the fossil basis of our epoch, it is indispensable to learn more about the fatal status quo. In the last decades, petroculture research has become a global endeavour in the humanities, but it is still not going strong in German academia. The most important contributions to the debate continue to come from the major extraction countries, especially the US and Canada.[5] Thus, the German edition of our *Atlas of Petromodernity*[6] from 2020 was the first major work in the field of cultural theory with an explicitly German background. And this is not only a geographical or a stylistic question or a question of the academic traditions involved, like following a narratological approach or a method from material epistemology. It also touches upon the very different experiences along the geographic petromodern production chain. In fact, it would be of great importance to complement the research and research perspectives from extraction countries—the beginning of the chain—with the perspective of a refining and consuming country like Germany. Petromodernism is a holistic phenomenon. To better understand it, one needs to tie together a large range of different sciences and technologies, but also of experiences in the contact zones of extraction, refining, consumption, and investment of the financial values created by oil. The overall approach needs to include the winners and the losers, the zones of sacrifice and those of pervert wealth, both in the global North and South, in

[5] Mitchell (2013); LeMenager (2014); Pinkus (2016); Szeman and Boyer (2017); Barett and Warden (2014).

[6] Klose and Steininger (2024).

Western, socialist, and developing societies, in short: it has to take into account the experiences of empowerment and oppression, caused by one and the same substance, across the world. Only by the broadest possible synopsis is a picture of the epoch possible. Of course, the *American way of life* is the most obvious, the most famous, and the most aggressive form of a petromodern culture, hence its academic scrutinising started in North America, too. And yet reflecting the *American century* cannot be done by just applying its own tools of interpretation. It takes much more to understand the epoch as a whole.

A central thesis of petromodernity sholarship is that modernity as a historical, epistemic, and reflexive epoch is more deeply connected to petromodern materiality than is commonly assumed, and that the very specific character of fossil fuels has sweeping consequences also in the political sphere. One of the most influential books in that respect was *Carbon Democracy* by Timothy Mitchell, which also highlights the political changes following the shift from coal to oil throughout the twentieth century.[7] Not just technologies, but almost the whole system of cultural coordinates is, one may argue, deeply rooted both in fossil energy and—which is often neglected—in fossil materiality. Prominent modern features such as the necessity of economic growth, modern techno-science with all its epistemological consequences, but also the welfare state, the political systems, the cult of individual freedom, and the highly differentiated spheres of art and cultural life seem to be driven by the influx of fossil energy, but also of matter, as paradigmatic modern materials such as plastics, concrete, steel or pharmaceuticals are based on fossil resources. An energy transition strategy beyond the fossil regime, then, cannot consist in technical diagnoses and their respective models alone. It also needs to acknowledge that the subjects who will live in a post-fossil world have been trained, to a significant degree, as petromodern subjects. Hence, the models to assess these petromodern subjects and their energy reality are techno-social models that also take into account the mediality of raw materials. The fossil regime has never been external to us. It runs right through our innermost affects and shapes our rationality. Not only 'our writing tools,' as Friedrich Nietzsche's influencial statement has it, 'are working on our thoughts,'[8] but also our fuels. They influence our minds

[7] Mitchell (2013).

[8] Nietzsche (1986, p. 172); cf. Kittler (1986, p. 304).

in a variety of ways and keep us, if we like it or not, embedded in a rationality of 'fossil reason.'[9]

An analysis of petromodernity therefore needs to include several transits through scales, histories, and geographies. What is most typical for the petromodern complex and its representation in scientific discourse, but also in science centres and museums, is a transit of fossil resources through a wide range of technical scales. In terms of the sciences involved, this points to a transit from geophysics and palaeontology to chemistry and up to the most advanced techniques of engineering and consumption. This is about the connection of very different time regimes and processes, from long-term temporalities of geological processes to short-term temporalities of technology, from the molecular to the planetary level, from deep-time natural history to present-time artificial materials and environments. A second major transit runs through various geographies with their respective historical and political settings. What is necessary to interpret the entire transit is a form of petrocultural comparison, for in a way all interconnected societies since about 1900 could and should be considered as 'petromodern.' This comparison of highly different 'oil encounters'[10] both on the peripheries but also in the centres of petromodern culture is of great importance for an assessment of the epoch of oil. In this paper, however, I can only give an outline of a future project.

On the one hand, petromodernity is a truly global epoch, in which all actual societies on the globe are in exchange via one and the same infrastructure and via one and the same petrochemistry. And yet, the individual position that a person or a whole society holds within this global system makes an important difference. It also makes a difference if one is dealing with a socialist or a capitalist, a social democratic or a despotic form of petromodernism, whether the interpreter is focusing on Norway or Azerbaijan, or whether one is dealing with Ludwigshafen, Louisiana, or Nigeria. This applies not only to a certain status quo but also to technological changes. A gain in sovereignty or in sustainability on the one hand can mean a loss on the other. The success story of German chemistry around 1900 with innovations such as synthetic indigo from coal tar was the failure story of Indian indigo farmers. Accordingly, the current energy transition will have to deal with complex scenarios of this very

[9] Klose and Steininger (2018).

[10] Ghosh (1992).

sort. Only if we attempt to put all these geographies, histories, and scales together in the true sense of a new, holistic history (or if we could agree on an exemplary yet representative setting), then we would be able to decide which aspects of petromodernism need to be transferred to the new epoch, what is worth fighting for and what is better left behind.

This analysis is further complicated by the question of a possible point of view. How can you describe a central factor of an epoch as long as you are is still in the middle of it? The situation would probably be easier if it were just a matter of understanding scenarios of mobility without oil in a technical sense—or of a world trade without plastic packaging; or of an urban development without concrete; or of an agriculture without artificial fertilizers made from natural gas; or of a pharmacy without petrochemicals. Instead, one has to deal with all these mutual dependencies at the same time. And what is more, in all these cases, we are facing a connection between material facts, abstract implications, and relations. Not only did fossil commodities shape what we perceive as facts today and with regard to history, they also infiltrate all kinds of role models and self-images of fossil modern people, and of almost all political systems of petromodernity. The individuals in the age of motorized individual transport are not the same individuals as before.

Recalling a well-known bon mot, one cannot see transparent glass while looking through it. Accordingly, with fossil raw materials, we are primarily referring to their application as technical things, concerning raw materials just as a means for gaining fuels and plastics. But we are also dealing with a group of subtle substances that rearranged the epistemic framework of our cultures altogether, the history and politics of modernity. This change of frame necessitates both small-scale, precise perspectives and a general, holistic overview at the same time.

It is difficult to render comprehensible both the dynamics, and the well-known contradictions of modernity—their 'dialectics of enlightenment' through intertwining progress and regress, emancipation, and oppression—by neglecting their fossil basis. In this sense, 'modernity' may seem congruent with 'petromodernity,' whereas the petro-perspective also sets a course on what we already know about modernity. Progress and catastrophe, freedom and enslavement, emancipation and regress, all these indissoluble contrasts that characterize the epoch of modernity are central to petromodernity, too. But there is something even more decisive. Natural history is in a very special way to be included in the tableau of modernity's contradictions, both through the geo-historical origin of fossil raw materials and through the ecological impact of their use. The epoch of greatest acceleration has a share in the longest course of time, not only unconsciously and indirectly, but explicitly through a whole set of highly sophisticated sciences. Oil can be used as a medium of reflection but also of connection. Not only does it connect the deep time of life on Earth, that is geology and biogeochemistry, with modernity; it also connects a very specific set of technologies and geographies with each other and with the various levels of natural history.

2 A Short Tour Through Petromodern Space

The following paragraphs will combine significant visual material and some short reflections from very different angles of petromodern culture and technology, providing some substantial insight into a large cultural field. As a method, this strategy has been put forward in the *Atlas of Petromodernity*[11] where we also set out with a piece of visual input to each of the 44 comparatively short essays. Here, the reflections will have to be even shorter, of course.

I want to begin by focusing petromodernity on a more general level and by one of the best-known milestones of modern technology: by fossil-fuelled space travel. Humans have reached the moon in the late 1960s. Given the very short human presence on the celestial body, the project has contributed to a novel planetary perspective. There probably would be no talk of 'spaceship earth'[12] without at least the possibility of space travel with real space ships. Manned spaceflight has provided the image of the blue marble; space telescopes and satellites have decisively enriched science, especially of Earth system interrelationships.

The fundamental role of fossil resources for this type of knowledge and human endeavour is often neglected. Yet there is no way of factual space technology without fossil resources. It is their energy density that provides for the fuels to leave the gravitational field of the earth, and only petrochemistry did provide the materials for leaving the habitable atmosphere. The Standard Oil advertising from 1959 presented here (Fig. 1) captures the connection in some kind of distorted yet lucid prevision: It will take another ten years for US-Americans to reach the moon, and of course,

[11] Klose and Steininger (2024).

[12] Buckminster Fuller (2008).

Fig. 1 To the Moon. Advert on fuel development by Esso from 1959. The Petroleum Engineer. Drilling & Production 31 (1959): E6–7. General Section, August, "The petroleum Engineer for Management" (© The Petroleum Engineer. Drilling & Production 31 (1959))

it will take much more than just the shallow drillings of the '69 ½ feet' achieved by the legendary 'Colonel Drake drilling' from 1859 to fuel a factual moon rocket. But stressing the importance of the most terrestrial and most ancient resources for the most celestial and supposedly most modern technology has perfectly hit the mark. Even if not every rocket has flown with kerosene like the early Soviet *Vostok* or the US-American *Vangard*, without fossil materials, space travel and thus the perspectives that space travel provides for planet Earth would be impossible. An innumerable amount of knowledge is connected to fossil space travel, through unmanned satellites and space telescopes, but also through manned space shuttles.

Space travel is of course the most extreme form of petromodern mobility. As such, it is part of a continuum that includes all types of motorized devices and the respective societal repercussions. In this respect, mobility plays into the tension between prosperity and destruction, liberation and enslavement. In addition to political freedoms, especially in Western democracies, promises of freedom in consumption and mobility are particularly characteristic of modernity. The car has developed in many countries into something like a cult object. Not everyone in the West believes in God, but almost everyone, in the last decades, believed in the promise of the freedom guaranteed by a fully fuelled car. There is actually no concept of individual freedom that would not include the freedom to travel, to exceed limits, and, as Peter Sloterdijk has pointed out, to drive.[13] It even tends to jeopardize ecologist convictions, e.g. when two Last Generations activists where caught on a holiday flight to Thailand, where they tried to take some days off from saving energy. Yet the desire scheme of individual transport is much more than just a psychological phenomenon. It is mirrored in a whole set of infrastructures, vast landscapes of urban sprawl and international networking where living without a car or travelling by plane is simply not possible.

On yet another level, petromodern mobility is connected to warfare and new possibilities of mass destruction and annihilation. Evidently, all wars since World War I, through Vietnam, the Gulf Wars, Grozny, or Syria, were petromodern wars. Tanks, aircraft, helicopters, cruise missiles—most, if not all, significant and iconic weapon systems of the twentieth and twenty-first centuries below the threshold of thermonuclear warfare and large nuclear aircraft carriers—were petromodern systems. This holds true from the level of vehicles down to the chemistry of the munitions. As the present war in Ukraine shows, it is petromodern tanks and fires that still define the horrors of war.

On its richly illustrated backside, the 1942 *Esso War Map* celebrates the enormous range in which oil can serve as a weapon. "Oil is ammunition, use it wisely," the footer says with pride. "Fuel for speed and power" in aircrafts, tanks, and other military vehicles are only the most obvious ways through which oil contributes to war. But readers of the advertisement also learn about petroleum wax for the United States Army ski troops or about killing body lice—the "enemy of all armies"—with special petroleum products (Fig. 2).

The cheerful self-confidence of a US oil company at war in 1942 is somehow stunning. In fact, Standard Oil was closely cooperating from

[13] Sloterdijk (2011, p. 97).

Fig. 2 Oil as Ammunition. Advert on various applications on the Esso War Map (1942). David Rumsey Map Collection (© David Rumsey Map Center, Stanford Libraries, https://www.davidrumsey.com)

the late 1920s until 1940 with I. G. Farben in Baton Rouge/Louisiana to develop, with the help of German chemistry, the very aviation fuels they praise in their advertisement and with the help of which they finally destroyed Berlin and liberated Europe from the NS-regime.[14] Explicit petromodern 'terror,' as the advert puts it quite frankly, is used to stop the even greater horrors of the NS terror—horrors that were themselves deeply connected to petromodern industries, to Blitzkrieg via tanks and Stukas, and to I. G. Farben's Auschwitz chemical laboratories in which, for example, the chemist and writer Primo Levi worked as a prisoner.[15] It is connected to millions of people killed by exhaustion gases from the diesel engines in the gas chambers of Sobibor, Belzec, and Treblinka.[16]

Another register of petromodern mobility is displayed in the reflections of the artistic Avant-gardes in early twentieth century. It was the bang of the combustion engine that provoked Filippo Marinetti's *Futurist Manifesto* in 1909: "We affirm that the world's magnificence has been enriched by a new beauty: the beauty of speed. A racing car whose hood is adorned with great pipes, like serpents of explosive breath—a roaring car that seems to ride on grapeshot is more beautiful than the Victory of Samothrace."[17] Whereas the connection of the aesthetic with the political sphere, the link of war, machines, and fascism, has been at the centre of the debate about futurism, the explicit petromodernism of this first step into artistic modernism is still about to be discovered by the retrospective theory of petromodernity.[18]

Interestingly enough, not only the Italian pre-fascist interpretation of modernism addressed the fossil basis of the new dynamics. In pre-revolutionary Russia, the futurist opera *Victory over the Sun*, which premiered at the Luna Park Theatre in Saint Petersburg in 1913, also connects a new aesthetics with fossil industrial means. In the opera, futuristic strongmen fight with modern technology against the dominion of the sun and the dependence of their civilization on natural cycles based on solar energy. The protagonists succeed in imprisoning the sun in a concrete cube and bring about the final victory of the industrial culture.

14 Stranges (2000).

15 Levi (1992).

16 Trunk (2011).

17 Marinetti (1909).

18 Cf. Klose and Steininger (2021).

Thus, the opera celebrates the dawn of a 'second nature,' built on the sources of fossil energy. The main protagonist of the 'Suprematist' movement, the Russian version of Futurism that was emphatically positioned against the right-wing political sentiments of the circle around Marinetti, was Kazimir Malevich. His *Black Square*, of which he later executed several versions on canvas and which, with its radical abstraction and spiritual condensation, was to be declared the 'zero point of painting' and one of the most important works of twentieth-century art, took the stage for the first time in the stage-design Malevich created for this opera (Figs. 3 and 4).

Retrospectively, a whole set of new aesthetics and artistic strategies arose from the impact of petromodern mobility. 'Aeropittura,' paintings from the mobilized and elevated perspective of airplanes, were an early example for the futurists' embracing of the new technologies. It led to further manifestoes on aeropainting, as in Marinetti's theses from 1929:

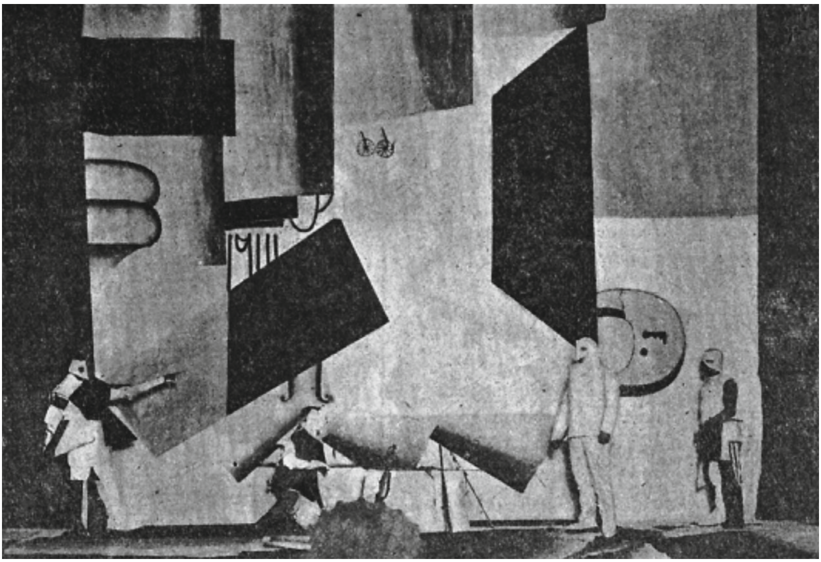

Fig. 3 Creating the Second Nature. *Victory over the Sun*. Futurist opera by Mikhail Matiouchine and Alexei Kroutchenykh (1913) (Wikicommons, Public domain, https://commons.wikimedia.org/wiki/Template:PD-Russia-expired)

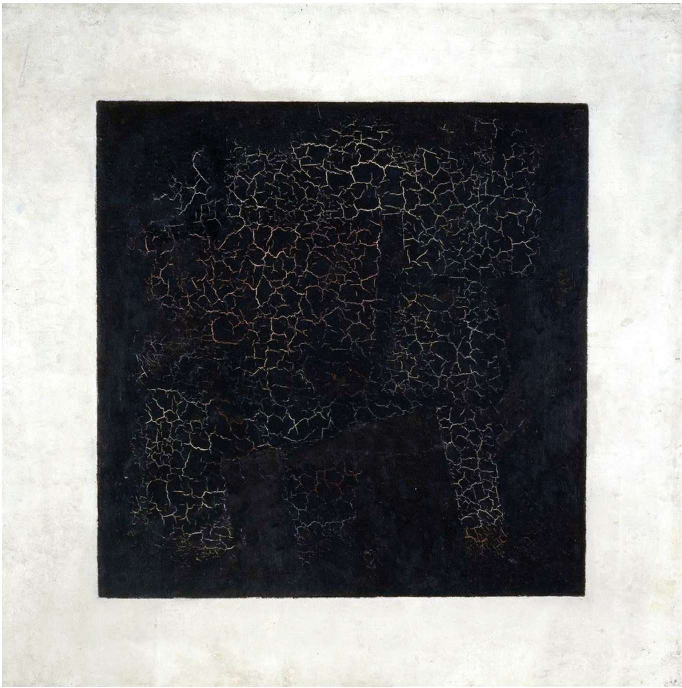

Fig. 4 Kazimir Malevich's famous Black Square (1915) which he originally created for the scenery of the opera *Victory over the Sun*. The opera praises the decoupling of human culture from the cycles of the sun—by use of fossil energy. Kazimir Malevich: Black Square (1915), oil on canvas, 79.5 × 79.5 cm. Tretyakov Gallery, Moscow (*Source* wikicommons, public domain)

> 1. The changing perspectives of flight constitute a reality which has nothing in common with the reality constituted by earthbound perspectives; 2. The elements of this new reality have no fixed point; 3. The painter cannot paint other than by participating in their inherent speed; 4. Painting from an elevated position leads to the contempt of the detail and to the necessity of synthesizing and transfiguring everything […]; 7. Every aeropainting simultaneously contains the tandem movement of the airplane and of the

painter's hand; 8. The pictorial or sculptural construct of aeropainting must be polycentric.[19]

From here ensues a long and fairly differentiated series on the aesthetics of speed that can be traced through the history of modern art. It comprises many influential positions such as Gerhard Richter's famous paintings of military aircraft, aerial images of warfare, but also of blurred moving vehicles like cars, boats and planes, such as 'Zwei Fiats,' 'Motorboot,' or 'Düsenjäger.'

It seems remarkable that both Italian and Russian Avant-gardes with their very different political agendas addressed fossil fuels as a radical new condition of radical new modern thinking and art. In a very prominent way, this highlights that there is not only one petromodern rationality. Petromodern materiality, too, has equally fuelled all political systems of the twentieth century, however radical, constructive, or destructive. Thus, petromodern materiality was necessary to National Socialism, to Stalinism as well as to the social democratic welfare states, and it is still essential for the most destructive forms of American consumerism, for Chinese communism as well as for all forms of despotism.

3 Is Oil a Natural or an Industrial Substance?

After retracing petromodern history from the 1950s to the first decade of the twentieth century, the next chapters follow the master narratives of oil within society, from oil wells to consumers. In the oil industry, a rather sharp distinction has been made between individual business units, concerning processes of 'upstream' (until the oil reaches the Earth's surface), 'midstream' (how it is distributed), and 'downstream' where it is processed through the refinery, takes various forms, and makes its way to customers of all kinds, to gas stations, to the chemical and pharmaceutical industry and, through their products, into our lives, bodies, and emotions. What is remarkable in this passage is which scales are traversed in the quantitative and qualitative categories of 'micro/macro,' 'fossil/modern,' 'nature/culture,' and which perspectives on the present become possible via these aspects of oil. The perspective on oil as a strange substance that is partly molecular, partly planetary, and ancient as well as

[19] Marinetti in: Schmidt-Bergmann (1993, p. 333).

modern may provide us with a kind of 'regard éloigné,'[20] a maximally distant yet clear-sighted perspective.

I want to illustrate this in the next two paragraphs with respect to two points in the technical journey of oil. I will focus first on 'upstream,' on the raw material itself, and on its status between a technical and natural substance, and then on 'downstream,' on the procedures of its chemical processing.

The energetic and material basis of petromodernity are hydrocarbon molecules formed in biogeochemical processes over millions of years. In crude oil, there are thousands and thousands of different compounds of carbon and hydrogen, but also compounds with sulfur, oxygen, nitrogen, etc. Excitingly, it is the molecular richness of crude oil that qualifies for an energetic and material resource, as well as for an epistemic one. On the one hand, it seems very obvious, that crude oil is a natural substance. It is produced by the Earth system itself without any human contribution. Similarly, the appearance at the surface in natural leakages, like in bitumen lakes in the Americas, in Mesopotamia, at the Caspian Sea, or else in small oil rivulets even in Central Europe, would count as a natural phenomenon. On the other hand, however, the abundance of this natural fossil substance in the technological metabolisms of modernity is far from being a natural phenomenon. Only by massive investments made by science and technology, this type of 'nature' appears as an exploitable resource. The quantity of drilled stretches can quite strikingly illustrate the scale of this endeavour. Since the beginning of petromodernity, oil and gas drillings have been performed to the quantitative equivalent of 4000 diameters through the entire globe, as modern statistics of drilling reveal.[21]

Yet the yield of this truly planetary endeavour is not only raw energy from planetary history. The yield is also planetary knowledge. Knowledge about geology and therefore geohistory is necessary to drill for oil in a planned and profitable way, which then creates further knowledge; an almost self-accelerating system which produces more oil and more knowledge with each twist. The big industrial institutions for the exploration and exploitation of the Earth's history are also institutions for the scientific interpretation of it. Even if their goals might only be defined

[20] Levi-Strauss (2001).

[21] Zalasiewicz et al. (2014).

by profit, what they create on the way is more than just new money. Sometimes, the output is spectacular in an aesthetic way, as in the case of the electron microscope photographs by the Norwegian Petroleum Directorate that cover fossil microorganisms in oil-bearing sediments. And sometimes, industry-related players create insights that an academic or state institution would not be able to afford (Fig. 5).

One impressive example are sediment samples from oil wells drilled by the Brazilian corporation Petrobras in the Atlantic Ocean. At a position, where the Amazon River plunges into the deep sea, several million years of South America's natural history are stored, in pollen, microfossils, etc. Based on the research with Petrobras drill cores, it was even possible to re-date the point in time when the Amazon no longer flowed into the Pacific but into the Atlantic Ocean, due to the uplift of the Andes.[22] In this case, not only the applied sciences, but basic research in palaeontology

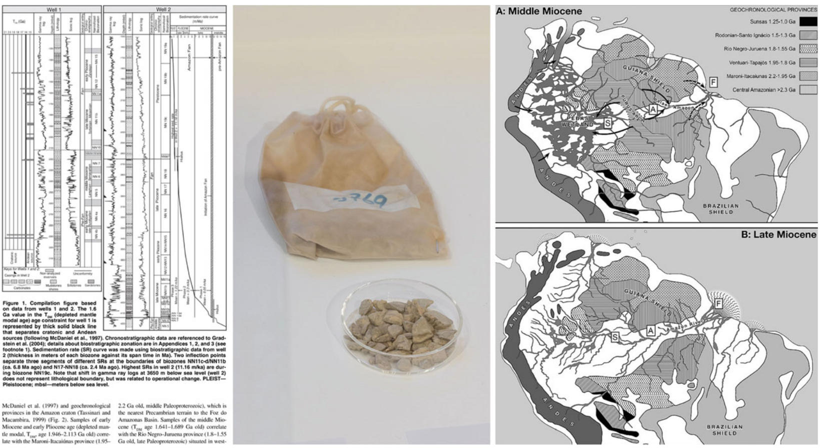

Fig. 5 Drilling Research. Change of the Amazon flow direction discovered from drill cores by Petrobras. Collage from geological research on a borehole at the Amazon fan: drill record, material samples, map of miocene South America, in: Jorge Figueiredo et al. (2009) (© of the image of the material samples, Marek Kruszewski, Kunstmuseum Wolfsburg)

[22] Figueiredo et al. (2009).

and the cartography of Earth history could benefit from industrial profit-making. No university in the world could have invested 103 million USD in a single well in 2002, but Petrobras did, for obvious economic reasons.

And again, the ontological status of these pieces of sediment remains somewhat doubtful. In a material way, they are the product of natural history. But in an epistemic sense, they carry with them the industrial and damaging present. It is only because there was a petromodern interest in this particular type of natural history that this object exists as a scientific object.

4 The Heart Chambers of Petromodernity: the Refinery

Crude oil—when it appears as a mass commodity at the Earth surface—is the final product of a whole set of sciences, technologies, and institutions. As the 'black gold' that connects strong boys, big business, and world politics, it is heavily represented in what is considered 'petroculture.' However, the crude black or brown substance is only half of the story. The technical and geographic networks of geology and drilling represent only one pillar of the full game. The other pillar is chemical engineering. It is here, where the 'molecular mobilization' of natural history[23] and the 'Great Acceleration'[24] not only of human history but of all Earth system processes is set in motion. What we see in the illustration below is a flowchart of the process landscape that stands between crude as a commodity and the automotive world that is propelled by this substance (Fig. 6).

Chemistry, as many scholars have famously stated, is the science of open-ended processes, and it is part of the logic of these processes that they are uncontrollable to a certain extent.[25] For instance, there are deeply asymmetric material relationships involved. The tiniest amounts of catalysts—substances that accelerate and steer chemical reactions without being consumed by the reaction—can process gigantic amounts of hydrocarbons.[26] These dynamics of acceleration of chemical processes have

[23] See the respective chapter in Klose and Steininger (2024).

[24] Steffen et al. (2015).

[25] Cf. Prigogine and Stengers (1984); Soentgen (2021).

[26] Cf. Steininger (2014).

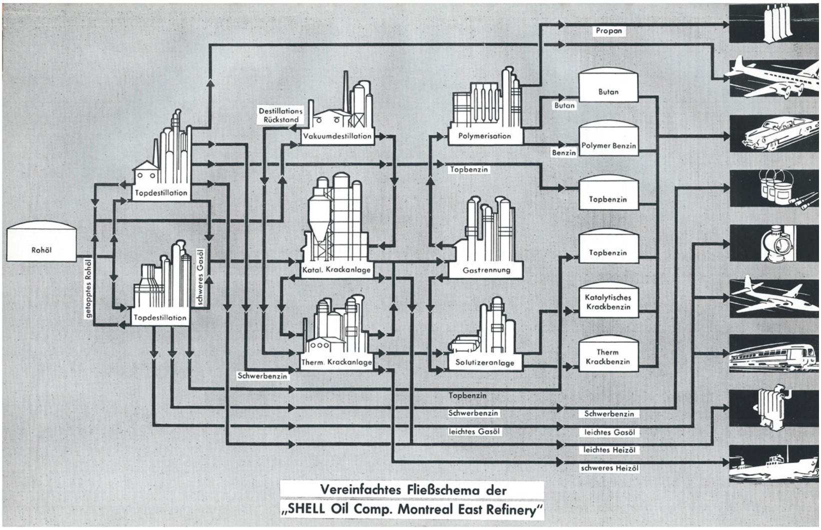

Fig. 6 Crude oil needs to be refined to propel culture. Flowchart from Gerhard H. Lehmann. 1955. Erdöl-Spaltung, ABC des Erdöls. Vol. 5., p. 35. Heidelberg (with permission from Süddeutscher Verlag, Verlagsgruppe Hüthig Jehle Rehm GmbH)

been crucial for the natural and cultural history of modernity and of the Anthropocene. Inasmuch as the term 'petromodernity' comprises more than just energy carriers or raw materials themselves, a closer look into the industrial histories and process landscapes of refineries also reveals that these prominent substances gained their historical impact only together with a large class of substances that helped to process them, in particular with metals and mixtures of metals.[27] What made history is not just oil, but a systemic complex of substances from an even wider and often precarious geographic range. Refineries and chemical plants appear as "planetary reactors."[28] Petrochemical landscapes, e.g. on the Mississippi River in Louisiana,[29] but also on the Rhine with places such as Rotterdam, Ludwigshafen, and Basel, and of course on the great Chinese

[27] Steininger (2014).

[28] Steininger (2021, p. 263).

[29] Cf. Misrach and Orff (2012).

Rivers, are hubs to process all types of chemical input from all types of geography and geohistory. Resources from the lithosphere, the atmosphere, and the hydrosphere are put into the chemical technosphere to change the biosphere and all the other layers of the Earth system.

Substances tend to undermine all boundaries, even when chemical process technologies try to contain them.[30] And even if the processes inside a chemical plant or refinery can be controlled and contained, it is almost impossible to control and contain the agency of their products. Thus, the interaction of chemical substances with the process scales of industries, technologies, economies, cultures, and ecologies has amplified and accentuated the material openness of chemistry.

Large parts of the industrial chemical history of the petromodern era appear as an interplay between new substances and new cultural practises. Often, new ways of usage had to be invented for substances that did not exist before, creating novel pathways of process evolution with ecological or cultural scales. Iron carbonyl, for example, that failed as an additive to motor fuels back in the 1920s (the non-poisonous alternative to tetra-ethyl-lead tended to harm the engines themselves) became crucial for the invention of the magnetic tape and subsequently of the once famous BASF audio cassette.[31] What was intended to provide smooth engine performance in cars now helped to create a whole branch of the cultural industry and its new life styles, but also offered feedback into the world of industrial process landscapes.

More famous than these interactions between the spheres of chemistry, the automotive industry, and popular culture, are the interactions between chemistry and 'agriculture,'[32] all the more so as this field is an essential part of the logic and logistics of petrochemistry—due to the fact that hydrogen (H) in ammonia (NH_3) fertilizers is not produced from water as one could presume, but from natural gas. The intended effects of products of petrochemistry, such as ammonia fertilizers or pesticides, are amplified by the unintended effects of these substances in the biosphere. Only a small amount, e.g. of the fixed nitrogen (N) from the air in ammonia (NH_3) fertilizers, will end up in plants and food.[33] A large

30 Cf. Barry (2017).

31 Zimmermann (1969).

32 Smil (2001).

33 Cf. Ertl and Soentgen (2015).

part is eroded into all types of bodies of water and affects various environments up to the infamous dead zones in oceans resulting from algae growth. Moreover, the use of pesticides, too, contributes to the local but also to the planetary decline of large parts of the biosphere. Here, the open processes of chemistry appear more destructive than creative. In fact, the application of petrochemical products and their impact on the globe have been labelled the sixth mass extinction in natural history. Life will not disappear, but new paths for evolution will be opened. In this respect, the products of the petrochemical industry have thoroughly shifted the process landscapes of this industry. The refinery as a principle is not only located where one can literally see the bunches of pipes and reactors. To a certain extent, the refinery is everywhere. Petrochemical products continue to react throughout the biosphere and within ourselves. We even eat fossil raw materials, via artificial fertilizers or, in certain cases, via CO_2 from the refinery, such as with Dutch tomatoes. To make them grow, CO_2 is directly pumped from petrochemical plants at the Port of Rotterdam into the famous Dutch greenhouses north of the harbour in Westland.[34]

An art work, dealing with the ubiquity of the refinery principle, is *Norco Cumulus Cloud* by the US-American photographer Richard Misrach.[35] The picture shows a huge cloud above a southern landscape. Only at a second glance, the source of the cloud may be seen: a refinery, looking small in the end of a swath in Louisiana, but in fact, one of the oldest and biggest refineries on the planet, the refinery at Norco in the north of New Orleans, run by Shell. Supposedly every afternoon, this artificial cloud appears above the refinery when the steams of the plant condensate in the air. This mechanism may not appear as regularly as Misrach reports, but nevertheless it is highlighting the well-known yet still unsettling fact that even the sky and the most majestic clouds are no longer natural objects.

[34] Cf. Klose and Steininger (2024).

[35] Misrach and Orff (2012).

5 How to Deal with a Substance that Connects Everything?

Scientific models of man-made present and future developments of the atmosphere are already very accurate. Yet much more difficult to model—as this essay tried to sketch out in an indirect way—is the present and the future structure of petromodernity. Technology, science, economy, politics, and culture all causally contribute, on societal and individual levels, to the dynamics of this epoch. Causal dynamics run from the most material to the most abstract parts of the system—and back. Material resources such as fossil fuels or the catalytic metals used in chemical plants contribute to the most important and iconic self-technologies of the era, such as individual transport and digital communication. But not only do materials, together with their technical performance, set the scene and limits for what individuals can do and even dream about. It is the most particular desire formed within the fossil state of modernity that tends to be the hardest and most complicated factor in modelling and managing the energy transition and its implications.

The whole cultural coordinate system has been elevated to an unprecedented state by the influx of fossil energy and materiality. The knowledge system of modernity is to a large extent a petromodern system, created by a fossil-fuelled techno-science. Satellites, data centres, but also surgical suites may appear less petromodern than drill-core storages or chemical laboratories, but they are unthinkable without petrochemical materiality, and so are all the effects they provide. Similarly, many concepts of our modern liberties, individualities, and desires are connected to the petromodern material system. Mass consumerism, the welfare state, and a political-cultural system that enables a wide variety of cultures, subcultures, identities, and life designs did not appear by chance in the course of fossil modernity. Child labour, for instance, has not only been abolished by progressive politics, philosophy, and law in many parts of the world, but also by engines and power stations that contributed to a world without hard physical labour for many if not most. The plasticity and dynamics of modern life styles were almost perfectly mirrored in the plasticity of petrochemical materiality. Whatever a human mind could imagine and ask for—be it a blinking sneaker or a diving suit, a syntheziser, a sex toy or a mars rocket—hydrocarbons would sooner or later provide for a material solution.

These standards of an almost total doability won't go away when the fossil base of modernity needs to be left behind. And it will take the work of many observers and interpreters of petromodern life to sort out what is worth to be preserved in a post-fossil world. Knowledge about an Earth that is older than 6000 years should of course be kept as well as liberal democracies with their complex and costly but balanced processes of decision making. A mix of high cultures and subcultures with all their sophisticated niches could only grow in the petromodern era, but also notorious despotism and ecological desasters.

Sorting out the achievements and the aberrations of the petroculture would require to connect petromodernity's most concrete material and technical aspects with the most ephemeral aspects of subjectivity, believes, and desires. It would take specialists both in holism and in detailism to get the full range of phenomena—displayed in the Earth system itself, in technologies and geographies, but also in the arts as the special detectors for subjective effects of natural-geographical-technological settings.

It is still an open question if the complex totality of all the physical things, substances, and processes, and all the cultural and technological things, substances, and processes with all their subjective reflections, can be represented in digital models in a fruitful way, or if this only serves a technocratic desire. Since the actual situation is unprecedented both in cultural and natural history, it will be difficult to extrapolate anything exact from previous constellations. As scientifically sound as climate models already might be, they still do not tell us much about the single historical events that might occur under the predicted parameters. History as the contingent interplay between geographies, politics, cultures, and technologies may for good reasons remain the domain of single-event knowledge without the need of exact causal laws. This renders the particular knowledge of historians or geographers no less 'material' than the knowledge of chemists or physicists. What is at stake is not so much the division between facts and interpretation or narration—as is often claimed when it comes to the divide between the sciences and the humanities or arts—but different types of equally hard facts. For it is the division between different types of facts that often affects the way in which something can or cannot appear as a significant event in the scientists' calculations and causal scenarios.

Even if the complexity of all the connected cultural and political events in petromodernity will not allow for digital models to predict stable pathways of the cultural future, it is worth mentioning that the scientists of the Earth system themselves gradually acknowledge that without at least trying to include and model the human impact on climate, biosphere, and landscapes, Earth-system modelling will not capture the factual processes of the Anthropocene—and that social parameters need to enter the calculus.[36] The interplay between the technical urgency to feed human actions, as data, into the scientific and technical models, to somehow manage the outcome of these actions, and the philosophical scepticism whether the contingency of history can be really reduced to such data will define how scientists and cultural theorists can further address the techno-natural processes of the Anthropocene. Bringing together all types of facts, the physical and chemical facts, and the facts that include or exclude people with their inherited or very new and market-made desires, is a necessary endeavour. Even if both parties do not come up with one compatible digital language or grammar, they better start to learn to take into account their different perspectives on the same substantial problem in a world where technical, natural, and cultural causalities do always interfere—whether we understand this interference or not.

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[36] Smith et al. (2022).

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The Energy Imaginary. Model Media in Literature and the Arts

Cycles, Spirals, and the Challenge of Scale: Literary Modelling in Climate Fiction

Stefanie Mueller

1 Introduction: A House on Fire

In order to convey the urgency of climate change, the urgency of acting in the present moment, Greta Thunberg once famously resorted to metaphor. During the 2019 annual meeting at the World Economic Forum, she began her statement, "I am here to say our house is on fire" (n.p.). She mentioned well-known numbers that speak to the irreversible effects that CO2 emissions have already had on the planet's climate. "At places like Davos," she continued, "people like to tell success stories."[1] Yet, climate change was not one of them and success stories or hopeful stories were not what she wanted to hear. She concluded her talk by saying that adults kept offering young people hope, but that she didn't want their hope. "I don't want you to be hopeful. I want you to panic. […] And then I want you to act. […] I want you to act as if the house is on fire. Because it is."[2]

Thunberg's appeal alerts us to the role of emotions as well as to that of the imagination when it comes to battling climate change. Unsurprisingly, therefore, literary critics and writers have pointed to the potential for

[1] Thunberg (2019, n.p.).
[2] Thunberg (2019, n.p.).

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literature to make a meaningful contribution to the discourse on climate change, which for a long time was dominated by politics, economics, and science. Yet how exactly would such a contribution work? A recurrent response to that question addresses the *challenge of scale* that climate change poses to any form of representation and hence communication: the fact that it is a planetary phenomenon and a phenomenon that unfolds over long time spans—in other words, a phenomenon that transcends individual, singular experiences, and perceptions.[3] Yet, a prerequisite for understanding and accepting the climate crisis in its full reality, and to consider responses to it, is to be able to imagine it.

The challenge of scale is also what many literary critics have identified as the biggest challenge to literary fictions specifically when it comes to telling stories of climate change: how to represent the spatial and temporal scales of climate change, which is to say, how to make them imaginable and experienceable for readers? This is a particularly urgent question for the novel in the realist tradition because, as critics such as Amitav Ghosh have pointed out, with its origins in an attention to the bourgeois individual and the mundane details of everyday life, the novel has acquired an impressive repertoire of narrative conventions to present small worlds, but may be severely limited in its affordances to portray planetary networks.

Scale and scaling are also central aspects of *models* and the work that models do, whether in the natural sciences, political science, or economics. In fact, as Mary S. Morgan explains, economic models have frequently been criticized for their small-scale rendition of worlds which critics equate with (over-) simplification and even triviality. Against such criticism, Morgan points to the practices of simplification, idealization, and compression in the arts and the humanities. Comparing economic models to poetry, Morgan writes, "Models for the economist, like sonnets for the poet, are means to express accounts of life in an exact, short form, using languages that may easily abstract or analogise, and involve imaginative choices and even a certain degree of playfulness in expression, all within a structure that follows certain rules – of mathematics or of length and metre."[4] In other words, the smaller scale of the worlds that are represented or rather modelled in novels does not necessarily limit the genre in its ability to meaningfully narrativize the climate crisis.

[3] See, for example, Clark (2012, pp. 148–166).

[4] Morgan (2012, p. 386).

But it does warrant closer attention as it implies processes of selection, transposition, and ultimately, modelling.

In this paper, I want to investigate scale as a central dimension of literary modelling in a contemporary US-American novel on climate change. I am interested in how literature models a world in which climate change is not a future event but a present reality for its readers and, as part of my inquiry, how interdisciplinary approaches to models and modelling can broaden our understanding of the kind of knowledges and, with that, the kinds of worlds that models produce. For this purpose, I turn to Jenny Offill's 2020 novel *Weather*, which is a US-American novel that initially appears more preoccupied with the everyday life of the liberal-democrat middle-class on the East coast in the times of the Trump presidency than with the climate crisis. Drawing on modelling theory by economic historian Mary S. Morgan and eco-narratologist Erin James, I want to suggest, however, that the novel provides the textual clues that allow its readers to model a specific form of reading practice, a specific mode of perceiving the world and as a result, to model a "storyworld" in which climate change is a reality that is difficult to grasp and to accept.[5]

2 Models and Modelling

Jenny Offill's novel *Weather* is a novel with little action, an impression that is heightened by its condensed and brief style which in turn has been compared to a "literate Twitter feed."[6] The novel consists of short to medium-length paragraphs that are separated by blank lines and which contain brief observations and descriptions as well as jokes, quotes from e-mails and letters, questionnaires, and snippets of dialogue. There is, indeed, very little action as the narrative follows Lizzie Benson, focalizer and protagonist, through her everyday life in New York City in the year leading up to and following the election of Donald Trump as president of the United States. Lizzie is a former academic turned college librarian who lives with her small son Eli and her husband Ben (a philosopher by training and a software developer by profession) in Brooklyn. At the start of the novel, Lizzie decides to accept a side job with her former advisor, Sylvia, whose research is on the social and cultural impact of

[5] James (2015, p. X).

[6] Oyler (2020, n.p.).

climate change. Sylvia travels a lot to give talks, attend meetings, and to inform the general public about climate change, including through a podcast called *Hell or High Water*. Excerpts from e-mails that Sylvia receives from her listeners and that Lizzie is tasked to answer pepper the novel, as well as anecdotes from Sylvia's meetings with wealthy donors and Silicon Valley entrepreneurs. In addition to this side job, Lizzie also becomes more involved in her brother Henry's life at the beginning of the novel. Henry has a history of substance abuse, and despite his successful recovery, he appears to still rely on Lizzie's emotional support. In the course of the novel, he meets a woman named Catherine, gets married, has a daughter, and finally, gets divorced. If Sylvia is the voice of reasoned doom in *Weather*, who consistently reminds Lizzie of the fact that climate change has already begun and is mostly irreversible, Henry emerges as a prophet of apocalypse whose emotional instability marks the other and extreme end of the spectrum of anxiety that the novel portrays, in particular with respect to parenthood.

It is safe to say that, on first sight, *Weather* is not a typical piece of climate fiction. While it does feature prominently whenever Lizzie interacts with Sylvia, climate change is not at the centre of the novel's concern. Of course, the definition of climate fiction or cli-fi has come under intense discussion in recent years. For a long time, cli-fi was associated closely with sci-fi and therefore with fictions set in the (near) future. Specific topics such as technology featured prominently and indeed, how accurately those novels portrayed the science behind climate change often featured in their discussions. In addition, typical cli-fi tended towards the depiction of events: catastrophic weather events that synecdochically represented what is unrepresentable about climate change and that frequently resulted in dramatic social and political upheavals. Examples include Margaret Atwood's *MaddAddam* trilogy (2003–2013), Paolo Bacigalupi's *Ship Breaker* (2010), Nathaniel Rich's *Odds Against Tomorrow* (2013), or Kim Stanley Robinson's *New York 2140* (2017). But in recent years, scholars have made the case for a broader definition of climate fiction, such as has been proposed by Stephanie LeMenager. In "Climate Change and the Struggle for Genre," LeMenager suggests to define cli-fi as fictions that address what she terms "the 'everyday Anthropocene'," by which she means to "imply the present tense, lived time of the Anthropocene."[7] In this regard, LeMenager sees climate fiction as "aspir[ing] to envision a climate change culture for readers who are in some cases losing their sense of what it means to be human, to generate culture, and to love."[8] From this perspective, Offill's *Weather* can be understood as a piece of cli-fi in which the climate crisis is not a future event that can still be prevented, but a present fact and hence the setting of a lived life. Its specific contribution to the discourse on climate change consists in its modelling of how to inhabit such a world: how to make a home, how to raise one's kids, and how to make (narrative) sense of a "catastrophe without event."[9] Yet what does it mean to say that the narrative *models* inhabiting a world?

While the debate is ongoing, philosophers of science generally appear to agree that it is difficult, perhaps pointless to define what a model *is*, because *anything* can be a model. It is the work models *do* in their respective disciplines, the knowledge and understanding that scientist gain through reasoning with them about the world, that defines them more than any ontological qualifier. What is certain, however, is that they have become a widespread tool of analysis in many disciplines, such as natural sciences, social sciences, or economics, for example.

In literary studies, the concept is less prevalent, but recent scholarship has explored the possibilities it offers and frequently so, by drawing on the work of New Formalists, such as Caroline Levine and Anna Kornbluh. Levine defines form—whether social, political, or aesthetic—broadly as "all shapes and configurations, all ordering principles, all patterns of repetition and difference."[10] Taking a functionalist approach, she is interested in the work that forms do in the world, in their "affordances."[11] Based on these ideas, Marco Caracciolo has argued that "contemporary narrative and scientific models of more-than-human realities can find a common ground in form."[12] In his discussion of three novels that

[7] LeMenager (2017, p. 225).

[8] LeMenager (2017, p. 222). The term 'Anthropocene' is not without problems. I use it here only in the context of LeMenager's ideas about a set of climate fictions with the demise of Western culture and how Western societies come to terms with it.

[9] Horn (2018, p. 8).

[10] Levine (2017, p. 3).

[11] Levine (2017, p. 6).

[12] Caracciolo (2019, p. 272).

engage with scientific models, Caracciolo emphasizes the role of analogy in both literary and scientific modelling, whether the latter occurs through "the global structuring of plot" or through "clusters of metaphorical language," for example.[13] Because he is specifically interested in scale as an anthropocenic challenge, Caracciolo combines the New Formalist approach with narrative theory and cognitive linguistics which also allow him to emphasize the bodily dimension of the human perception of scale.[14]

For the purpose of the present inquiry into *Weather*, climate change, and literary modelling, I turn to the work of literary critic Erin James and economic historian Mary S. Morgan. Morgan's *The Model in the World* (2012) is useful because of its broad scope of exemplary models and examples of model-based reasoning. Erin James' work on what she calls the "storyworld accord" is particularly appropriate for an analysis of cli-fi because it combines narratology and ecocriticism. James explains:

> I take my central premise from the work of cognitive narrative theorists, who see reading as a process of immersion or transportation. Such scholars define a storyworld as a mental model of context and environment within which a narrative's characters function. Like the similar terms *story* and *fabula*, *storyworld* is a term narrative theorists use to discuss what happens in a narrative. But more so than other terms, the storyworld highlights the world-making power of narrative texts. Storyworld scholars argue that narrative comprehension relies upon readers interpreting textual cues *to make mental models* of a text's world and inhabiting those models emotionally.[15]

It is important to stress that storyworlds are the product of the readers' interpretive activity: the model is not readily available in the text or deliberately designed by the author, it is the work of the readers who draw on their own knowledge and experience as well as on textual clues. The latter, as James explains, "come in many shapes and forms:" from references to setting to "sensory appeals." And because "mental models

[13] Caracciolo (2019, p. 270).

[14] See also Nitzke (2016).

[15] James (2015, p. X), my emphasis.

of a narrative's world are based upon an individual reader's presuppositions and interpretation of textual cues, no two storyworlds will be the same."[16]

James' explanation of the process in which readers create models of storyworlds and inhabit them emotionally shows some interesting parallels to Mary S. Morgan's explanation of the process of formalization or model-making in economics. For one thing, both are less interested in the future-oriented capabilities and properties of models, but rather emphasize their primary function of world-making. As Mary S. Morgan notes, "Model-making [...] is an activity of creating small worlds expressed in another medium."[17] Moreover, both portray this process as a combination of prior knowledge and creative intuition. If it is textual clues and personal world-knowledge in the case of James' readers, for Morgan, it is prior knowledge about the object of inquiry and intuition. Which is to say, for Morgan, the form and shape of the resulting model is not a prior given: "forming models is not driven by a logical process but rather involves the scientist's intuitive, imaginative, and creative qualities."[18] Finally, both James and Morgan emphasize an element of playfulness and open-endedness in their description of models and modelling. In James' case, it is the interpretive activity of the reader which is determined by their individual positionality which means that "no two storyworlds will be the same."[19] In Morgan's case, the "manipulability" of the model is what sets it apart from a mere representation such as "pictures", because it is only through manipulation that the model affords reasoning.[20] In both cases, the results of the activity—narrative comprehension and model-based reading—can be duplicated but they can also differ.

Based on James's and Morgan's work, *Weather*'s specific contribution to the discourse on climate change comes into clearer view. Through textual clues and narrative structure, the text encourages its readers to model a storyworld that is characterized by a specific form of perception of the climate crisis, that can also be characterized as an actual lack of attention. Moreover, by prompting its readers to model a mental image

16 James (2015, p. 22).

17 Morgan (2012, p. 30).

18 Morgan (2012, p. 25).

19 James (2015, p. 22).

20 Morgan (2012, pp. 381, 5).

of inhabiting the present moment, the novel foregrounds the challenge of scale: of paying attention to climate change as it unfolds over large spatial and specifically temporal scales. As readers read, they create a mental model of Lizzie's world in which they too have a hard time paying attention to the obvious clues and in particular the emotional politics of climate change. The narrative structure and aesthetic forms that afford this process of modelling can be described as cycles and spirals.

3 The Challenge of Scale

Cycles

When it comes to the experience of time in the novel, cyclical time clearly dominates the narrative. That is to say, that Lizzie's perception of her world—as protagonist and focalizer—is dominated by a cyclical temporality that characterizes generational time, seasonal time, or more generally, so-called natural time or time of nature. For example, when Lizzie is thinking about preparing her son for the future, she is simultaneously occupied with her own body's decline and with age: In the course of the story, she sprains her knee, has a conspicuous mole checked for cancer, observes how she can't stomach alcohol the way she could as a young girl, and notices how her marital sex life has changed. Other story elements also highlight this generational time, such as her sister-in-law's pregnancy and the passing of the seasons that Lizzie infrequently observes in the course of the year that the novel covers. All in all, the story thus emphasizes cyclical time, a time that implies stability and renewability. And this is precisely the crux of the matter, because even as we witness Lizzie worry and prepare for the future, the narrative runs along this rather stable temporality of cycles.

Highlighting the heroine's primary perception of life as following the stable temporality of cycles—babies are born, parents grow old, life goes on—the novel underscores a central challenge of scale for human perception and for the literary representation of the climate crisis. In his discussion of climate change as part of the reality that is now frequently called the "Anthropocene", Amitav Ghosh has observed the following about literary fictions:

> Here […] is [a scalar] form of resistance […] that the Anthropocene presents to the techniques that are most closely identified with the novel:

its essence consists of phenomena that were long ago expelled from the territory of the novel – forces of unthinkable magnitude that create unbearably intimate connections over vast gaps in time and space.[21]

In other words, both on the level of time and space—the novel (as opposed to the epic, for example) struggles to find modes of representation for our post-equilibrium world. A similar observation has been made by Rob Nixon, though with more dramatic implications. Nixon writes not just about literature but generally about the discourse on climate change. He has coined the term "slow violence" to designate the problem of recognizing and representing the violence incurred by environmental degradation, rising sea levels, and so forth.

By slow violence I mean a violence that occurs gradually and out of sight, a violence of delayed destruction that is dispersed across time and space, an attritional violence that is typically not viewed as violence at all. Violence is customarily conceived as an event or action that is immediate in time, explosive and spectacular in space, and as erupting into instant sensational visibility.[22]

What both critics highlight is that, when it comes to the climate crisis, there is no sudden, spectacular violence to depict, no dramatic climax to build up to. But Western literature, in particular the novel, has thrived on events (though not necessarily the spectacular), on singularities, and individuals. What is more, Offills's *Weather* suggests that this is not just a problem of Western literature, but of Western society and a media environment in which attention has become a valuable resource that can be converted into financial capital. On the level of story, therefore, *Weather* explores an observational practice—a mode of paying attention—that is geared towards ruptures and events and that therefore misses the slow, unfolding realities of the climate crisis.

A former academic and college librarian living in New York city, Lizzie is a representative of the educated and financially comfortable middle-class in the United States, an east-coast liberal who has plenty of material and symbolic resources available to her to learn about the climate crisis and to actually do something about it. Yet, in particular when it comes

[21] Ghosh (2017, p. 63).

[22] Nixon (2011, p. 2).

to the climate crisis, the novel is characterized by a conspicuous lack of attention and story, which can also be described as an inability to hold attention over longer periods of time, as well as a preference for novelty and small-scale patterns. The latter actually provide the novel with its title. Its title is explained early in the novel in a vignette from Lizzie's work at the library.

> Sometimes I ask my boss about the little patterns I notice at the library. She has worked here for twenty years. She sees everyone and everything. So how come three different people came in today and wanted to put up flyers about beekeeping? But this time Lorraine just shrugs. "Some things are in the air, they float around," she says, and I think of leaves, of something falling and accumulating without notice.[23]

With its reference to atmospheric accumulation and the seasons (leaves falling in autumn), the passage references weather as an example of patterns emerging over time that can be read and understood in some way if careful attention is paid. In this regard, Lizzie appears highly motivated, of course, and true to her claim she does indeed tend to notice little patterns, and not just at the library. As I explain in more detail below, the narrative discourse itself is evidence of her attention to little patterns. But on the other hand, there is Lizzie's *inability* to connect the dots, because—in this case—the most obvious explanation is the fact that increased death rates for bees have been reported in the last couple of years and in particular in the United States, where pesticides that use neonicotinoids had become widespread. Even in Europe, amateur beekeeping has therefore become more and more relevant. A dedicated pattern-seeker, Lizzie's attention for patterns appears overall skewed towards ruptures rather than long-term trends.

This becomes apparent when at least one disaster finally strikes: Trump is indeed voted into office, and at least the political atmospheric disturbances that had been accumulating seem to have come to a breaking point.

> After the election, Ben makes many small wooden things. One to organize our utensils, one to keep the trash can from wobbling. He spends hours on them. "There, I fixed it," he says.

[23] Offill (2020, p. 32).

> *A turtle was mugged by a gang of snails. The police came to take a report, but he couldn't help them. "It all happened so fast," he said.*
> And in the ether, people asking the same question again and again. To the yours-to-losers, to the both-the-samers, to the wreck-it-allers.
> *Happy now?*
> The path is getting … narrower. That's how Ben told me. He was doing the math in his head.
> But it could still…?
> It's not impossible.
> And so we stayed up and watched until the end.[24]

Apart from the deictic expression at the very beginning of the page ("After the election"), we would be hard-pressed to say what the narrator is talking about—the climate crisis or the political crisis. The most conspicuous emphasis in this passage is on time or rather speed. Because (as the joke in italics suggests), the political crisis didn't really happen fast—it's just that nobody paid enough attention—and the same can be said for the climate. What is more, while Lizzie proclaims that they watched until the end (which is presumably when all the votes had come in), there is no end. Despite all their foreboding and dread, the world does not suddenly end after Trump has been elected. Watching for the ending, as much as reading for the ending, is pointless in this situation, and the importance of this insight is stressed by the novel in a half-serious, half-humourous exchange between Sylvia and Lizzie later in the novel: "'Of course, the world continues to end,' Sylvia says, then gets off the phone to water her garden".[25] This insight into reading practices—whether they concern our reading of the world or of literature—is even more central to the novel's discourse and how it encourages its readers to model a world in which a specific mode of attention (or rather inattention) has become dominant.

Spirals

If the cycles and cyclical temporalities dominate the level of story in *Weather*, the level of discourse is structured by circles or rather spirals. That is to say, the way the story is told is almost circular. Again and

[24] Offill (2020, p. 111).
[25] Offill (2020, p. 198).

again, the narrator returns to topics and motives only to abandon them momentarily and inconclusively and then to return to them at a later point. In this way, the narrative ends up circling around the large issues that the novel addresses, in particular climate change, and while the topic always seems to figure in the story, it is never at its centre. Late in the book, Lizzie herself suggests that this mode of communicating about the world is social: "In some Zen monasteries, gossip is defined as talking about anything not directly in one's gaze."[26] Similarly, reviewers have compared the novel's style to social media, such as Twitter. What both of these characterizations suggest is that the novel does not seek to convey the idiosyncracies of a singular character. Instead, it tries to provide the textual clues that allow its readers to model a specific form of reading practice, a specific mode of perceiving the world and as a result, to model a storyworld in which climate change is a reality that is difficult to grasp and to accept.

As I suggested, the model of perception or attention that the text affords emphasizes the challenge of scale that the climate crisis presents to humans (both as readers of the world and of literary fictions). To return to the novel's title once more, weather is introduced in the text as the primary example of patterns emerging over time that can be read and understood in some way if careful attention is paid and Lizzie is highly motivated to do so—as is, presumably, the reader. But the problem here is the fact that Lizzie pays attention to the little patterns rather than the larger ones, or to put it differently, as scientists have to explain over and over again, weather is not climate. Similarly, the novel's narration is divided into brief paragraphs, some as short as two lines, that draw on a variety of short genres, whether anecdotes or jokes, as well as on an even greater variety of topics, with references to climate change sprinkled throughout. In this way, the text directs the reader's attention to such clues, yet also keeps her close to the text and thereby affords a model of reading that is geared towards little patterns as well.

Significantly, in her discussion of textual clues as providing the basis of the reader's modelling, James highlights the importance of "signals of perception" in the text, which include "chronology" and "dialect," for example, and she links them not only to the creation of a mental model of a specific socio-cultural and environmental world, but to the emotional

[26] Offill (2020, p. 176).

valences of that world: "These cues not only give shape to a narrative's storyworld, but also aid the transportation of readers to alternative times, spaces, and experiences."[27] Hence, it is also important to note that Offill's novel does indeed also suggest the modelling of a particular emotional response to the world in which Lizzie and her family find themselves, which is foreboding and indeed, anxiety. As a seemingly intangible object of threat, climate change is the source of anxiety for the characters in the novel, and through its diffusion of climate change's impact throughout the text, the novel affords this experience to the reader. Take Henry's nightmare, for example:

> I leave the baby in the car while I go into the store. It is so much bigger than I expected. I keep wandering up and down the aisles, putting more and more things into my cart. It is so full, I even fill up the seat part where the kid is supposed to sit. Suddenly, I remember Iris and run outside. It is a sweltering day and all the windows are closed. There are people standing around the car, trying to break in. A man is hitting the window with a hammer, but it won't break. A woman is screaming. The police come and they smash it open. They give her CPR, but she is already dead. I am standing in the crowd. Then they realize I am her father.[28]

In this way, *Weather* cannot only be said to afford the model of a specific mode of perception of the world, but it can also be said to highlight the experience of inhabiting that world: of living in a house that is on fire, to return to Greta Thunberg's phrase.

For Erin James, the advantage of using a storyworld approach (i.e. to study "the virtual environments that readers must model and inhabit to understand narratives")[29] consists in how it broadens the still dominant idea of what an environmental text or a piece of nature writing looks like because it brings texts into view that would frequently do not fall under this category, including "postcolonial texts that employ nonmimetic and nonrealist narrative strategies as a means of resisting imperial hegemonies."[30] Yet, it is precisely such texts that also afford readers the opportunity to broaden their understanding of what counts as

[27] James (2015, p. 42).

[28] Offill (2020, pp. 155–156).

[29] James (2015, p. XII).

[30] James (2015, p. XIII).

nature and how people live in very different times and places from their own experience of environmental degradation. "To use Lawrence Buell's succinct phrase, storyworlds can expose us to new environmental imaginations, or conceptions and experiences of a place based upon a subjective understanding of a particular environmental site. They can thus enrich our understanding of how others in different spaces and times perceive and live in their ecological homes."[31]

A similar claim can be made for the benefits of the literary modelling of climate change. Returning to LeMenager's argument that some cli-fi novels explore "the 'everyday Anthropocene,'" in a sense of "the present tense, lived time of the Anthropocene,"[32] we should also note the anthropological dimension implied by her argument. In the final pages of her essay, LeMenager argues that a specific socio-cultural problem for Western, Euro-American societies posed by climate change is learning to live with loss. Based on the memoir by Roy Scranton, LeMenager calls this the "theme of learning to die" in climate fiction novels and suggests that the latter serve a civilizational need in this regard:

> Learning to die, as a theme of cli-fi, is always in part the problem of coming back to oneself and one's defining conditions as problems of recalcitrant matter. 'Letting go' is losing any trappings of social transcendence – whether these are understood as whiteness, wealth, heteronormativity, or national belonging. When learning to die enters novelistic practice, it assumes particularity […] that invites readers' empathy, theory of mind, and, to some extent, identification.[33]

By modelling a world in which climate change has already begun to bring about irreversible change to the modes of living available to humankind, *Weather* does not introduce its readers to a world unlike their own, quite the contrary. But neither is the novel's emphasis on confronting its readers with a harsh reality; rather, it provides the opportunity to reflect on how this change is perceived and thus also narrativized: how Europeans and Euro-Americans make a home in this world, both through attention and inattention.

[31] James (2015, p. XIII).

[32] LeMenager (2017, p. 225).

[33] LeMenager (2017, p. 230).

The value of a transdisciplinary approach that focuses on the modelling capabilities of literary texts is—as Mary S. Morgan might put it—to alert us to the presence of two worlds: the world in the model, created by the reader based on textual clues, and the world to which the model speaks—the reality in which readers find themselves. As I hope to have shown, literary studies, the natural sciences, as well as economics do not only offer compatible theoretical approaches to models and modelling, but also compatible tools of inquiry into the conditions and affordances of this process.

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Literary Models of/for Resilience in Juliana Spahr's *The Transformation* and Kim Stanley Robinson's *The Ministry for the Future*

James Dorson

1 Climate Crisis and Resilience Thinking

Rarely do debates over energy transition occur without resilience being offered as part of the solution. Literally "an act of rebounding or springing back" (*OED*), resilience has obvious appeal in times of climate breakdown. The fragility of the interconnected world system—its supply chains, its food systems, its energy infrastructures—in the face of global warming has helped make the language of resilience ubiquitous across multiple climate actors and institutions, from community-centric organizations like the Post Carbon Institute and the grassroot Transition Network to advocates of a state-centered Green New Deal and international treaties like the Paris Agreement. With roots in complex systems theory and with multidisciplinary appeal across the fields of ecology, engineering, psychology, business administration, disaster management, and organizational theory, resilience names a state of continuous adaptation to changing conditions. Defined by a recent assessment report by the Intergovernmental Panel on Climate Change (IPCC) as "[t]he capacity

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of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure,"[1] resilience has become synonymous with survival in a warming world.

And yet, as a strategy for maintaining the "essential function, identity, and structure" not only of the biosphere, but of the cultural and economic practices that some critics argue have caused the climate crisis in the first place—practices given labels such as 'fossil capital,' 'extractivism,' and 'petroculture'—the concept of resilience, not surprisingly, also has its detractors. From a critical perspective, resilience is at best a technofix for mitigating the severest effects of extreme weather events, not averting them. At worst, it not only deflects efforts to decarbonize, but may even encourage the expansion of fossil infrastructures, as when energy companies or the US Department of Energy pursue resilience strategies against climate threats by diversifying their extractivist repertoire through methods such as fracking and tar sands mining, or by investing in new "carbon bomb" oil and gas projects.[2] Moreover, a number of critics have shown the convergence between resilience theory and neoliberal governance. In contrast to the focus in sustainability debates on conserving the precarious balance of ecosystems, a view of natural equilibrium under threat that famously informed the Club of Rome's report on *The Limits to Growth* (1972), the discourse of resilience regards instability and change as natural conditions of life. As Susie O'Brien writes, "[k]ey to resilience thinking is the challenge that it poses to traditional ideas of a harmonious balance in nature. Rather than persisting in a mythical state of equilibrium until something comes along to shatter it, the natural world is in a perpetual state of flux, in which continuity is maintained by constant adaptation."[3] By making disequilibrium the new normal, resilience thinking shifts the debate from preventing systemic disruption to managing the risks of systemic upheaval. Rather than a liability, system volatility creates opportunities for transformation and growth, a view that critics have argued echoes the Schumpeterian formula of capitalist innovation as "creative destruction." Jeremy Walker and Melinda Cooper, for

[1] ICPP (2022).

[2] The term "carbon bomb" is from Carrington and Taylor's (2022) exposé in *The Guardian*.

[3] O'Brien (2017a, p. 48).

instance, show how the resilience theory pioneered by systems ecologist C. S. Holling in the 1970s shares premises with Friedrich von Hayek's neoliberal economics promoted at the same time, principally the idea that instability is not only necessary but generative of new possibilities. As a form of crisis management, where fully predicting and preventing disruptions to the system is considered not only to be impossible but also undesirable, the ubiquity of resilience thinking today, according to Walker and Cooper, has given rise to a culture of constant emergency preparedness, "a call to permanent adaptability in and through crisis."[4] As such, the term 'resilience' has become indistinguishable from a larger entrepreneurial lexicon of corporate flexibility, economic deregulation, and demands for endless self-reinvention in a capricious labor market.

Despite such troubling associations, critics of resilience have been reluctant to abandon the concept. In fact, the term has flourished in the humanities as well, where it has gained traction through publications such as *Resilience: A Journal of the Environmental Humanities*. Acutely aware of the neoliberal resonances of resilience thinking, the editors of the 2014 inaugural issue of the journal defend their use of "resilience" by referring to its Latin root *resiler*, "meaning 'to draw back, distance oneself from an undertaking' or 'recoil in repugnance'."[5] Offering a creative reinterpretation of the idea of "bouncing back" as "disgust at the way things are, a necessary self-distancing from the normative," the journal intends to "*occupy* resilience", "to take resilience [...] back from the neoliberals."[6] As a burgeoning field, the environmental humanities have largely heeded this call to arms, not abandoning the rhetoric of resilience, but doubling down on what Imre Szeman describes as its radical potential for designating "the willingness to throw oneself into the labor of making a new world, in full awareness of the immense complexity of the social and physical structures already in place."[7]

In what follows, I inquire into this possibility of recuperating resilience for a more radical climate politics through a reading of two contemporary American literary texts, Juliana Spahr's *The Transformation* from 2007 and Kim Stanley Robinson's *The Ministry for the Future* from 2020,

[4] Walker and Cooper (2011, p. 154).

[5] LeMenager and Foote (2014).

[6] LeMenager and Foote (2014); original italics.

[7] Szeman (2014).

which each in their own way takes up "the labor of making a new world." Both texts respond to global warming by recoiling from our present path toward disaster, but they do so in aesthetically as well as ideologically very different ways. I argue that while the experimental form of Spahr's narrative mimics the entanglements of socio-ecological life, Robinson's novel gives prevalence to historical-political imagination for remaking the future. While both texts could be called 'resilience stories,'[8] Spahr's narrative performs resilience through its nonlinear form, whereas Robinson's novel shapes events into a blueprint for a more resilient climate future. As such, they each provide a different model for thinking and acting in response to anthropogenic climate change. Before turning to the readings, however, we should first consider what it means to think of these literary texts as 'models.'

2 Climate Fiction as Literary Modelling

I use the term 'model' deliberately in the sense of a representation of a formalized pattern of interaction whose function is at once heuristic, aesthetic, and instrumental. While the impact of literature on society may be incalculable, the recent surge in cli-fi should be recognized as a coproducer in the general climate knowledge of society. Like scientific models, fiction about climate change helps us understand the consequences of global warming. However, the knowledge provided by literary climate models should be distinguished from that produced by scientific models not only in terms of their explicit status as fiction, but by the particular kind of knowledge that storytelling involves. It is often observed that unlike weather, which is experienced directly, climate is an abstraction (the average of past weather) that we only know through our models of it.[9] But if scientific models allow us to grasp climate conceptually, they do not help us experience it intimately. While abstraction is necessary for *knowing* climate, it also prevents us from *feeling* climate, such as feeling the urgency of taking action when it changes. The exasperation of scientists in the face of climate inaction testifies to the failure of their models, not because they are not accurate enough, but because

[8] The term is O'Brien's (2017a).

[9] Cf. Edwards (2010, p. Xiv): "Everything we know about the world's climate—past, present, and future—we know through models."

abstractions by definition—from the Latin *abstrahere*, literally to 'drag away'—are detached from lived experience. Although works of fiction are also abstractions in the sense of abstracting thoughts and feelings into narrative patterns, storytelling not only drags us away from lived experience, it also drags us *into* an imagined world. When we read a novel, we experience a model world vicariously through its characters. Fiction thus offers a unique way of entering into and inhabiting a model. In other words, literature provides intimate experiences of models, or what we might call *embodied abstraction*. Intimacy means knowing something from the inside.[10] Intimate or embodied abstraction, then, refers to the experience of a model from within mediated by the aesthetic encounter. Of course, because all aesthetic experience is by definition mediated experience, which is to say experience at a distance, literary models only allow us to live partially inside of them: the immediacy of experiencing a literary model is qualified by the awareness of the medium providing it. If this metatextual dimension of literary modelling diminishes the sense of urgency gained from living inside a climate model, it compensates for the loss of immediacy by providing insight into the activity of modelling itself. Regardless of how one weighs these affordances of literary modelling, thinking about climate novels as embodied abstractions illuminates their particular contribution to climate knowledge, the way in which they allow us to know the abstractions of climate intimately.

Reading cli-fi as literary models is also illuminating in another way that both clarifies the stakes of resilience in climate politics and the approach to resilience in the two texts in question here. Drawing on the familiar distinction in model studies between models as representations of something already existing and models as designs for realizing something as yet nonexistent, I read Spahr's narrative as a model *of* resilience and Robinson's novel as a model *for* resilience.[11] In other words, while Spahr seeks to reflect entangled relations in aesthetic form—that is, to be a realistic model of interconnected social and natural processes—Robinson, in contrast, does not seek to represent things as they are, but to create a speculative design for what they could be. Similarly, I argue that the resilience debate is fraught by a blurring of two distinct

[10] The Latin *intimāre* means 'to make known,' *intus* means 'within' (OED).

[11] Geertz (2000) originally made the distinction between a "model of 'reality'" and a "model for 'reality'" (p. 93). McCarty (2004) later expanded on the distinction.

functions of resilience. On the one hand, resilience designates a method for apprehending nonlinear (which is to say irreversible) and emergent (spontaneous) instead of mechanical (predictable) processes. While this method gained popularity with the rise of complexity theory in the 1970s, it has affinities with older Romantic approaches like *Naturphilosophie* and Bergsonism as well as with more recent strains of neovitalism and New Materialism today. As a method, then, resilience names a critical epistemology that challenges the mechanistic underpinnings of modern institutionalized knowledge. Like models *of* something, this kind of resilience is scientific in the sense of trying to understand how the world works, even as it questions the very premises of modern science. On the other hand, resilience also designates a political design for a more sustainable future. In this sense, resilience is not a method but a goal; not a reflection of the world, but a condition of collective thriving to be aspired toward. In short, a model *for* something.

This is not to say that the distinction between models *of* and models *for* is not tenuous. Willard McCarty, who popularized the distinction, notes how the difference easily collapses, as the description of a structure, for instance of grammar, "may function prescriptively, as a model *for* correct usage," and "the architectural plan," for instance, "descriptively, as a model *of* an existing style."[12] In this sense, Spahr's resilience story could be read not just as a representation of entangled processes, but as a recipe for reassembling social relations in terms of their networked interdependence. Resilience as a method also implies a politics. Proponents for understanding natural and social processes in ecological terms as a web of interdependent processes encourage us to rethink political agency to better reflect the world's irreducible complexity.[13] Brad Evans and Julian Reid describe this tendency to model politics on resilience thinking as the "ecologization of the political."[14] A model *of* ecology becomes a model *for* politics. While the history of grounding political thought in changing conceptions of nature is long and intricate, the most immediate problem with rethinking political agency in ecological terms is that ecology entails a 'flat' ontology while politics deals with power relations that almost by

[12] McCarty (2004, p. 255); original italics.

[13] The list is long, but notable figures include Bruno Latour, Jane Bennett, Karen Barad, and Anna Lowenhaupt Tsing.

[14] Evans and Reid (2014, p. 162).

definition are hierarchical. Although a descriptive model "may function prescriptively," as McCarty writes, we should stress that the modal verb 'may' only denotes a likelihood.[15] The difference between a descriptive and a prescriptive model does not reside in the model itself, but depends on its institutional context (i.e., a description of a grammatical structure is only prescriptive insofar as it is disseminated through learning institutions and enforced by cultural practices). Insisting on the 'may' is to call attention to actors and interests. The political ambiguity of resilience discourse, what makes it difficult to separate 'good' resilience (a design for collective thriving) from 'bad' resilience (neoliberal crisis management), lies precisely in the slippage between a model *of* resilience and a model *for* resilience. Taking resilience 'back from the neoliberals,' then, requires more than militant rhetoric. It requires that we distinguish between the two functions of resilience, recognizing that resilience as a method for apprehending entangled processes does not automatically translate into a politics for designing a more resilient world, and that in some cases, the two may even work at cross purposes. The point of what follows in juxtaposing the very different models of resilience in Spahr's and Robinson's stories is to help us better distinguish between the two kinds of resilience, and to show why collapsing them into one another is detrimental to the shared project of making the planet livable in the future.

3 Juliana Spahr's Poetics of Entanglement

Juliana Spahr's extended autofictional prose poem[16] *The Transformation* is the story of three characters living in Hawaii and New York City between 1997 and the aftermath of 9/11. The experimental premise of the text is to narrate the lives of three unnamed and ungendered characters, referring to them exclusively with the third-person pronoun 'they.' As the title suggests, channeling Ovid's *Metamorphoses*, the narrative is about coming to terms with change of all kinds, from the shifting interpersonal relationships of the three protagonists to past and ongoing political and ecological disturbances, including "environmental collapse in

[15] McCarty (2004, p. 255).

[16] *The Transformation* is generically ambiguous and falls somewhere in between a long prose poem (214 pages!), an essay, a novel, and a memoir. The term 'autofiction' names *The Transformation*'s blend of fiction and nonfiction. In the afterword, Spahr describes it as "a barely truthful story of the years 1997–2001" (2007, p. 217).

all sorts of different areas."[17] Even before the story begins, the theme of transformation is evoked by the book's cover, which features a picture of a flower of the *Leucaena leucocephala*, an invasive plant species in Hawaii locally called *koa haole* ('haole' meaning foreigner), and known for being "adaptable, extremely fast-growing, thicket-forming, and difficult to eradicate" ("Leucaena"). While invasive species usually serve as warnings against disturbing the natural balance of an ecosystem, the plant is given pride of place on the cover not as a symbol of disruption, but of ecological adaptation and change. In other words, the *koa haole* functions as what Spahr elsewhere, in reference to another invasive plant species (the scotch broom), calls a "metaphor of resilience" ("Will There Be Singing"). That it spreads like a weed and transforms its habitat are not taken as adverse traits, but make the plant a positive model for survival in the irreversibly altered world of the Anthropocene, where regressive ideas like harmony and purity are replaced by what the narrator calls "new patterns of relating."[18]

Adjusting to evolving patterns is crucial for life in a world of political and ecological upheaval. That *The Transformation*'s hybrid protagonist embodies such "new patterns of relating" makes it a model subject for a changing world, where climate change in the text's self-described "holistic perspective" is but one of many interconnected concerns,[19] including colonialism, nationalism, sexual politics, species extinction, tourism, educational institutions, queer theory, the politics of language and art, and the war on terror. While such lists disperse the focus of the narrative, the recurrent return to what it describes as the "story of coming to an identity" of its three characters holds the narrative together.[20] 'Identity' here is not understood in the common sense of the word as "quality or condition of being the same" (*OED*), but defined by the shifting relationships that constitute the protagonists as a unit along with their relationship to the ever-changing environment. "They all had their own interests and these interests intersected and overlapped with other interests and they all felt they could be shaped by each other into some new

[17] Spahr (2007, p. 199).

[18] Spahr (2007, p. 21).

[19] Spahr (2007, p. 29).

[20] Spahr (2007, p. 22).

thing,"[21] as the narrator explains. The story's theme of ceaseless transformation, then, is not only symbolized by the invasive *koa haole*, but also by the kaleidoscopic identity of its collective subject, which, in turn, describes itself "through metaphors of invasive alien plants."[22]

This intertwining of natural and personal history is elaborated throughout *The Transformation*. The assembled self in the story is at once a model of complex entanglement and is itself modeled on the natural ecology in which it is enmeshed: "They lived among plants that grew into each other in various and unique ways."[23] The book opens with the lines: "Flora and fauna grow next to and around each other without names. Humans add the annotation. They catalogue the flora and fauna, divide them up, chart their connections and variations, eventually name them, and as they do this they read into them their own stories."[24] As a case in point, the narrator tells the story of another invasive species, the maracujá vine, which was first renamed the passionflower by Christian missionaries for its supposed resemblance to the crucifixion story, then became known in Hawaii as the *huehue haole*. Like these alien species, the characters in the book are a 'they' in the sense of being 'haole' (foreigners) on the island as well as having names and stories imposed upon them, like "a gender that was decided for them without their consent."[25] As the narrator explains, accepting their new identity means coming to terms with how "they were a they in the cruel inquisitive sense, in the sense of not being a part of us or we."[26] *The Transformation* thus describes itself as a "story about realizing that they cannot shrug off this they [...]. A story of how much this realization of being a they changed them and a story of embracing this change."[27] Such compulsive self-descriptions of the narrative's 'they' are typical of the genre of autofiction, where reflections on identity-formation function as part of the subject's self-composition. By referring to itself in the third person rather than in the first-person plural, the hybrid subject in Spahr's extended prose poem

[21] Spahr (2007, p. 15).
[22] Spahr (2007, p. 110).
[23] Spahr (2007, p. 31).
[24] Spahr (2007, p. 13).
[25] Spahr (2007, p. 22).
[26] Spahr (2007, p. 21).
[27] Spahr (2007, p. 21).

seeks to avoid basing its identity on exclusion and instead to embrace difference (as if to say, 'they are we'). But claiming the pronoun 'they' is also a self-distancing strategy: the narrating subject others itself in order to perceive itself *as a self*. In other words, the narrator models itself through its detached self-description, which in turn becomes part of the self it models. Constantly recomposing itself by reflexively describing its changing relations with itself and its environment, *The Transformation*'s 'they' constitutes itself as a model of proliferating difference.

Embodying difference and embracing change, the collective protagonist repeatedly finds a model of entangled becoming in the changing flora and fauna of Hawaii. Natural similes and metaphors for describing the 'they' abound. One passage describes them as "trying to be like the finches who grew new and different beaks in reaction to the wide variety of microclimates on the island."[28] Shortly afterwards, in one of many long enumerations, *The Transformation* describes itself as a "story of how they felt as if they were milkweed. As if there was an impingement, an attachment that grew out of them that scattered bits of them outwards into the wind and then there they were fluttering, moving, and scattering."[29] The passage continues:

> A story of how they were they as if they were a root and they could each cut from the root a sucker and then pull this sucker from the ground and transplant it in a dark soil so that a new shoot would grow. A story of how they were a spawning mullet-they, traveling through tidal zones searching for food, who guzzles up a seed-they which lodges in the mullet-they's stomach. And then a story of how they were a sooty storm petrel-they who eats the mullet-they and thus the seed-they and then passes the seed-they as excreta into a muddy bank-they in another part of the ocean-they.[30]

This radically ecological version of the self as a food web, existing in a cyclical state of mutual transformation, is further conveyed by what critics describe as Spahr's "ecopoetics."[31] In contrast to more mainstream realist novels that also thematize adaptation and resilience, such as Richard Powers's Pulitzer Prize-winning *The Overstory* (2018), Spahr's resilience

[28] Spahr (2007, p. 21).

[29] Spahr (2007, p. 22).

[30] Spahr (2007, pp. 22–23).

[31] Cf. Chisholm (2014).

story performs what it preaches by refashioning language itself into a model of complex entanglement. Self-consciously inspired by experimental modernist poetry "that used fragmentation, quotation, disruption, disjunction, agrammatical syntax and so on,"[32] the story repurposes Gertrude Stein's famous line "the difference is spreading" for a vision of sprawling socio-ecological interdependence and adaptation.[33] Consisting largely of a series of catalogues that resist hierarchical organization, but instead are related metonymically as sentences accrete through a parataxical structure of repetition and variation, *The Transformation* is an aesthetic experiment in how to represent entanglement in the overwhelmingly interconnected world of the Anthropocene. As the narrator explains: "they needed to think about how things were connected."[34]

This urgency of grasping connections leads not only to the narrative's grammatical realization of entanglement, but also to what Sianne Ngai describes as the "compulsive proliferation of reticular metaphors" in the text.[35] While Ngai shows how Spahr's story shares a connectionist approach with Latourian actor-network theory, she also argues that it goes beyond ANT by its aesthetic totalization of networks, which by definition are expansive and untotalizable, "through symbolization or metaphor."[36] Just as *The Transformation* continually models its collective subject as it reflects on its own self-composition, it also abstracts from the connections it makes by seeking to grasp them on a metalevel through metaphor. In other words, the text functions on two levels. On the one hand, through its autofictionality and ecopoetics, it works as a kind of radical realism that rejects conventional grammatical and narrative structures in favor of a closer aesthetic approximation to what it perceives as the actual entanglements of life.[37] In this sense, the text functions as a

[32] Spahr (2007, p. 61).

[33] Spahr (2007, p. 11). Spahr wrote her dissertation on Stein and avant-garde poetry at SUNY Buffalo. She has also written the afterword to the centennial edition of Stein's *Tender Buttons* (1914).

[34] Spahr (2007, p. 147).

[35] Ngai (2012, p. 379).

[36] Ngai (2012, p. 379).

[37] Autofiction's mix of fiction and nonfiction typically rejects emplotment in favor of a more fragmented style considered to better reflect lived experience. Although David Shields prefers the term "lyrical essay", his *Reality Hunger: A Manifesto* (2010) is the most influential argument for the hybrid genre's reflection of real life.

description of a structure in the world—that is, as an aesthetic model *of* real-world processes. On the other hand, by continually reflecting on the attempts of its characters to identify connections as well as trying out different metaphors for best describing them, *The Transformation* not only enacts entanglement, but reflexively models it in the process of performing it. This second function is not descriptive; it abstracts from description to create a conceptual tool for grasping relations. The function of metaphor here, then, is not only totalizing in the sense of offering a comprehensive model of networks. Metaphorical totalization also has potential prescriptive power by providing a map of coordinates that not only allows us to know things, but to act on them. In other words, through the instrument of metaphor, the interpretation of the world can become a design for remaking it.[38]

This power of metaphor is what makes the search for the right one in *The Transformation* so "compulsive." Failing to grasp the shifting web of relations they are enmeshed in by only "chart[ing] their connections," the hybrid protagonist realizes that "they had to stop making maps that were limited by their vertical or horizontal axes. Or charts that started with two options and then spread from there. They need[ed] a new sort of conceptualization that allowed for more going astray than any map they had ever seen."[39] While mapping is a spatial metaphor, the perpetual flux and reflux that *The Transformation* thematizes requires a conceptual metaphor that apprehends nonlinear processes and feedback systems. The metaphor that the story ultimately settles on for this "new sort of conceptualization" is that of blood circulation. When blood circulation was first discovered in the seventeenth century, it was conceived as a centralized, mechanical system modeled after hydraulics.[40] But Spahr revamps the metaphor by making the body monstrous. "They needed to become monstrous in their heart," the narrator says, "they needed at least two hearts in their body, maybe more."[41] The last four pages of the narrative consist of a list of

[38] I draw here on Gareth Morgan's insight in his classic *Images of Organization* (1986) that "the way we 'read' organizations influences how we produce them" (p. 344).

[39] Spahr (2007, p. 211).

[40] Cf. Canguilhem (2000, p. 77).

[41] Spahr (2007, p. 209).

all the things and connections that the collective protagonist had discovered up until then, now figuratively pumped through the veins of their nonnormative body:

> So they began to pump through these new hearts without thought or discrimination or rationality about their limits all they could in the hope that it would eventually reach the palm of their writing hand. […] [T]hrough the pulmonary veins they pumped long sentences and lists of connections […]. Pumped with the left atriums attempts to map things out through writing so as to understand them. Pumped through the mitral valves the words of others. Pumped with the left ventricles the admission that they didn't have any real answers, only the hope that if they kept writing others might point them to answers. Pumped through the aortic valves changes. With grief, with worry, with desire, with attachment, with anything and everything, they began listing, inventorying, recognizing in the hope that a catalogue of vulnerability could begin the process of claiming their being human […].[42]

The process of writing becomes a form of embodied circulation, reflexively incorporating the text itself into the connections it traces. The circulatory system of the multi-hearted, which is to say decentralized and complexified, body is a metaphor for the "new sort of conceptualization" that *The Transformation* models. It is an apt metaphor for embodied knowledge: not the "blind sight" of objectivity, but "situated knowledge" from a particular standpoint.[43] It also turns out to be a perfect metaphor for illustrating both the nonlinear flow of networks, a conceptualization that allows for "going astray," at the same time as it contains the open-ended flow conceptually through the metaphor of the body. Replacing progress with process, linearity with looping, and closure with cataloguing, the biological metaphor of fluids circulating through the monstrous body gives aesthetic shape to a model for more resilient thinking and acting in precarious times.

If this model *for* resilience has little prescriptive power in the literary context of Spahr's experimental prose poem, it nevertheless embodies a kind of critical climate approach in the humanities with greater normative pull. This is exemplified by what Kathryn Yusoff and Jennifer Gabrys

[42] Spahr (2007, pp. 211, 213–214).

[43] See Daston and Galison (2007, pp. 17–19) on objectivity as "blind sight." On "situated knowledge," see Haraway (1988).

refer to as a "relational approach to climate change,"[44] or by what Solvejg Nitzke and Eva Horn call "a cultural approach to climate."[45] This approach pushes back against the scientific abstraction of climate as average weather in favor of a more situated understanding of climate as inextricable from cultural practices. As Yusoff and Gabrys argue, this cultural or relational approach helps us "see continuance and shifts, thresholds and various open-ended forms of becoming that are enabled and perceived through an imaginative reckoning with the world of climate."[46] Distinguishing their approach from scientific modelling, they take it to be "in distinct contrast to the causal models of climate-change science that imagine humans as either drivers of climate change or recipients of its effects, rather than as a heterogeneous and differentiated social body with distinct desires, constraints, and imaginations."[47] Recasting "climate change as something that is not 'out there'," but as "something 'in here,' entangled in contemporary practices and future possibilities," they argue that such a culturally situated conception of climate is "paramount to building resilience and adaptive capacity."[48]

By not just taking embodied cultural knowledge as a complement to scientific climate knowledge but as a countermodel to it, this approach to climate is not only indicative of a longstanding preference for cultural particularity over scientific abstraction in the humanities, but also of how the concept of entanglement is transformed from being a description *of* socio-ecological processes to being a model *for* political agency in precarious times. In short, the relational theory of climate does the work that Spahr's literary text alone cannot: it translates a poetics of entanglement into a politics of entanglement.

[44] Yusoff and Gabrys (2011, p. 530).

[45] Horn and Nitzke (2020, p. 1). The 'relational' approach is further elaborated in Yusoff (2018). Horn and Nitzke draw on Mike Hulme's critique of objective climate knowledge in, for instance, *Weathered: Cultures of Climate* (2017).

[46] Yusoff and Gabrys (2011, p. 530).

[47] Yusoff and Gabrys (2011, p. 517).

[48] Yusoff and Gabrys (2011, p. 529).

4 Kim Stanley Robinson's Transition Fiction

Kim Stanley Robinson's acclaimed 106-chapter sci-fi novel *The Ministry for the Future* tells a very different kind of resilience story. The novel opens by raising the stakes of climate change: in 2025, a lethal heat-wave sweeps over Northern India killing 20 million people in a matter of days. This extreme weather event has a mobilizing effect, catalyzing a chain of geopolitical actions that ultimately comprise a best-case scenario for energy transition to renewables. The novel is "pragmatopian" in the sense of being set in the near future and combining a utopian vision of planetary decarbonization with a realistic roadmap for achieving it.[49] Like its polyphonic structure comprised of multiple voices and styles, the novel does not imagine one single exit strategy from fossil fuels, but a patchwork of initiatives—what it calls a "cobbling together from less-than-satisfactory-parts"[50]—ranging from permaculture to geoengineering and from ecoterrorism to a "Climate Coalition of Central Banks" that issues a carbon currency to provide quantitative easing out of the fossil economy.[51] These initiatives are from below as well as from above, represented contrapuntally in the novel as it alternates between institutional and everyday perspectives. *The Ministry for the Future* is a transitional novel—or what Gesa Mackenthun calls a "transition story"[52]—in that it imagines the necessary steps between two states—one being a fossil-fueled capitalist economy, the other a post-capitalist green future—without making any leaps in history.[53] Put briefly, it stages what it calls (borrowing

[49] The term "pragmatopia" is commonly used to describe Charlotte Perkins Gilman's feminist novels during the 1910s. Defined as a "realizable, possible, or achievable utopia" (Kessler 1955, p. 7), the term is well-suited to describe *The Ministry for the Future* as well.

[50] Robinson (2020, p. 505).

[51] Robinson (2020, p. 342).

[52] Mackenthun (2021, p. 1).

[53] In an interview about the novel, Robinson explicitly claims that he wants to bridge what he calls the "Great Trench" that typically divides present society from the utopia: "Famously, from Thomas More (*Utopia*) on, there's been a gap in the history—the utopia is separated by space or time, by a disjunction. They call it the Great Trench. In *Utopia*, they dug a great trench across the peninsula so that their peninsula became an island. And the Great Trench is endemic in utopian literature. There's almost always a break that allows the utopian society to be implemented and to run successfully. I've never liked that because one connotation of the word 'utopian' is unreality, in the sense that it's 'never going to happen.' So we have to fill in this trench" (O'Keefe 2020).

from John Maynard Keynes) a "revolution without a revolution"[54]—or, what the Left would call the "transitional demands" that lead beyond capitalism.

If one of the hurdles to mobilizing a mass movement against climate catastrophe is the abstraction of climate modelling, Robinson's novel provides a visceral experience of a climate future in which "[t]he world is careening toward disaster."[55] Writing about the catastrophic imagination, Eva Horn argues that "[future] fictions are a way of giving tangible shape to the intangible. They create something that can be narrated, represented, and experienced—a concrete and model situation in which the future can be grasped and thus emotionally processed."[56] Horn reads future scenarios in film and literature as "epistemic tools to understand and discuss potential futures,"[57] and contrasts such narrative scenarios with scientific modelling: "Their epistemological advantage over abstract models of the future lies in their ability to go into detail, offering a thick description of the future that is meant to analyze and understand the complexity of its often simultaneous and interrelated aspects."[58] While Horn's reading of cli-fi as "giving tangible shape to the intangible" aligns with what I call the embodied abstractions of literary modelling she reads scientific and cultural modelling as epistemological rivals. I take the relationship to be more parasitic: literary modelling feeds on the abstractions of science. Imagination is not an alternative to scientific models, but a way of building upon and extending them, taking over where science leaves off. This relationship is implied by the very name of Robinson's genre of choice: science fiction. True to the genre, *The Ministry for the Future* extrapolates from the present, speculatively extending climate models into a more intimate, and therefore also more terrifying, experience of futurity. In fact, Robinson's fiction openly embraces the pedagogical function of abstraction, often exposing his work to charges of being clumsy or didactic. As one chapter explains, with a nod to William James, the role of science is "to invent, improve, and put to use an ideology that explains in a coherent and useful way as much of the blooming buzzing inrush

[54] Robinson (2020, p. 320).

[55] Robinson (2020, p. 109).

[56] Horn (2018, p. 15).

[57] Horn (2018, p. 10).

[58] Horn (2018, p. 18).

of the world as possible. What one would hope for in an ideology is clarity and explanatory breadth, and power."[59] From the unsubtle climate disaster with which *The Ministry for the Future* opens to the explicit theorizing and metatextual comments of its multiple narrators and characters, the novel similarly illustrates the instrumentalization of literature for didactic purposes. Some chapters are set up as Socratic dialogues, seeking to engage readers directly in Brechtian-style political education. Others read like advice manuals for collective organizing. Such 'committed' uses of literature reflect back on its function. For Robinson, literature does not stand opposed to or apart from science or politics by its irreducible singularity, but is one tool among many for shaping perceptions.

If the confusion of science and ideology in the quote above resonates with advocates for embodied versus abstract knowledge, who argue along Foucauldian lines that power and knowledge are inseparable, Robinson's novel regards power and knowledge as inseparable in a different way. Whereas proponents of embodied knowledge take the modern 'power/knowledge' complex as a reason for challenging modern science in favor of more culturally situated practices of knowing, *The Ministry for the Future* skips over epistemological revisionism and aims directly at political change. The novel plainly distinguishes between means and ends. "Economics was a tool for optimizing actions to reach goals," one chapter explains, "the goals could be adjusted, and should be." The point is not to reject economic methods, but "re-orienting economics' ultimate goals to human and biosphere welfare." [60] In short, don't throw out the baby with the bathwater. What the novel repeatedly tells us is that we should not discard our available tools, but make better use of them. "Do you ask your calculator what to do with your life?" another chapter asks. "No. You have to figure that out for yourself," it answers.[61]

The Ministry for the Future's determined focus on the political prize of a decarbonized future shifts the debate over resilience from methods to goals. The program is in the preposition of its title: the ministry *for* the future. The title refers to the novel's primary actor: an international agency established after the 2025 Paris Agreement to protect the rights

[59] Robinson (2020, p. 41). The reference is to James's oft-cited description of infantile experience as a "blooming, buzzing confusion" in *The Principles of Psychology* (1890).

[60] Robinson (2020, p. 366).

[61] Robinson (2020, p. 166).

of "all living creatures present and future,"[62] and with the actual legal, economic, and political weight to accomplish its mission, if not without challenges and setbacks that reflect the protracted struggle of real-world politics. As a large-scale, state-sponsored, hierarchically organized institution with multiple subdivisions, the Ministry for the Future is hardly a model of resilient organization. Nor is the somewhat clunky organization of the novel itself, written in Robinson's typically heavy-handed style that gives plot precedence over polish. Yet if neither the ministry in the novel nor the novel itself are themselves resilient designs, they are nevertheless designs *for* resilience in the sense of laying out a program for collective thriving. That the global ministry is the primary driver of this program does not exclude more bioregional approaches. Chapter 85 is composed of a long list of local environmental NGOs enthusiastically presenting themselves to the reader. The novel also embraces the idea of interdependence: "the world as a commons, one ecosphere, one planet, a living thing they were all part of,"[63] as one character puts it. But if interdependence is presented as a fact of life, it is not one to be mirrored or modeled.

This is not to say that political change in *The Ministry for the Future* does not require a method, only that ecomimesis is not it. A model *for* resilience, the novel suggests, requires a different narrative temporality than the circular time of entanglement explored in *The Transformation*. While Spahr's means-oriented focus on perpetual transformation privileges emergent processes, Robinson's ends-oriented focus on transition revives an older model of temporality: the historical narrative. Events in the novel may appear to be driven by chance, but they do not simply happen: they are *made to happen* by actors. Events are filled with intentionality, replacing what Walter Benjamin referred to as modernity's "homogeneous, empty time"[64] with a historiographical conception of time as inherently meaningful. Everything is not just connected, but *causally* connected. Nor is this simply extrapolation from the present to the future. Instead of narrating the future from the present, the present is narrated from the future.

[62] Robinson (2020, p. 16).

[63] Robinson (2020, p. 510).

[64] Benjamin (1968, p. 261).

A historical narrative should be distinguished from the algorithmic logic of scenario thinking that Horn attributes to speculative fiction. Scenarios narrate a hypothetical sequence of events that follow each other mechanically: if A happens, then B will happen, followed by C, D, E, F, and so on. Because scenario writing, as Horn notes, "sees the present as a branching point of multiple futures,"[65] the genre per definition pluralizes the future.[66] Once a path is chosen, a necessary chain of events follow, but the initial paths to choose from are infinite. In contrast to the conditional 'if–then' structure of scenarios, the causal principle that structures Robinson's novel is of the type that Hayden White calls "narratological causality," which he defines as

> a mode of causality that consists in a seizing of a past by consciousness in such a way as to make of the present a fulfillment of the former's promise rather than merely an effect of some prior (mechanistic, expressive, or structural) cause. The seizure by consciousness of a past in such a way as to define the present as a fulfillment rather than as an effect is precisely what is represented in a narrativization of a sequence of historical events so as to reveal everything early in it as a prefiguration of a project to be realized in some future.[67]

Rather than multiplying the future, as scenarios do, narratological causality singularizes it. *The Ministry for the Future* implicitly reflects on this difference between scenario thinking and its own narrative structure in an exchange between the novel's two most prominent characters, Mary Murphy, who heads the titular ministry, and Frank May, a traumatized survivor of the deadly heatwave. In response to Mary's prevaricating reply to what we can know about climate change that "[w]e can only model scenarios", Frank angrily replies: "You know. *You know the future*."[68] But the novel's singularization of futurity primarily operates through its temporal organization. In *Archaeologies of the Future*, Fredric Jameson—to which *The Ministry for the Future* is dedicated—compares utopian

[65] Horn (2018, p. 180).

[66] In his account of futurology that popularized scenario thinking in the 1960s, Williams (2016, p. 522), notes how the genre of scenario writing always stresses conditionality: something "might be," "may emerge," "could follow."

[67] White (1987, p. 149).

[68] Robinson (2020, p. 96), original italics.

fiction to "the radical simplifications of the maker of models."[69] He describes the proleptic structure of sci-fi, its characteristic future-past tense, as "transforming our own present into the determinate past of something yet to come."[70] Narrativizing the future as already past, *The Ministry for the Future* is less concerned with modelling a particular future scenario than with modelling a particular way of thinking. This is not merely cli-fi as a thought experiment, but a way of countering the demobilizing "doom gloom" that casts a pall over much of the genre. As Jameson writes elsewhere, "a genuine historicity can be detected by its capacity to energize collective action, and […] its absence is betrayed by apathy and cynicism, paralysis and depression."[71]

Robinson notes in an interview how sci-fi, "being set in the future, has a historical relationship that runs back to the present moment," in contrast to a genre like fantasy, which "doesn't run back to our present in a causal chain" (Plotz). As a historical narrative of the future, *The Ministry for the Future* not only models energy transition, but *theorizes transition itself through its form*. While Spahr's poetics of entanglement breaks up the causal structure of narrative into a series of interconnected fragments metaphorically reassembled in the monstrous body, Robinson's novel arranges particular events into a sweeping narrative of causal progression toward a decarbonized future. This is neither biological time, where everything flows, nor the algorithmic time of scenario thinking, where events have no inner necessity, but historiographical time—a prerogative not of nature or machines, but of the human imagination.

5 Conclusion

Early on in Robinson's novel, as the Ministry for the Future is weighing its options, one member of its executive group voices a harsh critique of resilience thinking:

> Some things we can mitigate, some we can't. Some things we can adapt to, others we can't. Also, we can't adapt to some things we are now failing to mitigate. Need to clarify which is which. Mainly need to tell adaptation

[69] Jameson (2007, p. 11).

[70] Jameson (2007, p. 288).

[71] Jameson (2015, p. 119).

> advocates they're full of shit. Bunch of economists, humanities professors, they have no idea what talking about. Adaptation just a fantasy.[72]

The comment that there are some things we cannot adapt to diagnoses a blind spot in resilience thinking: that "resilience can be and has been eroded, and that the self-repairing capacity of eco-systems should no longer be taken for granted."[73] That this critique in the novel is voiced by an ecologist, who blames the disciplines of economics and the humanities for muddling the stakes, suggests how ecological models have been adopted by other fields and misused, making resilience only the latest concept developed in the life sciences to be applied to culture and society. The extreme weather event that *The Ministry for the Future* opens with demonstrates the limits of a system's capacity for 'bouncing back.' Robinson's near-future world is not simply in a state of flux, but on the brink of collapse. Critics of network theory point out that seeing connections everywhere blinds us to *dis*connection, either to what is not part of a system or the places in a system where connections fail. As Ngai notes, a perspective that assumes that everything is connected entails an "exclusion of exclusion."[74] And what is categorically excluded from resilience thinking is the possibility of change that cannot be adapted to.

This means that some forms of change need to be prevented. Here the privileging of entanglement as a methodology encounters another limit. Horn writes that "[t]o take specific measures of prevention, we not only need a clearer scenario but also a designated agency to hold responsible for the looming danger."[75] Gesturing at one point toward such accountability in *The Transformation*, the narrator observes "how the weather was changing because of the devotion the government that currently occupied the continent had to oil."[76] Yet the text's causal attribution of climate change to the burning of fossil fuels is dispersed in the web of connections that it traces. In the narrative's refusal of semantic hierarchies, oil becomes simply another item on a long list of interdependent causes and effects. Yusoff and Gabrys' relational approach that refuses to privilege "humans

[72] Robinson (2020, pp. 54–55).

[73] Folke quoted in O'Brien (2017a, p. 288).

[74] Ngai (2012, p. 384).

[75] Horn (2018, p. 231).

[76] Spahr (2007, p. 197).

as either drivers of climate change or recipients of its effects" echoes the diffusion of agency across multiple human as well as nonhuman actors that various theories promote, most notably ANT but also related posthumanist and New Materialist theories. But several critics recently have voiced skepticism against the attenuation of human agency at the very moment when coordinated action on an unprecedented scale is needed for addressing the climate crisis. As Andreas Malm, for instance, puts it, "any call for a more environmentally beneficial practice by necessity puts humans front and center."[77]

The literary models that Spahr and Robinson offer engage with these debates both directly in their metatheoretical self-reflections and indirectly through their form. Rather than a prediction of the future, Robinson has described sci-fi as "more of a modeling exercise, or a way of thinking."[78] In different but similar terms, *The Transformation* says that its characters "needed poetry because it reshaped their mind, because it resorted things in different, sometimes beautiful, sometimes troubling patterns."[79] Both writers take literature as a means for reshaping not just what we think, but how we think. They each model patterns of actions and events as a conceptual instrument for helping us imagine climate change and our response to it. Only the principle of interaction in their stories differs. Spahr's narrative accommodates personal and political events to an ecological model of entanglement figurately represented by the monstrous body that circulates everything within it. While the body is an apt metaphor for embodied knowledge that counters scientific abstraction, the metaphor itself abstracts entangled processes by recomposing them into a conceptual model for all interaction—in the novel and beyond. In contrast, *The Ministry for the Future* has no qualms about abstraction. It suggests that we redesign rather than reject models as epistemological tools, but also crucially embraces historical abstraction in its form by turning the present into the past of an already fulfilled future. Its vision of future resilience ultimately does not depend on humans thinking more ecologically, but on us thinking more historically.

77 Malm (2018, p. 116).

78 Plotz (2020).

79 Spahr (2007, p. 115).

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Modelling the Future with Miniature Worlds

Øyvind Eide

1 Introduction

In 1996, Keith H. Basso published his seminal book *Wisdom Sits in Places: Landscape and Language Among the Western Apache*. Here he explains how wisdom for the West Apaches is seen as a type of foresight, a heightened mental capacity facilitating the avoiding of harmful events by detecting non-apparent threatening circumstances. Wisdom is produced and sustained by smoothness, resilience, and steadiness of mind, abilities that are not given at birth, but must be consciously cultivated by acquiring right knowledge and apply it critically to the workings of the mind.[1] In this article, it will be suggested how miniature worlds as modelling and simulation tools can be used to further a similar type of wisdom and how this can be connected to the general concept of modelling literacy, which is now being recognised as one of the core literacies for the twenty-first century.

[1] Basso (1996, p. 130).

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Defining models and modelling across disciplines and areas of research and practice is in itself a complex task. The basis for the approach behind this article is the relationship between modelling and the future in the context of the humanities and of cultural heritage. The emphasis in understanding models here is on the activity of modelling. We are less focused on the question what a model *is* than rather on the problem what we can achieve by modelling and how this is achieved. We focus on the modelling activity of which the model (as an object or representation) is an integral part—together with the actor(s) running the modelling process, the model target that contains the objects and procedures that are being modelled, and the aim of the modelling process at large.[2]

The ontology of the models themselves is mainly interesting with regard to their form and to the way how the form influences their possible uses in modelling. Hence, we see *models as a type of media products*.[3] "Every medium has the capacity of mediating only certain aspects of the total reality",[4] thus media possess a set of affordances making some uses possible, or at least easier, at the expense of others. A media product in this sense is everything that can be used for communication, from a wave of the hand to call for a waiter's attention to a poem, a symphony, or a computer game.[5]

Elleström established an analytical distinction between four basic media modalities that are present in any media product. The configuration of the modes of these four modalities is different for every expression, but it also forms the classes called media. A process of modelling involves creating new media products based on a set of modelling targets. Insofar as the modelling targets themselves are media products, modelling is a form of *media transformation*, a process of translation from one medium to another in which the media configuration of modalities defines the affordances for the process and also influences the possible outcomes.[6]

Complementary to the media product perspective, we see the relationship between the model and the modelling target in the light of Peirce's semiotics, understanding it as an iconic relationship in which models are

[2] Gelfert (2016), Marras and Ciula (2016), and Ciula et al. (2023).

[3] Elleström (2021).

[4] Elleström (2010, p. 24).

[5] Elleström (2018).

[6] Elleström (2014) and Ciula et al. (2023, chapter 4).

related to their targets in some sort of similarity function, where the similarity is either image-like, structural, or metaphorical.[7]

2 Modelling for the Future

While the preservation of objects in museum collections is a task directed towards documenting the past, it is also strongly connected to the future. In 1904 and 1905, the ninth-century CE Oseberg Viking ship was excavated in Norway, in a process following the highest contemporary scholarly standards. The huge amount of documentation held today by the Museum of Cultural History (KHM) at the University of Oslo establishes a set of models which can be used to understand what the archaeologists found in the mound, as well as to provide hypotheses about how the objects looked when they were buried and in which processes they played a part.[8]

A hundred years after the excavation, a heated debate ensued in the Norwegian government, at the University of Oslo and in its affiliated Museum of Cultural History about moving the ship and other finds to a new museum, and quickly became a talking point with the media in Norway. In order to clarify the preservation state of the objects, a report was written by the shipping certification company Veritas.[9] Here the possible consequences of different future scenarios[10] were presented in a so-called stress report. The aim of the report was not so much to document possible future developments but to influence future decisions—the aim was to change the future.[11] This, however, is a common feature with several types of models. The rationale of modelling in conflict studies partly lies in the hope of preventing future wars, while climate models are designed and used to reduce climate change through influencing political and economic decisions. Indeed, museums are also relevant for the

[7] Kralemann and Lattmann (2013) and Ciula and Eide (2017).

[8] Eide (2018) and Ciula et al. (2023, section 4).

[9] Hørte et al. (2006).

[10] Scenario-based planning will be briefly mentioned below, but a closer study of the relationship between modelling, simulations, miniature worlds, and scenario-based planning methodology, important as it is, is beyond the scope of this article and it will have to be examined in more depth in future research.

[11] Eide (2018).

development of climate models,[12] as museum collections include exhibits that play a vital part in documenting environmental change, thus giving additional evidence to historical climate change and its consequences for different species.[13]

Literature has also been written as a tool for social and political change through the documentation of assumed weaknesses pertaining in the current society, explicitly expressed as a literary programme for developing a sexually liberated anarchist society by the Norwegian bohemian and anarchist Hans Jæger (1885). He later described this political development in terms of a simple exponential growth model.[14] We will see in the course of this paper how literary models, though not being miniature worlds in the sense used in this article, still have strong connections to the modelling aspects of miniature worlds; Jæger himself rendered one of his attempts to change society in the form of a drama text.[15]

In order to connect models of the future to simulations, we will now focus on miniature worlds. This is surely not the only way to develop simulations; today, computers are even seen as the most prominent tool for developing and running simulations. While the power of computer simulations cannot be questioned, especially not in games and gamification-based pedagogical systems, there still exists a unique communicative power in tangible physical models which is hard to replicate in computer systems, with parts of these models moving around while being expressed through and within a specific social setting. Furthermore, in order to understand the way computer simulations can assume a similar role like miniature worlds, the links between such physical modellings with simulation systems and computer versions of these models are highly significant and will be discussed later in this article. Both computer simulations and physical miniature worlds can be used to influence, or at least prepare for the future. In order to better understand these functions, thus laying the basis for the further development of modelling literacy, it is necessary to clarify the different ways in which these modelling procedures 'do their job' and how the different affordances of technical media may influence

12 See, e.g., Robbirt et al. (2014).

13 Ewers-Saucedo et al. (2021) and Andreone et al. (2022).

14 Jæger (1906).

15 Jæger (1884). On Jæger generally, see Fosli (1994). On the literariness of his texts, see Eide (1995).

their possible rhetorical strategies. This article represents a small step in that direction which needs to be followed up by further research about the mediality of miniature worlds and computer simulations in order to develop a clear understanding of how both of them function as models.

3 Miniature Worlds

The intentions and appearances of models differ, having consequences for the intended similarity functions regarding the model targets as well as for the freedom of the modellers. The modalities of the media types, or formalisms, used to express the models provide affordances for the modelling process. In the following, we will look at one specific type of models, namely miniature worlds, and investigate their use for modelling the future. The Münster LMET conference in October 2021, on which this publication is based, has made explicit the relevance of miniature worlds for energy transition strategies by means of an exhibition on *The Blind Spots of Modelling*, curated by Tobias Becker, that was on display during the conference. It was explicitly called to the attention of the participants as an artefact highlighting the different modelling principles behind scientific and artistic practices. Using the real-space of a miniature world exhibition to represent possible full-scale worlds, it created a fictional space of possibilities where possible worlds can form the basis of a set of stories about a variety of possible futures (Figs. 1a and 1b).

The technical media setting of the exhibition is a room with 3d miniature objects that can move and change lights, together with texts and 2d visual documents which form a part of the model as a complex media product.[16] The qualified medium of the modelling language is a mix between engineering and art, at least if we base our analysis on the explicit intention of the creator. This intention did not only guide the design of the installation, but also influenced the way it is seen by an informed audience, especially in a setting where this intention is called strongly to the attention of the audience. The double perspective steers

[16] The exhibition can also be seen as a collection of different models. These are different perspectives, which, as in modelling more generally, are selected for their usefulness rather than for their exactness or accurateness. For this exhibition, in the context of the LMET conference and of energy transition more generally, the role of the exhibition as such is discussed in the light of modelling. In such a scenario, not only the creating and use of models but also their analysis is based on a pragmatic understanding of modelling (Marras and Ciula 2016; cf. Ciula et al. 2023).

Fig. 1 (a) LMET exhibition: an energy transition model with Tobias Becker and Veit Hagenmeyer (© KIT). (b) Artwork by Tobias Becker, pointing to the grounding of perspective (© Tobias Becker)

the modelling practice in two different directions: towards clarity and reproducibility with respect to the principles of modelling in energy engineering, and towards the creative expression and attempts to make the viewers reconfigure their previous understanding of the artwork parts, as well as to relate the different types of modelling for mutual observation and evaluation of the procedures involved. A major aim of the exhibition was to highlight exactly this critical tension in the art of modelling in general, using a combination of quite different qualified media meeting in a common technical medium.

Miniatures have a long history and their role in society, tracing back to prehistory, is complex and has many facets. Indeed, "the widespread urge to remake the world in miniature suggests that changing the scale of things opens up pathways for people to reimagine the world".[17] It is beyond the scope of this paper to give an extensive introduction to miniature worlds. What is important for the argument here is how making humans reimagine the world is strongly connected to the ability of modelling through miniature worlds to influence the future, thus providing a core quality of modelling literacy. In order to highlight that point, I will focus on some examples from cultural practice.

While the cultural understanding of miniatures varies and is often connected to play and games, there are many examples of how miniatures are used in cultural practices which are understood to influence the future. Children's plays are seen as preparations for adult activities, for instance, with miniature animals preparing for farming, miniature pottery preparing for adult production,[18] or doll play in miniature houses as a preparation for adult social interaction.[19] Miniature worlds are also more directly used to influence the future, e.g., in the architectural setting presented in Sillar where miniature houses and objects are put together to obtain full size versions of the same houses and objects in the future.[20] In the Sami tradition, a complex layer of model worlds has been identified, in which the layout of the turf hut is seen as a scale model of the cosmology in which one finds oneself, a structure which can also be found depicted

[17] Foxhall (2015, p. 4).

[18] Sillar (1994).

[19] Flanagan (2009).

[20] Sillar (1994, pp. 53–54).

on the drums traditionally used by the noaide, the Sami shaman.[21] With Rydving, this can be seen as a movable sacred space, while also being a miniature version of the cosmos[22] (Fig. 2).

In this article, the perspective is on miniature worlds as models rather than on the role of single miniature objects as models. The technical medium of miniature worlds will not be strictly defined in this paper. It refers loosely to any scaled-down 3-dimensional[23] representation of

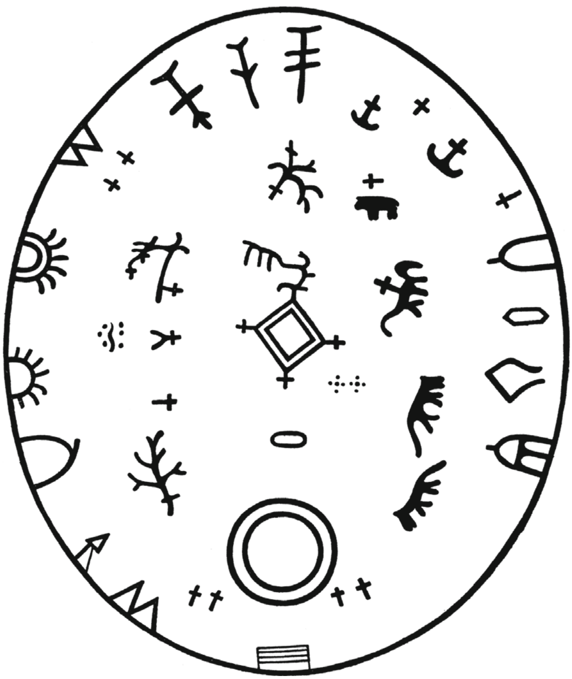

Fig. 2 Example of a Sami drum. University of Oslo, Museum of Cultural History, UEM30331 (https://commons.wikimedia.org/wiki/File:Sámi_mythology_shaman_drum_Samisk_mytologi_schamantrumma_001.png)

[21] Mathisen (1997, pp. 124–125, 129).

[22] Rydving (2010, pp. 117–118).

[23] Also 2½-dimensional worlds are included, see definition below.

real and/or fictitious environments, with or without moving parts.[24] By extension, it also includes projected versions of such worlds expressed on 2-dimensional surfaces when these projections are based on 3-dimensional geometric data, as in certain kinds of video games and VR systems.

Miniature worlds can have their spatiotemporal modalities in spatial dimensions only, that is, in systems which do not change during the time span of a normal observation session. They can also have time-based components, either in fixed time, such as a model railroad system with fixed patterns of movement, or they can be less fixed, as one typically observes in different types of interactive and performative systems. A doll house in itself is spatial only, but once it is used by children in play, the play is a time-based application of the spatial doll house, in line with performative arts. Puppet theatre is a performative art form with specific rules for interaction depending on the diverse traditions to which the plays might belong.

Miniature worlds can also be run as museums where one can pay to experience the wonders of the model world, such as Miniatur Wunderland in Hamburg, Germany,[25] or Legoland in Billund, Denmark, and elsewhere (Figs. 3 and 4).[26] These worlds are models simulating cities and landscapes in different countries, but also explored and enjoyed for their inherent aesthetic values and mechanical complexity. The double nature derived from Becker's exhibition above can be connected to this pattern. The spatial organisation of model worlds is similar to what in cartography is known as 2½-dimensional maps.[27]

> '2½ dimensions' is a cartographic concept for a map in which the height is expressed as real height. The map can for example be an object made of polystyrene. It is not fully 3 dimensional because there is only one Z value

[24] A well-known example is miniature parks, often referred to also as miniature cites and model villages. The semantic and historical differences between constructions referred to by these three terms are interesting, but beyond the scope of this paper.

[25] https://www.miniatur-wunderland.com.

[26] https://www.legoland.com.

[27] The double nature of aesthetics and simulation is available across visual media. Historical maps can be criticised for their lack of realism, but still enjoyed for their beauty. Conversely, paintings are used as historical documents through their showing cityscapes, plant species, etc. The potential of this double nature is often not explicitly called to the attention of users, and can also be expressed differently: for many cartographers, the beauty of a map is connected to, rather than contrary to, its functionality.

> possible for each X, Y pair; caves cannot be visualised. Terrain contours visualised on computer screens are also called 2½ dimensional even if they are expressed on a flat screen, as they visualise 2½ dimensional data.[28]

In classical Geographical Information Systems (GIS), the data were expressed as 2½-dimensional spatial data, whereas Computer-Aided Design (CAD) systems had full 3-dimensionality introduced already in the late 1990s. Full 3-dimensionality is now commonly accessible also in GIS software, but many datasets are still expressed in 2½ dimensions. It is also the case that CAD and GIS software express their interactive interfaces on 2-dimensional screens, e.g., when these are creating stereoscopic illusions through head-mounted displays.[29] In design and

Fig. 3 Legoland (Attribution and license: https://commons.wikimedia.org/wiki/File:Billund_Legoland_12.jpg)

[28] Eide (2015, section 2.1).

[29] In map creation, 3D-illusions were also created with mechanical systems, as when stereoscopes were used to create base maps based on overlapping sets of aerial photographs.

Fig. 4 Miniature Wonderland. Freddy and Gerrit in Rio de Janeiro (Attribution and license: https://presse.miniatur-wunderland.de/download/)

architecture, physical 3D-models can look quite similar to the miniature worlds described above. Today, they can also be printed out from digital data.

The movement from board games to computer games saw a mix of 2-, 2½- and 3-dimensional systems for the internal storage of the worlds of the games. Some games are quite close to miniature worlds as discussed above, such as *SimCity*. The level of interactivity, however, is often significantly higher and the steering systems for non-playing characters (NPC) are more complex. The scholarly understanding of computer games conceived of them both as narrative systems and as simulations. While prose literature is generally seen as a narrative system, it has also been explicitly addressed and promoted as a simulation-like system aiming at documenting the present and even changing the future, as in the Jæger example above.[30]

While prose and poetry establish virtual spaces expressed in text, performative arts have a different perspective and theatre as a text-based

[30] Scenario planning as a type of strategic planning also uses both narrative forms and simulations for long-term organisational or society level planning.

performative art form[31] also consists of a stage space which provides a model world representing the world of the theatre fictions. For some types of puppet theatre, the theatre stage is indeed a miniature world. The space of the stage is a concrete space, yet it is also a representational space simulating the space of the narrative. Especially when theatre is connected to virtual reality, novel questions about the narrative and simulation strategies are being asked, opening up for new ways of understanding how theatre models our world in the context of old and new performative, visual, and written media.[32] Based on the history and current development of these media types, new ways are being introduced to discuss how engineering simulation systems are using a diverse set of metaphors in order to present models of energy systems and energy transitions that are aimed at communicating specific messages.

Similarly, the miniature plays in the Andes can be connected to the energy transition discourse, in so far as the energy needed for land and animal production is generated through activities in which miniatures play a major role.[33] In this sense, miniature worlds act as the meeting place between energy system simulations and visualisations,[34] literature, and (computer) games. The power grid can be visualised and interacted with in the form of 3D-based computer systems. Once these systems are actually used to steer aspects of the power grid, they are becoming frontends to control rooms. They are all using the modelling of their different targets to establish simulations that are intended to communicate in certain ways. Models are always pragmatic in the sense that they are made by someone with some purpose. Miniature worlds are simplifications and extensions of an external reality or fiction, which means that they are models which, by being used in simulations that influence the people involved, turn into conceptional models. Through this influence, these models release a potential to change the future, not least at a political level. In many cases, this is their explicit goal.

[31] It is common for the theatre of the last centuries to base its performances on written and printed texts, but this was not always the case as theatre texts were, especially in earlier periods, often transmitted only orally.

[32] Eide and Schubert (2021).

[33] Sillar (1994, p. 55).

[34] Energy Lab 2.0, cf. https://www.elab2.kit.edu/index.php.

4 Back to Modelling Literacy

Because models are used to change the future at a societal/political level, modelling literacy is important. In order to understand how decisions are made, in energy transition as well as in the handling of Covid and in the development of childcare, models and modelling practices are key. Model worlds have a significant potential as a corner stone in communicating modelling literacy, in their physical form as well as in the form of digital media products such as simulation systems, games, and gamified educational tools.

The communication of complex phenomena and processes through toy worlds is, as exemplified in this article, a wide-spread practice because it works so well. It is a way to visualise the future, or more precisely, possible futures, in the same way as literature, film, and other art and media forms have done for a long time. The use of miniature worlds as a creative modelling activity may thus empower the members of a society to reimagine the world or possible worlds—especially against the world-building of political propaganda. Thus, modelling literacy may lead to political literacy.

Coming back to the West Apaches, wisdom is learned through mental development. Knowledge must always be useful in practice. As modelling knowledge, it is connected to places and to stories. Objects with a unique appearance are easier to recall, thus places enhance memory, they are containers of wisdom. Stories juxtapose characters with smooth minds with characters whose minds are coarser. The group as a whole is shaken, but saved by the former, their qualities are revealed to all when wisdom wins.[35] Modelling is one of the tools that can help us developing wisdom in this sense, and miniature worlds, with their complex spatial outlay, are one of the modelling tools that can be the basis of gaining the modelling literacy needed to solve our common challenges.

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[35] Basso (1996, pp. 134–135).

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Models in Art: A Visual Approach to Energy Transition

Tobias Becker

Contemporary art has always been committed to reflecting on its media, thus models and such items that possess the qualities of models are also being addressed in this field. For many artists, the model is the medium of our time. Its ambivalent nature between existence and non-existence, between antetype and copy stimulates reflection on the various realities we live in, as they are just as ambivalent in many respects. Thus, over the past decades, versatile 'model languages' have been developed in the field of art that question and reflect reality as a complex structure.

As a cultural practice, modelling is firmly anchored in almost all areas of our lives. A conscious reflection on the functions and meanings of the model as a tool for creating, understanding, and changing both existential and conceptual spaces has always been of great appeal to artists. In its classical function as a tool in design, simulation, planning, and analysis, the model is put to use with its most intrinsic qualities: as something that references and as something that asserts. These qualities carry grand narratives, for models mark and occupy an intermediate space between imagination and realisation, past and future, promise and fulfilment. Conceiving of a model in this way, one easily encounters the abundance of

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association and meaning deriving from it: The model provokes questions about desire and reality, about the possible and the impossible, and it may even question the relationship between the factual and the construction of our individual environments, i.e., between our various selves.

We can no longer be sure of reality. Networks of mediacy span over reality; in many places, it is hardly possible to tell real space and model space apart or trace their interconnections. Physical spaces of experience increasingly overlap in our perception with artificially simulated spaces. Spatial entanglements, constructions, infiltrations, pathways of attention, etc. make space appear diffuse. The navigation through these spatial conglomerates takes place unconsciously rather than consciously, and passively rather than actively. For that reason, many artistic endeavours show a gesture of experiment and dedication when it comes to modelling: an urge to recognise and vitalise the model—notwithstanding its intransigence, inauthenticity, suggestive agency, or superficial clarity—and to apply it to unveil a world of the same nature.

By using a language of modelling, the spatial renderings encounter an adequate medium to make these multi-layered structures visible, to verbalise them, analyse them, and to bring them into meaningful expression. Thus applied, the model will no longer function as a reference for future artefacts nor as a recapitulation of the past, but rather as a tool for reading and deciphering the present, and for making it feasible.

The models and modelling methods discussed in the present volume are primarily scientific and technical in nature. In this article, they are contrasted by a whole culture of aesthetic models and model languages from the field of visual arts, which are following their own laws. This chapter examines a number of fundamental aspects of the model as an artistic medium from different perspectives. As an introduction, it is necessary to give a brief description of intellectual and linguistic approaches, as well as an associative interpretation of the *beingness* of the model from an artistic perspective. Model languages in art forgo scientific accuracy, they pursue precision of a different kind, as artists primarily look at the model from the outside, understand it as an instrument of orientation, of cognition, and explanation of the world, and use it reflectively as well as poetically.

Models as objects of reflection have a comparatively short history in the visual arts. It was only in the 1970s that artists consciously turned to the model and recognised its potential for artistic expression. In the section ‘The Model in Art: Doubt and Critique, Proposition and Play,’ the genesis of the model in art up to the present day will be traced briefly using the examples of some of the protagonists in the field, each with their own strategies and approaches in dealing with the model.

From my perspective as an artist who works with models and who had the opportunity to present projects in an exhibition as part of the LMET conference 'The Modelling of Energy Transition: Cultures / Vision / Narratives,' I will describe and reexamine my artistic work in the last section of this article, using three of my model-related exhibits as examples.

1 Properties of the Model-like and Possible Artistic Interpretations

As an artist, one can freely expand on the characteristics of the model, charge them through narrative, and take poetic turns. In the form of a short mental excursion, the following are considerations and notions that pick up on certain aspects of the essential being of the model and think through these associatively, thus preparing the ground for the artistic formulations that are discussed later.

First of all, the model constitutes a *beginning*, in setting up a design and in finding ideas and a form. The model initiates, it carries ideas that hold something much larger, a loose sketch that stimulates the viewer to a thoughtful further development of the idea. In its immediate manifestation before us, it tells us of *remoteness*, of the horizon that we can never arrive at, of the molecules that move in worlds that we cannot reach with our fingers, of a building that will perhaps come into existence in the future, and of an economy that no one has ever seen as such. At the same time, the model is an extract, an abstraction, and a constraint. Compared to reality, it is always simpler. This is one of the essential features of the model. It explains things mainly through its *limitation*. It summarises. It clarifies. A cut-off world is the price.

The model manifests itself as a 'shifter,' as that which references, similar to a demonstrative pronoun. It says: This, here! It means always something other than what it is. In this sense, the model exists only in relation to its reference object. And this is always 'elsewhere.' The model—with all its potential for richness—always retains a strange emptiness. Its character of emptiness evokes the inventory-taking of a 'not-being-there,' the yearning for an *elsewhere*. The model explains and illustrates. It builds bridges and closes gaps. It is the *missing link*—in the perception, in the mind, in time. Between people, between things and places. It connects, it heals. The model is a *pattern*, an ideal, a distillation, the—presumed—idea behind things. It seems universal and pure, whether in the past or in the future or across the world. At the same time, it demonstrates patterns and dissonances through this pretence. The imponderable. And offers access to that which is in between. The model says: Look *here*! It draws attention, makes obvious, it strips bare. The model is dedicated to the place, the situation, the thought. It fully formulates the moment. Each detail that is delineated tells of seriousness and importance. Also in the fleeting gesture, the brief statement, it says: Here! Everything shifts into the now.

2 The Model in Art: Doubt and Critique, Proposition and Play

Models as tools of design, of artistic approach, and experimentation, especially for the development of sculptural works, have always had their place—next to the classical human model—in the visual arts. But only in the 1970s, did artists look more consciously at the model, especially the architectural model, and began to read it as a discrete artistic medium and to incorporate it into their understanding and their work.

The conception of the (architectural) model as a discrete artistic medium in art must be differentiated from the rich tradition of contact between architecture and sculpture. In architectural design, sculptural factors appear much earlier, just as pure sculptural expressions often borrow from the model and architecture. These phenomena remain, however, largely in the modes of architectural design or sculpture, even if ambivalences in the reading of these objects arise between disciplines and 'between scales.' Kazimir Malevich's famous work *Arkhitekton Gota* from 1923, for instance, would be an example of this; it reads as a model of utopian architecture as well as an abstract sculptural statement.[1] The approach to the model as an artistic medium must also be distinguished—beyond formal affinities with sculpture—from the diverse and highly creative manifestations of the model within architectural practice, such as those brought together in the 2012 exhibition 'Das Architekturmodell: Werkzeug, Fetisch, kleine Utopie' [The Architectural Model:

[1] Fondation Beyeler (2005).

Tool, Fetish, Little Utopia] at the Deutsches Architekturmuseum in Frankfurt am Main.[2]

For the 'models in art' addressed in this text, however, the general characteristics of the model as a provisional solution, as a reference, as a proposal, etc. are invoked conceptually and used as a point of departure for the artistic message. This emerging interest in the model was a result of a general discontent with the prevailing artistic media and genres in the 1970s. As many other artistic languages changed and expanded through this questioning of classical forms of expression and presentation in art, as well as their institutions and avenues of distribution, the model also gained a new prominence in the discussions of the time. Among the protagonists who contemplated the model in this way were, in the beginning, mainly exponents of American conceptual art. Like many other artists of their generation, they also dealt with questions of authorship within art and with the role of the viewer, like, for instance, the artist Dan Graham, one of the main figures of this art movement. According to him, it was the exhibition 'Architecture I', which opened in autumn 1977 in the then very influential Leo Castelli Gallery in New York, that provided him the occasion to more precisely consider the model as a communication medium or artistic medium. Rather unusually for an art gallery up until this point, a number of prominent international architectural positions were shown with drawings and models, including works by Richard Meier and Aldo Rossi . The exhibition was nevertheless typical of the time in its approach and another example of how the disciplines of art and architecture, even if laden with conflict, still entered into a dialogue in which the model played a substantial role as a (design) medium.

In the field of architecture, heated debates developed around the status of the model in relation to drawing in the process of architectural design. For example, under the title 'The Architecture of the École des beaux-arts', Arthur Drexler, the then director of the architecture and design department of the Museum of Modern Art, exhibited architectural drawings of that same school in 1975 and thus fuelled a debate on what he called the outsized and unjustified prominence the architectural model received in the twentieth century.[3] In another instance, the director of the Institute for Architecture and Urban Studies (IAUS) in New York,

[2] Elser and Schmal (2012).

[3] Drexler (1977).

the architect Peter Eisenman, initiated the exhibition 'Idea as Model' in the same period (1976) and brought together 22 contemporary architectural as well as artistic positions with the aim of understanding and establishing models, independent from their practicability, as generators for ideas and concepts for new spatial designs. He reinforced references to the artistic positions of minimal art and land art, so as to shine new light on the respective boundaries of architecture and art; the publication *Idea as Model* followed four years later.[4]

Just as this exhibition extended into the field of visual art, architecture likewise became the focus of the then current generation of artists. Architecture embodied a reality beyond the art establishment, beyond all self-referentiality in the languages of art.

Architecture and urban space with its fragile publicness were declared fields of artistic work and discussed in a variety of ways, including the stance of vehemently attacking architecture—which was understood as a manifestation of the existing political as well as economic power relations—and intellectually as well as physically opening it up, like Graham's colleague Gordon Matta-Clark with his spectacular cuts carved through existing architecture. The dynamics in the discovery and acquisition of new artistic languages, strategies and fields of work, as practiced by Matta-Clark and Graham at the time, were, as already indicated, embedded in a larger debate around the expansion of the concept of art. The highly regarded essay *Sculpture in the Expanded Field* from 1979 by art critic Rosalind Krauss gives an in-depth understanding of these currents. Krauss rigorously observed, analysed, and commented on events in the American art scene of the time. She programmatically located the sculptural practice of her generation between the poles of sculpture, landscape, and architecture in order to outline a perspective of sculpture beyond traditional artistic disciplines and classifications.[5]

While Matta-Clark's incisions into buildings were borne by a grand gesture, Graham pursued a different strategy, and in 1978, following the exhibition 'Architecture I', presented the work *Alteration to a Suburban House*, which, due to its purely model-like language—a classical architectural model in appearance—can be read as a representative and a key for this period (Fig. 1). With this work, Graham communicated not just his

4 Pommer and Hubert (1981).

5 Krauss (1979).

thoughts on this *Alteration to a Suburban House*, but also put forward an understanding of the model as an autonomous and discrete artistic medium. The model was no longer seen only as a necessary intermediate step in the development of a work, it was adopted as an end in itself.

The work is interesting in two respects, on the one hand, as new paths were laid on the level of media, and on the other, as it also conformed to the political demands of the then current artist generation. The model seemed to artists—not only to Graham—to be a democratic medium, as it not only pushed the author into the background, but was also easy to read and not hidden behind the codes of elitist art languages. Thus, Graham's *Alteration to a Suburban House* is not to be taken as an 'ingenious' design for a possible future house, but as a commentary and a contribution to the debate on the then prominent discussion around public and private space. The work examines this uneasy relationship using the example of the suburban house, the epitome of the private sphere, designed by Graham with a transparent front. The separation into private and public space was thus visually dissolved and, in doing so, questioned these demarcations, their backgrounds in culture, and their social as well as psychological consequences. With this approach, Graham developed

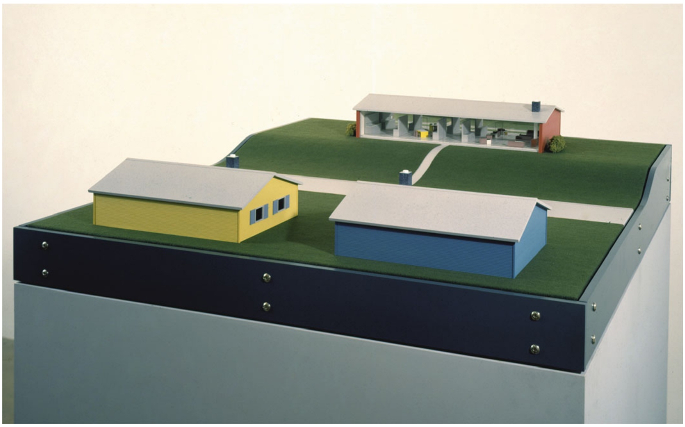

Fig. 1 Dan Graham, *Alteration to a Suburban House*, 1978/92, wood, felt, and Plexiglas, 28 cm × 109 cm × 122 cm (Courtesy of the Estate of Dan Graham and Marian Goodman Gallery, © The Estate of Dan Graham)

over the next decades a myriad of spatial configurations and openly accessible pavilions, which through their constructed reflections, partially or fully transparent and evoking ambivalent moments of observing or being observed, all drew from the direct experience of communication, boundaries, closeness, and distance. These factors are experienced through the pavilions in a compressed and distilled form and can therefore, as a matter of course, be called models, too—models for curated moments of experience.

This brief look at Graham is intended to illustrate the social context in which the model found its role in art. Parallel to his activities, many other artists, especially American artists, discovered the model for themselves in the 1970s, for instance, Laurie Simmons. She took a somewhat different formal approach, as she did not exhibit models as Graham did, but created model-like situations on a small scale, and then captured them photographically, in order to later exhibit the photographs.

With her early works, like the series *In and around the House* (1976–78), Simmons enters mentally as well as emotionally into the very suburban houses that Graham discussed from a different angle (Fig. 2).

She arranged these interiors as small doll's-house scenarios, assigning various roles to the dolls, in the same way children play with them to learn about the world.[6] Her scenes—visible through the details that hint at the commodity fetishism of the consumer society—are embedded in a promising narrative and evocation of the ideals of the American post-war period in the suburbs. Her works can at the same time be read as feminist explorations of the traditional domestic role of women and of their opportunities and limitations in these surroundings. By using the model, Simmons's works create a certain tragicomedy. They are at the same time succinct and unpretentious; the nature of playfulness and experimentation, which are inherent to models because of their provisional character, is played out here to best effect. Her model-like constructions remain afterimages in the memory and stand in constant competition to the idea of similarly constructed realities, to which Simmons refers back. She questions the realism of images and, using the model, reflects on the construction of images and their influence on our perception and understanding of the world. This approach was picked up years later by many

[6] Nitsch (2003).

Fig. 2 Laurie Simmons, *Untitled (Woman standing on Head)*, 1976, black and white photograph, 13.5 cm × 21 cm (Courtesy of Laurie Simmons)

European artists, such as Thomas Demand, Oliver Boberg, Lois Renner, and Edwin Zwakman and carried on under different circumstances.[7]

In Germany at the beginning of the 1980s, a loose group of like-minded artists from the milieu of the Kunstakademie in Düsseldorf were coming into the spotlight. These colleagues and friends were known as the Modellbauer, the 'model-builders'—Ludger Gerdes, Thomas Schütte, Harald Klingelhöller, Wolfgang Luy, and Reinhard Mucha. They were interested in objects situated between sculpture and architecture.[8] It was perhaps the Konrad Fischer Gallery in Düsseldorf that made artists like the Modellbauer aware of the latest trends. The Konrad Fischer Gallery was one of the first German galleries to show artistic positions of American minimal art, land art, and conceptual art, and it had a significant influence on the Düsseldorf art scene. This is how at the beginning of

[7] Christofori (2005).

[8] Hartung (2018).

the 1980s, Thomas Schütte, later one of its most prominent exponents, began to use this artistic language, and started to build models (Fig. 3).[9]

Unpretentiously assembled from rough chipboard, Schütte's models are ironic, often convoluted, and on all accounts political commentaries, depictions, and reflections of contemporary social themes. His models often adhere to the visual forms of architectural models, but draw their power and also their charm from the fact that they are not intended to be realised, but rather to be understood as proposals for possible other/ better worlds. Schütte also sees the model, similarly to Graham, as a

Fig. 3 Thomas Schütte, *Haus für den schüchternen Verleger [House for the Shy Publisher]*, 2006, polyester, wood, 221 cm × 270 cm × 150 cm (Courtesy of Thomas Schütte, © VG Bild-Kunst, Bonn 2024; photo: Haus für den schüchternen Verleger, 2006, Nic Tenwiggenhorn, © VG Bild-Kunst, Bonn 2024; Creative Commons license terms for re-use do not apply to this picture and further permission may be required from the right holder)

[9] Thomas Schütte (2010).

fitting medium with which to enter into conversation with reality and to make artistic statements more legible and more discursive for societal debate. The appeal to architecture that is always concomitant with the artistic model, as practiced by Schütte, is rooted precisely in the irrevocable functionality of the architectural. His models range nimbly in the interplay between nonfunctional autonomy and a possible but unintended anticipation of being purely purpose-bound, between an individual standpoint and social relevance. Some of his models that have been realised as built architecture remain strangely in a playful and propositional mode. These phenomena were recently the subject of the exhibition '(im)possible! – Artists as Architects' at the Museum Marta Herford.[10]

The explanation of Schütte's approach should not distract from the fact that works using models have passed through, and continue to pass through, the most multifarious forms. From the 1980s until today, numerous independent artistic positions have emerged which are shaped in various modes. Thus, the model has received a great deal of attention over the last 20 years through different specific exhibitions. The 2001 exhibition 'Archisculptures: Über die Beziehungen zwischen Architektur, Skulptur und Modell' [On the Relationship between Architecture, Sculpture and Model] examined these very relationships.[11] Another survey exhibition titled 'Update – Die Welt als Modell' [The World as Model] took place in 2010.[12] The most far-reaching exhibition in Germany to date was certainly 'What Models Can Do: A Brief History of the Architectural Model in Contemporary Art' in 2012.[13]

Positions were discussed that can be distinguished once again according to their strategic orientations. Thus, many artistic projects using models range across classical communicative structures; technically, they are presented like architectural models: on tables or sometimes on the floor. They are miniature worlds that in their manifestation pose questions of architecture or of society as a whole. Often, it is the museal environment that makes the intentions of the model visible, distinguishing it from the architectural model and inviting open interpretations. Elements of Schütte's models belong here, but also countless other positions. Mike

[10] Schloen (2015).

[11] ARCHISCULPTURES (2001).

[12] Update – Die Welt als Modell (2010).

[13] Was Modelle können (2014).

Kelley, for example, presented his work *Educational Complex* from 1995 under a glass dome on a large table with trestles, i.e. in a classical form (Fig. 4).

Made of white cardboard, approximately 20 buildings are densely arranged on the surface of the table and easily discernible as architectural models. But here, too, it is the context of the museum and the meta-narrative provided by the title of the work that redirect the viewer's focus from the buildings to Kelley's own biography and socialisation. The buildings, it transpires, are replicas of all the educational institutions that Kelley passed through in his life. In this way, the act of model reconstruction is a confrontation with one's own—perhaps acquired or even imposed—self-image, memory, and view of the world. So the model is applied here as a tool of reflection of one's own biography. A number of contemporary

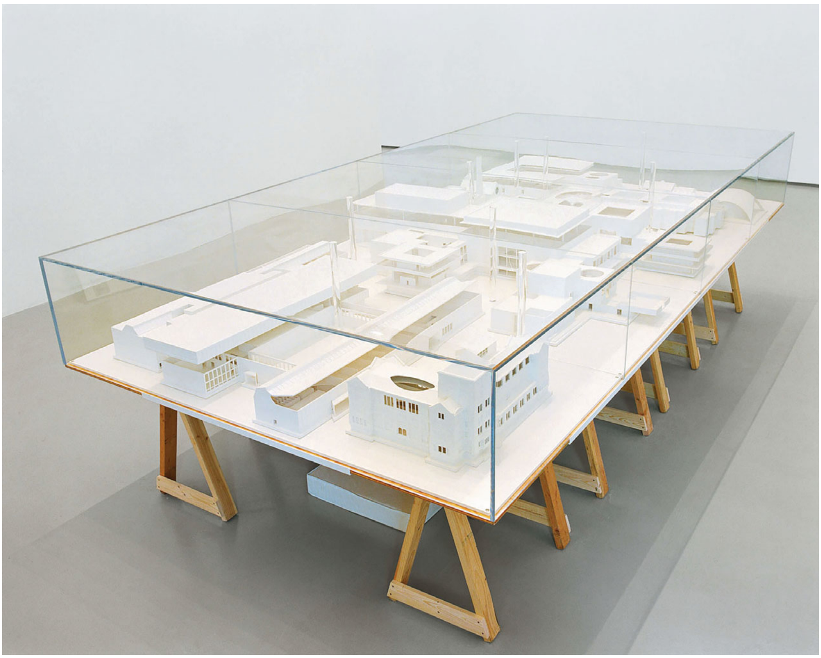

Fig. 4 Mike Kelley, *Educational Complex*, 1995, painted foam core, fiberglass, plywood, wood, plexiglass and mattress, 146.7 cm × 488.2 cm × 244.2 cm (© VG Bild-Kunst, Bonn 2025)

artistic positions can be identified which, by using models, are oriented towards classical forms of representation of the architectural model, not least in order to subvert or reconceptualise it. Katrín Sigurdardóttir and Larissa Fassler, for example, are representatives of this manner of play.

A somewhat different formal approach is the correspondence of model and sculpture, a 'sculptural examination' where the immediacy found in an object's materials and forms runs counter to its referential (and therefore model-like) nature. Yet this ambiguity, which is one of the basic features of sculpture, gets even more pronounced when sculptures are exposed as models by suggesting a specific (yet unfathomable) functionality, as e.g. in the works of Manfred Pernice (Fig. 5).

Fig. 5 Manfred Pernice, *Weinberg [Vineyard]*, 1997, wood, pressboard, paint, 110 cm × 270 cm × 295 cm (Courtesy of Boros Collection, Berlin; photo: Boros Collection, Berlin, © NOSHE)

Pernice is interested in the interpretation of different object traditions like sculptures, models, or designed objects, as well as simple functional objects (containers) and furniture. He merges these traditions in his works and even within an individual object in such a precise way that they acquire a maximum of uncertainty. Atmospherically, the works remain appealingly indeterminate, ranging between pure abstraction and profane banality. Thus, Pernice questions our perception and categorisation of the material world as well as our orientation that emerges from it. Other examples of artists engaged in sculptural practice via modelling are, to name just a few, Rita McBride, Isa Genzken, Lorenz Estermann, Zora Jankovic, Wolfgang Weileder, and Tim Ullrichs.

Another strategy, as practiced by Laurie Simmons around two decades before, is the photographic staging of models. This approach differentiates itself significantly and leads to positions like that of the artist Oliver Boberg, mentioned briefly above. In his model photographs, Boberg distils our idea of certain architectural languages and phenomena, such as passageways in public space from the 1960s and 1970s in Germany (Fig. 6).

He relies on an archive of countless documentary photos, merging their architectural essence in an image of the 'ultimate passageway'—a distillation, a memory, which never existed in this exact form. This work is made with the images of an architectural memory. The model-making here is set in parallel with the modelling of images of architecture that pertain to our cultural memory. Other representatives of model photography include the already mentioned artists Thomas Demand, Edwin Zwakman, and Lois Renner, as well as others like the artist duo Cortis & Sonderegger, or Thomas Wrede.

One of the most important and practical characteristics of models is their scalability, a quality that many artists have strategically brought into play. In experiencing the world, we find that all the things have their dimensions and fit harmoniously into what we call reality. A salt shaker is smaller than a rubbish container, an office building is bigger than a shoebox. Something with an incorrect proportionality immediately draws our attention to it. Ina Weber has built models predominantly out of concrete and ceramic tiles for many years.

Relying on humour, her work is a constant play with scale and expectation, down-scaling objects as well as recontextualising them. Models are mobile and can be readily taken from place to place. Weber plays with our perception with an extremely enjoyable as well as charming senselessness.

Fig. 6 Oliver Boberg, *Passage*, 1999, photograph, 40 cm × 50.16 cm (Courtesy of Oliver Boberg)

In one of her works, for instance, she places a small bird bath, approximately one and a half metres long, on a lawn in the park (Fig. 7). The bird bath appears to be an ordinary swimming pool with lanes, starting blocks, and a diving board. It is not clear who is being addressed here, birds or people? The work invites us to ask these kinds of questions and to reassess, for a moment, the relationship between people and animals. See also, for example, artists who make use of scale in their artistic work: Charles Ray, Peter Fischli & David Weiß, Claes Oldenburg, Christian Haake, or Ron Mueck.

This brief and, of course, incomplete outline can only serve as an impression of the richness and complexity of the model as it is used in the visual arts. However, it points to the fact that artists using models with their projects mainly work on the level of commentary, just as art in general. The model, though, often makes artistic statements which are much more tangible and easier to approach. In fact, the use of models takes art down off its pedestal by creating an accessible language. Because of this, model art puts on display the problems of the time and

Fig. 7 Ina Weber, *Vogelbad [Bird Bath]*, 2009, reinforced concrete, tiles, stainless steel, 41 cm × 159 cm × 135 cm (Courtesy of Ina Weber, © VG Bild-Kunst 2022)

it comments on them with a keen sense of doubt, critique, humour, proposition, and play. Moreover, this pragmatic stance enables insights that exceed the discourse of models in art. By showcasing the mechanisms, hopes, and strategies, but also the intricacies and failures tied to modelling, the use of models in the arts develops an explanatory epistemological force. Not only by comparison or by analogy, but also by exhibiting a cultural technique at work can model art unveil the 'art of modelling'—in general and as a tool in various disciplines. Thus, modelling itself is made transparent by the models of art.

3 The Blind Spots of Modelling

This is where energy transition and model art meet. In the LMET exhibition 'The Blind Spots of Modelling,' models and modelling techniques from energy technology were juxtaposed with models from the visual arts in works whose model aesthetics derives from my own artistic practice. I took this invitation as an opportunity to review two model traditions that starkly differ not only in their origin, but also in their intention and appearance, and as a chance to stimulate reflection on the constituting factors that are hidden behind these respective forms of expression. While the scientific model is bound to having the greatest possible proximity to reality and usability, the artistic model is designed free of obligations and also operates in self-reflective and media-reflective modes that, by intention, can address and play out the possibilities and limits of a model language. The exhibition provided insight into the practice of modelling from two perspectives and thus functioned as an aesthetic counterpart to the critique of modelling put forward in the context of the conference.

First, certain 'blind spots' in the processes of energy transition modelling were isolated and exemplified. In addition, several thematic areas emerged, each of which identified core problems in modelling processes.[14] These problems were not only energy-driven but inherent to a lot of modelling processes in technology and science. In the set-up as well as in the implementation process, various difficulties arose, not least in the contact zone of cognitive, technological, and social engineering, most prominently in what may be addressed as *model amnesia*. This fallacy occurs in the case where the suggestive power of a modelmaker's own model appears so conclusive that the aesthetic effect outshines the model's projected purpose. In this situation, there is the considerable danger of creative self-delusion and of failing to meet the objectives of the modelling process. A more technical problem is the *scaling* of fragmented relations in larger environments, which is related to uncertainties belonging to the scaled location (e.g. its informational density; Fig. 8). Thus, deviations from the meaning of scaled information can occur, which may be unintended and difficult to handle, especially when different types of scalings and different degrees of abstraction meet.

Difficulties also arise in estimating the future development of highly complex technical processes, involving context problems or what one may call the (temporal) *horizon problem*. As much as such projections are desired (as they make predictable, at least to some extent, the course of events), the modelling of future scenarios inevitably reaches its limits. Expectations of this kind towards the model often cannot be fulfilled by model objects, and they may not be compatible with the intentions or the capabilities of the modelmakers involved.

[14] This exhibition will be documented in a separate publication in the Palgrave Macmillan series 'Poetics of Modelling.'

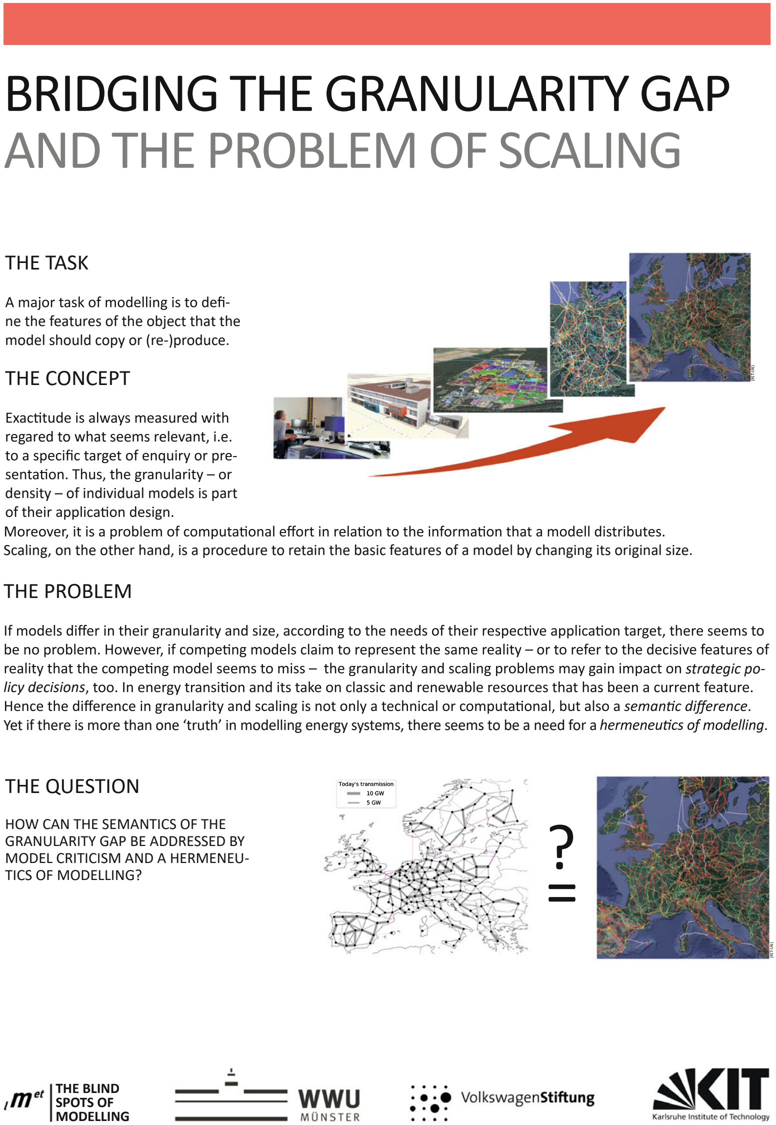

Fig. 8 Exhibition poster (Courtesy of LMET; © text: Robert Matthias Erdbeer, © photos: KIT Karlsruhe, © layout: Tobias Becker)

Such difficulties, which must be anticipated—and ideally resolved—in technical and science models, are a fascinating starting point for the artistic work with models as well. Thus, at the exhibition, artistic works and groups of works have been curated around such problems of modelling in order to initiate a conversation about their 'blind spots'. In this respect, artistic works can function as a contrast medium for rendering perceptible the challenges of working with models in general.

Model amnesia, *scaling,* and the *horizon problem* are common features in the modelling procedures, and—their difference in circumstances, goals, and discourse notwithstanding—they refer and give their names to mechanisms that are also negotiated in art. They serve as points of departure for artistically exploring the blind spots, the fallibilities, and the inadequacies of a 'model' construction. Models in the arts are not employed to search for answers or solutions, they are fabricated to discover questions. For this purpose, they are usually decoupled from any functional technical context, as they are no technical aid nor a means to an end. From this perspective, the works of art shown in the context of the LMET exhibition may be seen as 'close-ups' or as meta-models: they refer to and reflect the art of modelling as well as the technique of modelling in the visual arts.

4 Three Model Projects: Model Amnesia, Scaling, and the Horizon Problem

In this final section, I would like to illustrate my working methods by introducing three examples from my visual works. This rather unconventional 'self-description' aims at offering a deeper insight into the genesis of artworks that use models as creative devices. These works or work collections have been juxtaposed—at the LMET exhibition 'The Blind Spots of Modelling'—with samples from the problem areas in energy technology mentioned above.

Model Amnesia: Cloud Studies

I built a cardboard model of a sky thick with low-hanging clouds. This served as a template for my future painted and drawn studies. Different perspectives on the model generated ever-changing visual manifestations of the clouds. I captured this diversity of forms in numerous studies. Technically, this brief description outlines my entire procedure. The *Cloud*

Studies project is an investigation into the construction of the world through the model and at the same time a tragic story of the self-delusion of a landscape painter.

In its ephemeral manifestation, the cloudy sky is perhaps one of the last refuges of the undefined and the ‘Other’, a distant site of longing and an antidote to the concrete, factual world, a place of belief and transcendence. With the wish to capture this ‘place’, to get hold of it, I recreated the cloudy sky as a model based on a photo of clouds (Fig. 9).

I resolved the fleeting cloud forms with cardboard and battens, creating geometric, almost architectural forms that are easy to build. I confined the depth of the sky to about one metre; in width the model spans about two metres and in height about 80 centimetres. Though illogical in its spatial conception, this endeavour makes it possible to transpose a vast sky hanging with clouds into a manageable object, to make it accessible, a gesture that is not only contrary to the subject but also and above all represents a massive presumption. The background of this undertaking was an interest in the mechanisms of construction inherent in every representation of landscape—and generally in every image that is made. Even in the classical cloud studies *en plein air*, cloud formations are still subjectively ‘constructed’ despite the proximity and immediacy of the experience, in that the clouds are transferred from the infinite spatiality of the sky to the limited surface of a painting—a considerable accomplishment. I confront these circumstances with an experimental set-up to interrogate the relationships between the perception of natural objects

Fig. 9 *Cloud Studies*: photographic template, 2015; model, 2015, cardboard, wood, 100 cm × 200 cm × 80 cm (Courtesy of Tobias Becker, © Tobias Becker)

and their construction as a landscape. For what is it that I paint as a landscape painter if I paint a landscape? Is it not just my own conception of 'landscape' that is reflected in the picture? That is shaped through the choice of the subject, the part of the landscape portrayed, the composition, and so forth? And shouldn't it be possible to read a representation of landscape as a self-portrait?

The cloud model hangs on a wire at eye level and is designed with a prominent front view. If the gaze is on that front view through a narrowly defined visual frame, then the model 'works' properly. An image emerges because an illusory space is created; cumulus clouds recede towards the horizon providing a view in the vast landscape that is deeply anchored in our existing visual archive (Fig. 9, right image). However, if the object starts rotating slowly around its own axis, this illusionary space gradually disappears. The image disintegrates and the model is no longer a reference to the cloudy sky, it appears as what it is—a somewhat clumsily built provisional construction made of wood and cardboard (Fig. 10).

Assuming the role of a traditional landscape painter who does nothing other than paint his idea of a landscape, I now addressed my self-constructed model as a material reality. Over a period of several months, I produced a whole collection of around 40 paintings and 70 drawings and watercolours with dimensions ranging from postcard size to larger formats of up to 180 centimetres by 230 centimetres. I worked in an artificial situation, observing with great commitment, almost maniacally, how I studied drastically different views and details of the cloud model, painted atmospheric spatial scenarios, and inflected the clouds through various times of day and night. The act of painting was not just about learning and understanding the cloud formations, it was also a form of surrender and enjoyment; the studies are full of curiosity, carried by a longing for contact with and an experience of the endless cloudscape (Figs. 11, 12, and 13).

What I missed in my painterly enthusiasm was the fact that the illusory character of the model—my personal concept of it—is no longer properly visible in all the perspectives outside the frontal view, it completely disintegrates into parts and becomes unreadable as the subject 'cloud'. Undaunted, though, I continued painting my cloud studies. Due to the model's rotation, the topic no longer appeared as an abstracted sky that could be geometrically resolved quite easily—a view that is all too familiar in light of the history of abstraction in painting—it appeared before my eyes as a large and heavy architectural monstrosity. The cloud subject

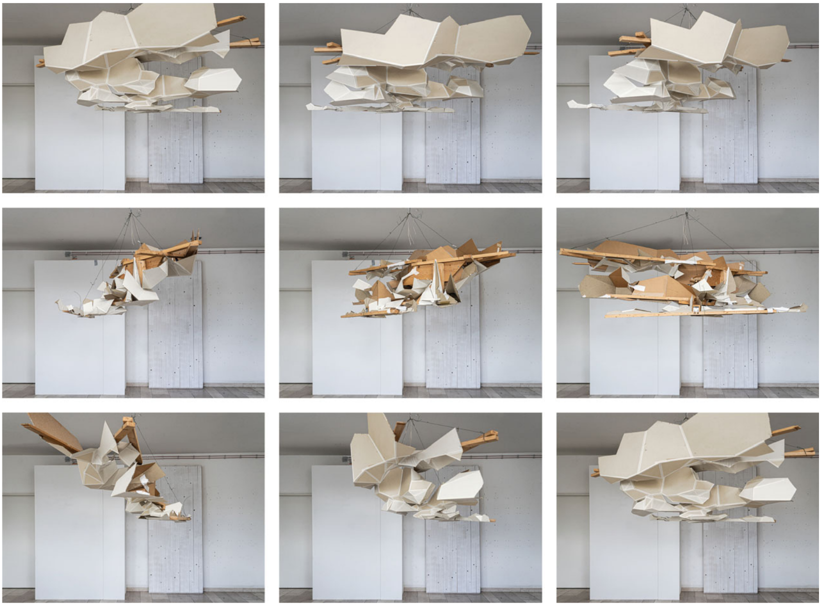

Fig. 10 *Cloud Studies*: model in rotation (Courtesy of Tobias Becker, © Tobias Becker)

transformed itself through its rotation and the subsequent erroneous perspective views, without my having registered these transformations as such. I no longer painted a cloudy sky, but rather my own almost claustrophobic creation.

What I tried to capture here, as the constructor of the model and the painter of his own construction, is in fact a rather banal situation: the very human wish for congruence—or harmony—between the self-constructed images and that what one experienced as being true. In the scope of model criticism, this would represent a good example of a model amnesia.

The Horizon Problem: Things from the Horizon

The series *Things from the Horizon* came about after I travelled west across the United States for several weeks. Travelling through the bleak and endless territory of the west brought to mind the American Dream. What is it that the west holds? What do people long for? What is it that we

Fig. 11 *Cloud Study (white)*, 2015, oil on canvas, 30 cm × 40 cm (Courtesy of Tobias Becker, © Tobias Becker)

search when searching the horizon? I literally tried to focus on the things on the horizon, on these small, indefinable, and vague shapes. I wanted to hold these things in my hands, I wanted to see them up close, so as to understand what this dream is all about. I turned my observations and ideas into a model and I made these things and dreams from the horizon tangible—and for sale.

The horizon is depicted here as a place of longing. Turning towards it gives us orientation in space and time. Beyond the horizon, we can shape for ourselves a direction and goals. The prerequisite for this, however, lies in the acceptance of the unattainability and inaccessibility of the horizon itself. We can accept this inaccessibility but only from a position of humbleness, which teaches us that we are subordinate to space and time. Hardly anything confronts us with our limitations more resolutely than the horizon.

Fig. 12 *Cloud Study*, 2015, oil on canvas, 100 cm × 140 cm (Courtesy of Tobias Becker, © Tobias Becker)

To use the vague forms that one can hardly make out on the horizon, to force them into tangible proximity, and to substantiate them in material form, runs counter to the reference to the horizon mentioned above. But this is exactly what I do with my model-like replicas, with reference to the functions and characteristics that the model carries in itself. The model calculates and illustrates through its attempt to leverage and even out the distances, as is the case with the horizon things. Something improper seems to be inherent in the model, as it is intrusive in its logic and it tends to override the system of reference. To transform desires and longings into models or objects leads to a materialistic view of the world. Ideas and wishes and the unattainable: they turn into commodities and objects of desire as soon as they become tangible. But they do not reveal themselves, because they elude attribution. They continue to point to something very far away. But as objects they are presented on a narrow white table, like the most valuable objects in the display case of a luxury shop (Fig. 14).

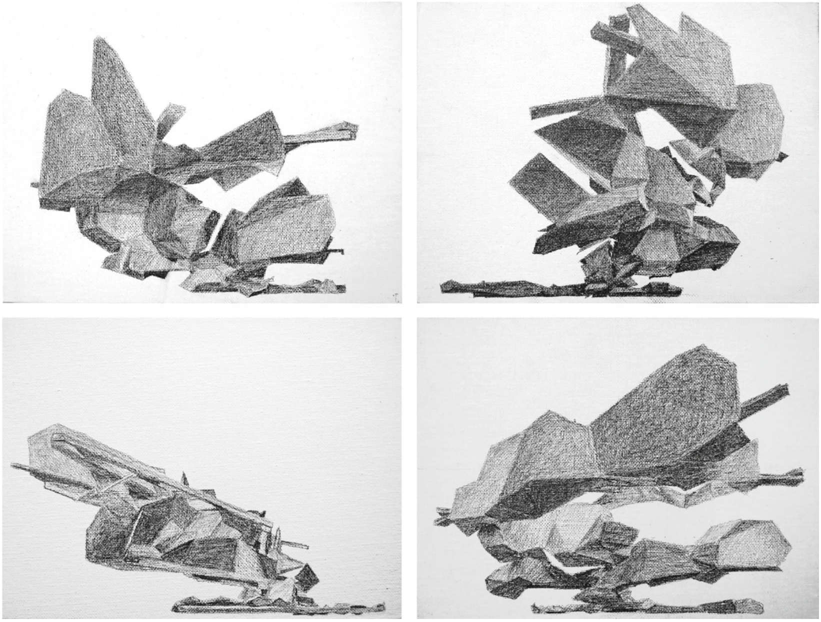

Fig. 13 *Cloud Study (lead) I–IV*, 2015, pencil on cardboard, 18 cm × 24 cm (Courtesy of Tobias Becker, © Tobias Becker)

Technically, I have zoomed into a west-facing photo of a wide landscape in Montana, a view so wide that I came as close as possible to the shadowy outlines of unrecognisable objects (Fig. 15).

You can sense rows of trees there, sections of hills or rocks … but you cannot be certain. These blurry shapes, though, formed the basis of very concrete objects: organic and pliant in their form, smooth and shiny on their surface with an iridescent and unexpected chromaticity that makes the objects appear even more diffuse (Fig. 16).

Thus, through the model-like reconstruction of an idea on the horizon, something different has been achieved than originally intended. No longings become visible and tangible, no resolution is presented, and one does not understand the forms in the close-up view any better than from a distance. What one can read in *Things from the Horizon*, though, is the ideological framing that accompanies this modelling process; that

Fig. 14 *Things from the Horizon*, exhibition view (Courtesy of Tobias Becker, © Tobias Becker)

Fig. 15 *Things from the Horizon*, 2007, photographs (Courtesy of Tobias Becker, © Tobias Becker)

objects for sale take the place of vague desires, or that they turn into such things as soon as they become concrete.

Fig. 16 *Things from the Horizon*, 2007, foam, plaster, spray paint, 18 cm × 90 cm × 18 cm, detail (Courtesy of Tobias Becker, © Tobias Becker)

Scaling: Infinity (*Collaborative Project with Stamatis Papazoglou)*

Stamatis Papazoglou creates his paintings with a great deal of physical exertion. Coloured paper is glued in layers on mostly large-scale canvases and then in large part sanded off, only for the canvases to be papered over and sanded down again. Through this elaborate as well as strenuous process, he produces very detailed abstract structures which sprawl across the canvases like a subtle visual noise (Fig. 17).

I examined the details of this 'noise' more closely. Before my eyes unfurled, an infinite deep pictorial space made up of equally infinite forms. I responded to Papazoglou's image production with a completely different way of working. In an almost pedantic way, I turned these accidental micro-forms of two to three centimetres into three-dimensional cardboard objects. I developed models from selected details (Fig. 18).

These translations were accompanied by multiple formal uncertainties. For one, I transferred two-dimensional phenomena into spatiality, for another, I scaled up the detailed shapes many times the size of their original measurements. I created white objects that in size and appearance recall elegant or even extravagant architectural models (Fig. 19).

These objects are positioned opposite the paintings. The way they correspond unveils the individual artistic concept at work: their visual languages, dynamically juxtaposed and incompatible, yet dedicated to the same topic: infinity. The type of infinity that I contrasted with Papazoglou's deep pictorial spaces is the infinity of possible transformations and translations of forms, embedded in the dialectics of construction and deconstruction marked by our different ways of working.

A central factor here was a change in scale. The information that was enlarged in the scaling process establishes, in its scaled dimensions, a relationship to its—new—non-scaled surroundings. The granularity, the resolution of these two now joined realities had to converge, so that

Fig. 17 Stamatis Papazoglou, *Untitled*, 2018, paper, spray paint, 180 cm × 220 cm (Courtesy of Stamatis Papazoglou, © Stamatis Papazoglou)

Fig. 18 Infinity: Stamatis Papazoglou, *Untitled*, 2018, paper, spray paint, 82 cm × 80 cm, with marking (Courtesy of Stamatis Papazoglou, © Stamatis Papazoglou); Tobias Becker: *Model (Infinity) 02*, 2019, cardboard, 82 cm × 71 cm × 25 cm (Courtesy of Tobias Becker, © Tobias Becker)

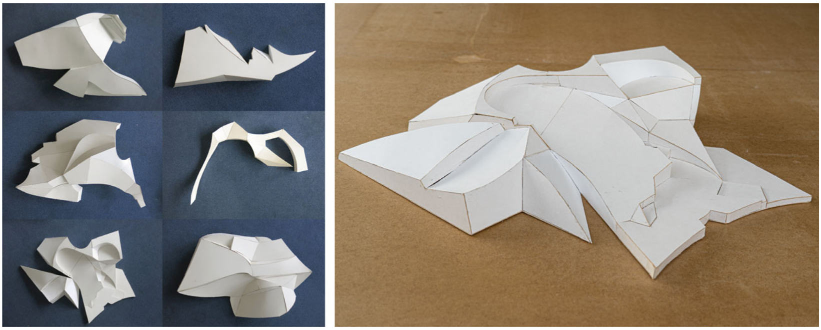

Fig. 19 Infinity: Tobias Becker, *Models (Infinity), series 01–06* (Courtesy of Tobias Becker, © Tobias Becker), *Model (Infinity) 02*, 2019, cardboard, 82 cm × 71 cm × 25 cm [same as in Fig. 18, right] (Courtesy of Tobias Becker, © Tobias Becker)

an adequate, meaningful correspondence could develop. In addition, the scaled 'empty information space' had to be filled and reinforced with new material, so that it fit into the new surroundings. The means and ways, materials and media with which the missing granularities were generated to adapt the scaling to its new surroundings, have been manifold and replete with pitfalls, for shifts in meaning tend to undermine the aims behind this change in scale. In this specific case, the replenishment with 'granularity' consists just of white cardboard and the associative artistic considerations for the spatial translation of the two-dimensional information. Strategically, the project uses the formal uncertainties in scaling mentioned above for a compositional recreation of the same information. Thus, these accidental forms and traces of Papazoglou's 'destructive' method open ways to generate the 'constructive' architectural models that refer to possible future spaces. These transformation processes, translations, and changes of scale are virtually *infinitely* repeatable. Thus, in a second step, I constructed the cardboard model as a 3D rendering and transferred it into digital surroundings where other readings are being applied (Fig. 20). This is further reference to the complexity of the model in its forms, interpretations, and contextual dependencies, and despite all its potential for clarity, the model remains elusive.

In looking at the mechanisms of artistic modelling in artworks that make use of models as a topic and a leitmotif, this article has shown how

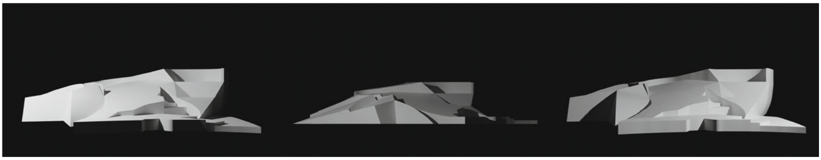

Fig. 20 Infinity: Tobias Becker, *3D-Rendering of Model (Infinity) 02*, 2020 (Courtesy of Tobias Becker, © Tobias Becker)

modelling in art may function as an epistemic tool for analysing models in general. By putting forward a 'critique of modelling' of some of my own works, my aim is to provide a mode of model criticism that enables us to spot the mechanisms, hidden strategies, desires, and blind spots of modelling in various disciplines. How this affects the case of Energy Transition has been outlined in the paragraph about the LMET exhibition; I will elaborate on this in the forthcoming exhibition volume.

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