

Principles, challenges and guidelines for a multi-model ecology

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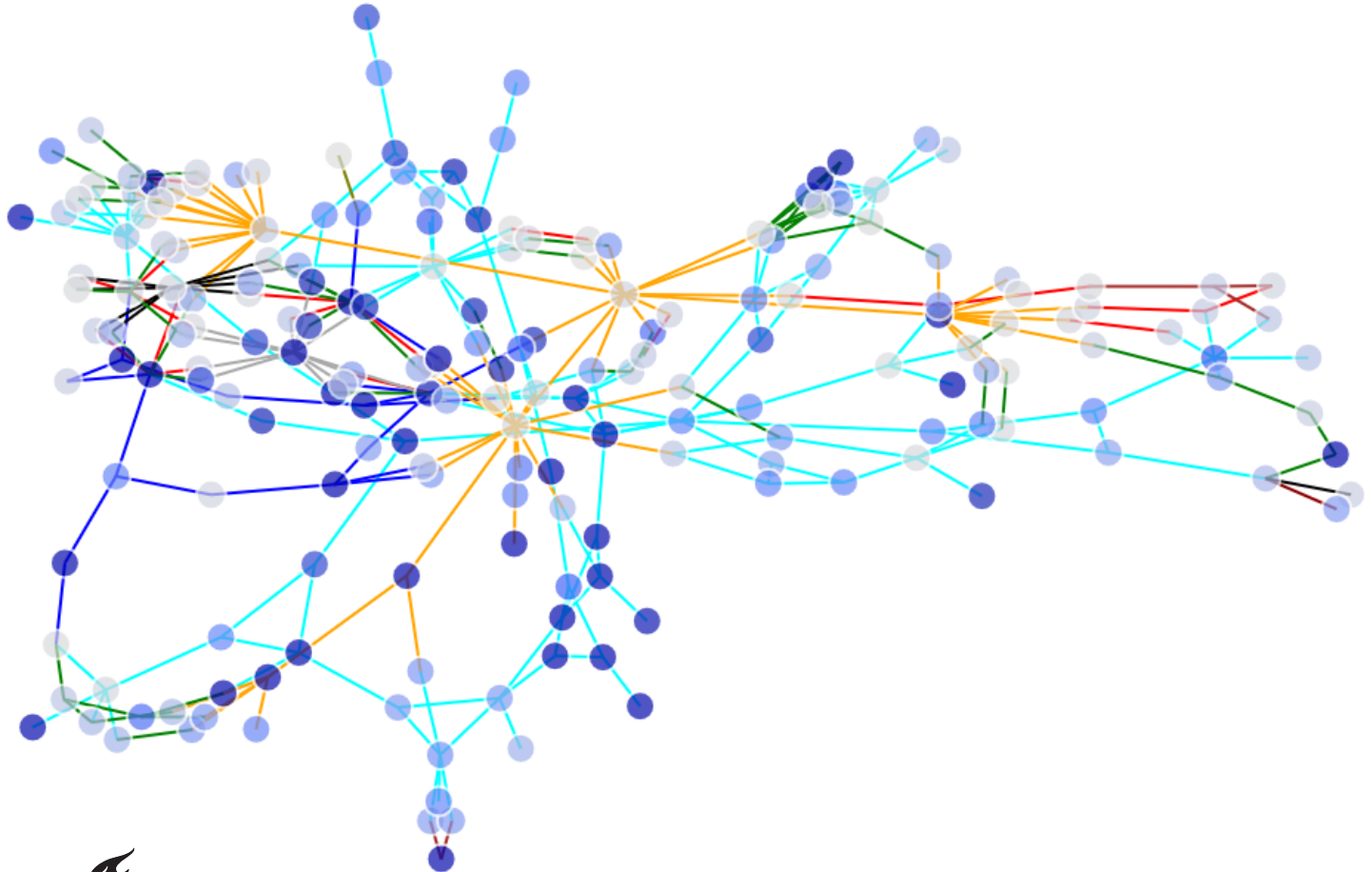
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Introduction

Societal transition to sustainability (the energy transition, resource transition, circular economy) requires a coordinated effort of a large number of diverse societal actors. Such joint action needs a shared understanding about what the world is, what the possible actions are, and what the possible effects of such actions may be. Quantitative modelling is one of the ways to identify and explore these actions and their effects. Where models are loosely defined as *simplifications of reality, created from a particular perspective* ("All models are wrong, some are useful [3]).

Given the complexity of the challenge, considering the problem from a multitude of perspectives can help us get a more coherent and less biased understanding of the "right thing" to do. Using multiple models allows these multiple perspectives to be systematically explored, compared and brought together ("All models are biased, therefore we need more of them" [8]).

While creating models to understand a particular part of reality is already hard, creating models that interact with each other is much harder, especially in a *uniform and structured way*. Combining existing models to form a coherent and consistent understanding of the world pushes the boundaries of science and human cognition.

The goal of this document is to provide a conceptual basis for developing a way of thinking, platform for combining existing models and developing new combinable ones, and supporting institutions needed in order to rise to the challenge of understanding and managing complex societal challenges such as the energy transition.

This document is meant as a start of a long term social and technical process to identify, specify and develop a publicly accessible, open and free digital infrastructure which in principle should allow an arbitrary number and types of computational models, simulations and analyses to interact with each other in a uniform, structured and consistent manner, within a so called multi-model ecology (MME). It builds forth from the Good Modelling Practice for policy support[6].

Such an ecology will facilitate a more systematic approach to modeling coupled energy systems and provide a more reliable basis for decision making under a deeply uncertain energy transition. The document will focus on high level principles, methodological challenges and design guidelines, and will consider technical implementation details and data aspects out of scope.

1.1. MM ecology vision

The core vision underlying this document is that of a multi-model ecology (or ecosystem) [1, 2], presented in figure 1.1.

An ecology can be defined as the "totality or pattern of relations between organisms and their environment". A multi-model ecology is then defined as *an interacting group of models and data sets co-evolving with one another within the context of a dynamic socio-technical environment*.

A multi-model ecology is a perspective - a way of conceptualizing systems of interacting models that emphasizes their evolutionary and socio-technically embedded nature. Viewed through the lens of multi-model ecologies, models and simulations are not isolated elements in a vacuum, but entities co-evolving with one another in a changing environment. The socio-technical context of a multi-model ecology consists of the actors and technologies that make model development a feasible and valued

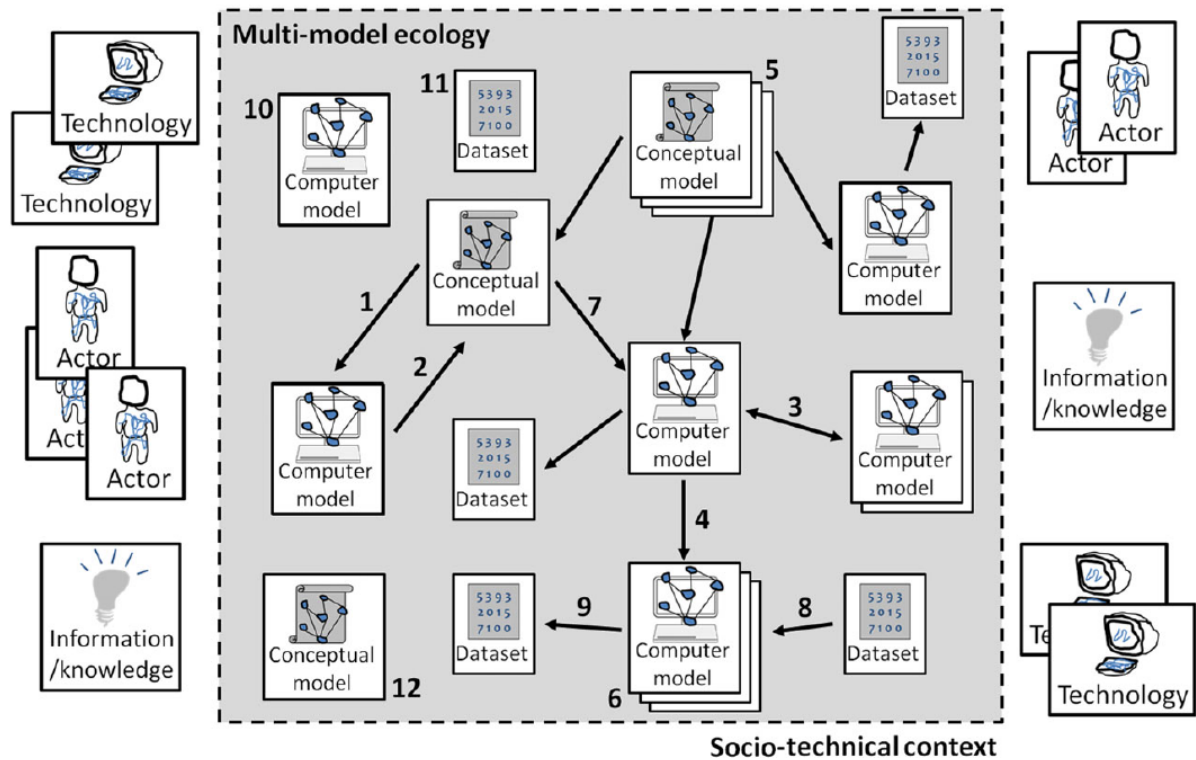


Figure 1.1: Multi-model ecology [1]

undertaking, as well as the knowledge, information, techniques, and theory that inform model development.

The actors of the socio-technical context may include stakeholders, policy makers, funding agencies, researchers, scientific reviewers, domain experts, software developers, and others, each possessing their own set of mental models. Technologies may include technologies such as computational hardware, software platforms, and programming languages, as well as methods such as participatory methodologies and good modelling practices. The actors, technologies, and information/knowledge may change over time. Actors may move on to new organizations or roles, improved software platforms and programming languages may emerge, and new methodologies and techniques may be developed. Likewise, funding for and political and/or academic interest in, particular topics may periodically emerge or evaporate.

Additionally, new knowledge, information, or theory may become available, feeding the development of new models. Models in a multi-model ecology are constructed with different scopes, resolutions, and perspectives, and different models may represent different theoretical viewpoints. Independently, each model provides a partial picture of the components and relationships underlying the problem at hand. Together, they may provide a multidimensional, multi-perspective representation of the relevant systems.

In a multi-model ecology there is no central controller and no fixed starting point for interactions. Any existing or new member of the ecology can initiate a cascade of interactions, leading to an *emergent* multi-model structure answering a particular question.

1.2. MM Interface

The multi-model interface, presented in figure 1.2, is the key component of a multi-model ecology. It is the thing that enables model, data and users to interact. We define an interface broadly, encompassing the notions of a software interface (API), a structured data representation, a software daemon and a structured social process.

The upper, red part of figure 1.2 is the multi-model realm, where the modellers and users are. The user experiences the logical work flow described by the red arrows. Modellers who wish to have their

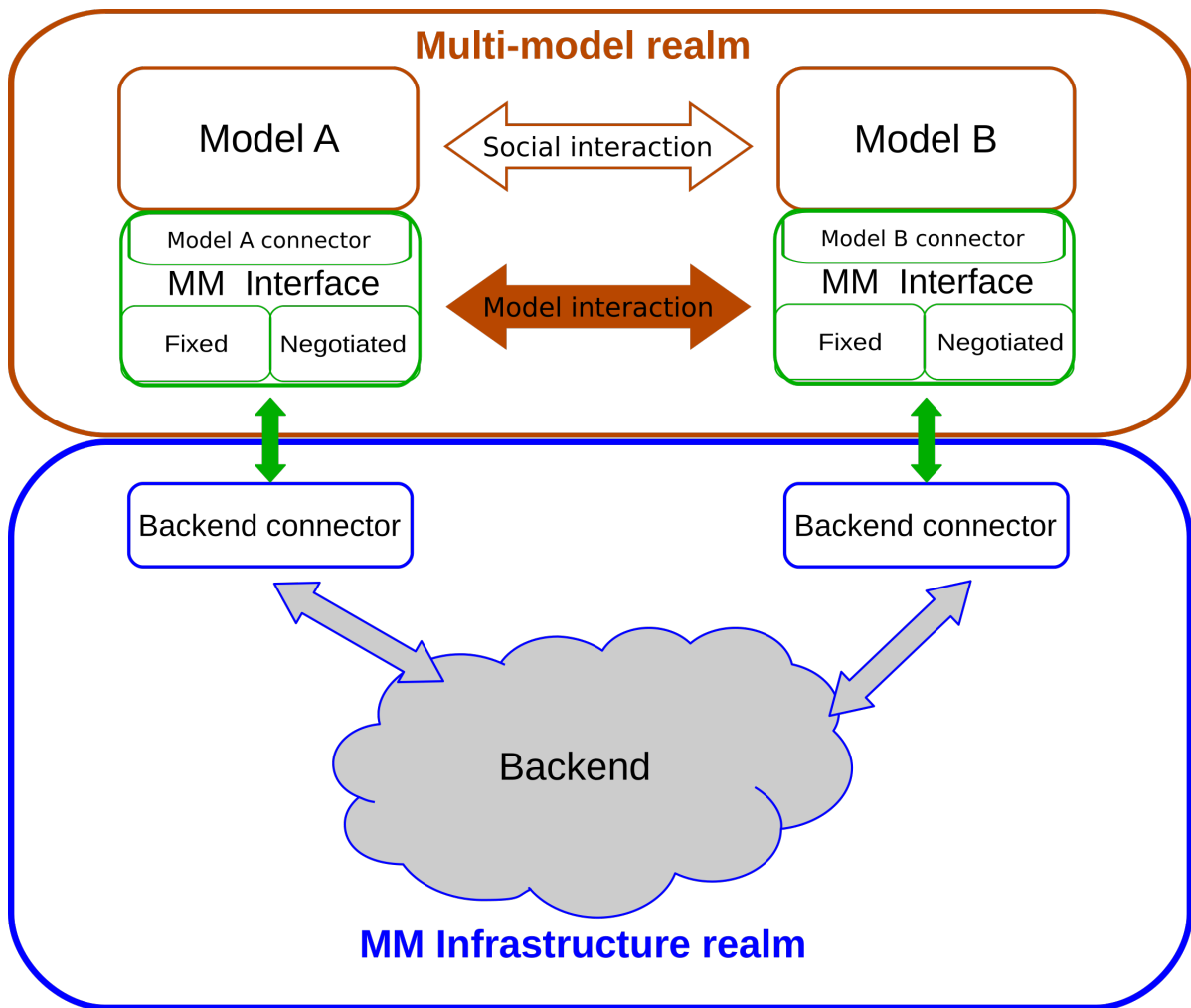


Figure 1.2: Models and their interaction (red), interfaces (green) and infrastructure (blue)

models interact negotiate about what the models are and what should be exchanged between them in order to meaningfully interact. Model A and Model B can then start interacting without direct human intervention. In order to do so, models use the MM interface (the green parts of the image) to send a request message using the interface. The interface consists of a model connector, which operates through the models API to translate internal model variables, actions, etc into a uniform and structured message, that consists of a fixed part and a negotiated part.

The fixed part describes the model metadata such as ID, address etc that are universal for all models that take part in the ecology. The negotiated part of the message, whose structure is agreed upon by modellers, and is specific for interaction between model A and Model B, contains specific variables, values, units, actions, data etc. That message is received by the Model B interface, is interpreted and converted into API calls by the model connector and passed to the model which performs the desired computation and, using an agreed message structure returns the data to Model B.

The interface (green rectangles) is also a software daemon, a service that listens for incoming messages and sends an answer and/or further request messages to other models.

In order for the multi-model ecology to function, several additional technical infrastructure components must be in place (in blue), namely the backend connector, which connects the model and its interface to the backend, which handles the message passing. While the technical details of the MM infrastructure are of great importance and must be carefully constructed, they are a technical problem for which many options exist.

The multi-model realm of figure 1.2 is the conceptually and methodological challenging part and the rest of this document will focus on it.

1.3. Running example

In order to make the document less abstract, we will use a running example for illustration purposes throughout the document.

Lets assume we wish to explore the impact of deep decarbonisation of the petrochemical industry on the energy infrastructure. What are plausible decarbonisation pathways, and can the current infrastructure support them, and if not, what kind of investments do we need to do to enable it?

We will focus on a industrial region, in which many different companies are located, each converting crude oil, or one of its derivatives, into products. Some of these companies can invest in new, carbon free technologies, that use large amounts of electricity, taken from the local high voltage grid. These industries are very sensitive to the global oil price, and will base their investments on it. But, even if the price is right, if the electricity infrastructure is not sufficient, they will not invest.

In order to answer our modelling question, we might use the following multi-model ecology:

System Dynamics model (SDM) A continuous and homogeneous stocks and flow model of a crude oil market price, driven by various geo-political parameters, over the next 50 years.

Agent Based model(ABM) A discrete, heterogeneous model of many different companies, including the infrastructure provider, describing the company investment behavior, within a single year, over a 5 year period.

Load flow model (LFM) A real time simulation model of the energy flows throughout the local high-voltage grid, modelling capacity limitations and cascading failure on the sub-second timescale.

As the model run starts in 2020, the ABM asks the SDM, "What is the current price of crude oil?" SDM considers the various parameters influencing the flow of oil, and the demand-supply equation equilibrium answers "42\$/barrel". The ABM asks each individual company to consider whether they would invest or not. Company A, inside of the ABM model asks the LFM "Can I connect this 200 MW device at this point in the grid? The LFM answers "Yes, but only from 2023 onwards"

The LFM can give that answer because it computed energy flows under thousands of hourly load profiles scenarios, determined that 200 MW cannot be added to the current infrastructure without jeopardizing its stability on particularly wind-still days when the inflows from the offshore windmill are very low. It then sends a message to the infrastructure provider in the ABM "Can I add a power line at this location? The ABM, after computing the cost/benefit of a new client vs costs, answers "Yes, add it, but due to build time, is will only become available in 2023". After all the agents are done, the year is finished, and the process repeats 5 times, until 2025.

1.4. How to use this document

This document provides a vision for starting the process of growing a multi-model ecology and the required interface. It is not meant as a technical specification for implementing a specific MME and MMI. We develop this vision starting with a high level overview of the principles behind a multi-modelling approach. We outline the major methodological challenges involved in multi-modelling. We then translate these into requirements for models to take part in a multi-model ecology. We close the report by discussing the social, organizational and institutional aspects of MME operation and evolution. We end with our advice on how to proceed from here.

2

High level principles

This chapter addresses the high level principles that are fundamental to the multi-model ecology vision. We understand principles as "the spirit" of the ecology, core ideas and necessary conditions for the ecology to work. Given that an ecology is not designed at once but rather it grows and evolves, specific rules and conditions are near impossible to make, and instead the principles provide guidelines for operation and development. They are derived from the insights of the authors and best practices from the multi-modelling academic literature. The 6 principles are :

- Model as a service
- Loose coupling
- Openness and no barriers to entry
- Embracing FAIR
- Growing into complexity
- Embracing the social process

2.1. Model as a service

Our key vision is that models are conceived as independent software entities, that listen to a shared message infrastructure, and act/react when needed or desired, offering "model result services". These models are owned, built and maintained by one or more organizations working on the energy transition, are either in public or private domain, open or closed source, using public or private data. As long as a model can send or receive a message with at least one other model, the model is a part of the multi-model ecology.

2.2. Loose coupling

We aim for a very basic, low level structure, upon which messages between models can be passed. Except for the fixed part of the interface, which must be unified in order to make communication possible, the exact structure, format and content of inter-model communication is agreed upon between the modellers. There is no predefined structure of model interaction, but rather a cascade of interactions across a network of models and data. From different starting points, meaning different modelling questions, very different interactions structures may emerge out of the same multi-model ecology.

The interface specification can also be understood as a contract that is agreed upon by all who wish to take part in the multi-model ecology. If you "promise" to send a message using the interface specification, the interface "promises" that it can be received by the the recipient.

This does not mean that it makes sense that the question is asked or that that the message can be understood by the recipient; neither are part of the interface contract. How the models understand the question and how it answers is up for agreement between two specific models, expressed using the interface structure and vocabulary.

2.3. Openness and no barriers to entry

It is paramount that the interface specification is based on open source software and open standards. If a multi-model ecology, that the MMI supports, is to be used in a public debate, its inner workings (in terms of how the interaction actually take place) must be publicly accessible and verifiable. Furthermore, if it is to serve a public function, there should be zero or minimal barrier to entry, meaning that anyone should in principle be able to connect a model to the interface, without artificial, technical, organizational, or financial limitations. Do note that while everyone should be allowed to speak through the interface, nobody should be forced to listen. The latter is, again, up to the individual models to agree on and make sense in relation to the modelling question.

2.4. Embracing FAIR

The Dutch government has embraced [5] the FAIR principles [10] for data. We believe that the same principles should apply for the multi-model ecology, interface and models taking part. FAIR for the MME/MMI could be defined as :

Findable easy to identify and find for both humans and computers, with metadata that facilitate searching for specific models

Accessible stored for the long term so that they can easily be accessed and/or downloaded with well-defined access conditions, whether at the level of metadata, or at the level of the actual model,

Interoperable ready to be combined with other models, without ambiguities in the meanings of terms and values

Reusable ready to be used for future research and to be further processed using computational methods. This requires adequate information about how the model is to be used and an appropriate license

2.5. Growing into complexity

A multi-model ecology is a Complex Adaptive System, for which Gall's 'law' [4] applies : : "A complex system that works is invariably found to have evolved from a simple system that worked. A complex system designed from scratch never works and cannot be patched up to make it work. You have to start over with a working simple system. "

We cannot expect to design some interfaces, deploy a communication infrastructure and have the ecology magically work. We must grown into the complexity, by creating simple, yet useful interfaces, model couplings and rules of engagement. Given that the only constant is change, any design we initially come up with will eventually become inadequate. Every decision should be taken from the perspective that the the ability of the system to adapt must not be reduced.

2.6. Embracing the social process

As already hinted at throughout the previous discussion, the multi-model ecology and its interface are socio-technical systems. It is impossible to create and maintain by only technical means. The definition of problems, identification of models and data, interpretation of outcomes and sense making interactions is a social process that must be explicitly acknowledged, consciously designed to be evolveable and embedded in wider institutions if it is to endure over time.

Challenges of multi-modelling

Building, analyzing and using models is challenging at the best of times, requiring careful and deliberate choices on problem statements, system definitions, choice of modelling formalism, implementation details, verification, validation, analysis etc. When using multiple models together, especially when they are developed by different people and for different purposes is exponentially more difficult than working with single model.

In this section we will identify some of the key challenges that arise when models are combined. They are meant both as general methodological attention points for multi-modellers and users during sense-making and as requirements for the multi-model interface. It should be noted that we are operating at the very edges of modelling science. While this is an ongoing academic debate in the literature, we are still very far from solving these issues.

We will discuss the challenges from the 'inside-out', starting with the core ontology of a model and finishing our discussion with analysis and interpretation. For each challenge we will present a definition, an example and the challenge.

3.1. Incompatible ontologies

Definition By ontology we mean the fundamental "truth" or the basic concepts underlying the model. This ontology is often implicit, but can also be explicitly defined as a formal, computer readable ontology.

Example 1: Ontologies

The load model is based on laws of nature, specifically Ohm's law and Kirchhoff's laws. These laws describe basic concepts such as current, voltage and resistance and their relationships, which are unambiguously defined. Furthermore, there is no alternative set of equally plausible laws and their meaning is not open to interpretation.

The ABM describing the company investment behavior is built using the accounting ontology, defining concepts such as profit, margin, CAPEX, OPEX, net present value etc. While these concepts can be precisely defined, there are multiple plausible ways to do so. Furthermore, the modeller could have chosen a number of alternative ways to describe the firm, like the production theory from microeconomics.

Challenge Models based on the same ontology are fundamentally easier to connect than those with (possibly radical) different ones. It does not mean that they can be trivially connected, since any of the challenges discussed in the rest of the chapter still apply. When ontologies are different, the social process must ensure a correct and useful translation and interpretation of concepts takes place.

3.2. Multi-formalism alignment

Definition With model formalism we mean the fundamental mathematical or algorithmic representation underlying the model. There is a plethora of formalisms, each with their own strengths and weaknesses. None of them are by themselves correct or incorrect, only more or less useful for a particular problem.

Example 2: Formalisms

The oil market model is a System Dynamics model. The formalism used is that of coupled partial differential equations within a continuous time domain. Such differential equations cannot be solved analytically, and must be evaluated using an iterative numerical solver, such as the Runge-Kutta method.

The investment model is Agent Based. The basic formalism is that of coupled state machines within a discrete time domain. These are typically represented using a computer programming language such as Python or Java.

While SD has a continuous representation of time, its solver works in discrete time steps. ABM also has discrete time steps, which for this model are defined as 1 year. Should the models interact by running their time steps in parallel, passing data back and forth each time step of the ABMs clock and SDs solver? Technically this is trivial, but conceptually it makes no sense, as every timestep of the SD solver has a different, unpredictable length. Therefore a different, much more complex, interaction structure has to be designed to get meaningful interaction.

Challenge The main challenge we have to deal with is to explicitly decide what it means when different formalisms are connected. Alternatively, given the meaning we wish to express, what is the correct way to connect them. Furthermore, is the chosen interaction structure meaningful? How can and should a model outputs be used, given that it is produced in a specific fashion? Can the meaning of that output even be represented in the other formalism, e.g. when a model does not have a representation of time.

3.3. Conflicting rationalities & abstractions

Definition We define rationalities as sets of intentions, perspectives, motives and logic that the model creator has. Rationalities necessarily bias the way a model question is posed, how the model is constructed and how the outcomes can be and are used.

Abstractions are the specific ways a part of reality is represented in the model. They depend on the rationality of the modeller, the ontology and formalism used, and the purpose of the model. Even when modellers use a shared ontology (such as the laws of nature), the abstractions used can differ substantially.

Example 3: Rationalities & abstractions

Our SD model of the global oil price is constructed from the rationale of exploring the interplay of geopolitical forces, technological development and resource availability per continent. The rationale behind ABM's representation of investment behaviour is the representation of actual decision making behavior of firms, who own and operate technological assets of particular type.

SD abstracts technology as a factor affecting oil demand in a country. The ABM abstracts technology as a mass balanced input-output transformation of oil to specific products.

If an ABM would ask the SD what is a countries current dominant technology, the answer could not be understood as it is abstracted in an incompatible manner. Part of the reason for this incompatibility is the difference in rationales, namely a high level exploration of assumed interplay of forces vs representation of specific behavior observed in reality.

Challenge The key challenge is to identify and make the rationality behind the model explicit. This requires that the modeller is aware of her world view, biases and frames, and that she can articulate them in a way that others can make a useful interpretation of the model from their own perspective. Identifying abstractions is equally difficult, as it requires stepping back from the "well, its just logical" and relating ones choice of abstractions as explicit as possible to possible alternative ones. Different abstractions, as is the case with formalisms, are not per se a problem, but we must be very aware which abstractions are used in different models, especially when applied to the same concept.

3.4. Scaling

Definition By scale we mean the spread between the smallest and largest system dimension that a model is capable of describing, and are a part of the system boundary description. Model scales can be identified across a number of dimensions, most common being : time, space, energy, mass, social, economic and institutional. Scale is strongly linked to the concept of system boundaries, discussed in [6].

Example 4: Scaling

The SD has a single country as a smallest element of analysis, and the entire world as an upper limit for the spatial scale.

Time scales from is from 1 year to 50 years. Processes and mechanisms that are shorter or longer that this period can not be described.

The ABM model has a firm as the smallest organizational element, and the regional industrial network as the largest. Since it considers local contracts, national regulation and EU regulation, its institutional scale is broader than its organizational, going from region to supranational.

The LFM does not have temporal scale, is it computes the equilibrium state of the grid without any dynamics.

Challenge Challenges for model coupling mainly rise when scales overlap and when they are non-contiguous, i.e., there is a gap between their scales. If they overlap, can we assume that phenomena at the same scale are directly transferable? Does overlap on one scale make them comparable, and what is the effect if other dimensions do not? When model scales are separate, how do we scale the outcomes up or down? Can we take a model that operates on a 1x1 km and just multiply it by 1000 to get the 100 km x 100 km number to feed to the bigger scaled model?

3.5. Model fidelity, resolution, accuracy and precision

Definition These four properties of models and their outcomes are closely related, but are fundamentally different. By model fidelity we understand the ability of the model to describe mechanisms, processes, events, entities etc, and how close they correspond to the real life. It can be understood as the degree of similarity, or measure of realism of the model. Model resolution is the level of structural and behavioural detail that events, mechanisms, processes, etc are described in, regardless of how realistic those model elements are.

Model accuracy is the degree to which model outcomes are different from the "true" state of the world that the model tries to describe. It is a measure for the error the model is making, so it deals with questions such as "is the number that the model reports correct?". Precision is the measure of the stochastic variability in the model outcomes, so if a model run is repeated many times, how much variability is there in the outcomes. It can also be understood as the number of significant digits in the answer, regardless of how 'correct' the number itself is.

Example 5: Fidelity, resolution, accuracy & precision

The load flow model (LFM) has a high fidelity, as it directly describes the laws of nature. It has high precision, as it consistently provides the same answer with the same input parameters, and its accuracy is more than sufficient for the task at hand. It does however make systematic errors, as it assumes DC current flow, whereas the grids is AC. An AC grid flow model would have much higher fidelity and accuracy, but at the cost of a much more complex model structure and much longer computational effort.

The SDM also has a relatively high fidelity, as it explores the interactions between well documented and realistic mechanism. Its resolution is very low, as its smallest level of detail is a country. Its accuracy is relatively low, as such a model cannot capture the many details that drive the current oil price, and its precision is low, as it contains chaotic feedback loops which provide a wide output band.

Challenge When models of incompatible scales are to be linked, we can be almost certain that their ontologies, formalisms and rationalities are different. The process and meaning of up and down scaling of results must be carefully explored.

Furthermore, when connecting models in a model ecology, we can think of these properties as the space of *useful ambiguity*. Is the error margin on my model results relevant for the model who receives them? Am I being overly precise, and can maybe perform a faster, less precise run? How much am I allowed to round off your results?

3.6. Variability, uncertainty and noise (propagation)

Definition We understand variability as the loss of precision due to models internal mechanisms. Specifically, models with stochastic components and complex time dependent mechanics with feedbacks will display variability in outcomes, and are usually analyzed and interpreted using statistical properties of these outcomes over many model runs.

Input data is uncertain when we can assign a probability distribution to the value of a variable. This input uncertainty is modified as the model mechanisms operate on the variable and its value. Depending on the specific mechanics, the uncertainty can be greatly reduced or increased.

By noise, or modelling artifacts, we mean effects of outputs that are not driven by the model mechanisms or data uncertainty but by limitations of the formalism used, limitation of the particular software used etc. Key is that they do not represent meaningful information, and are therefore noise that only obscures the true outcome of a model. Examples are roundoff errors, aliasing, biases in randomness etc.

Example 6: Variability, uncertainty and noise

The SD model uses an iterative numeric solver to compute the integral of the coupled partial differential equations. Under specific, not necessarily obvious, conditions interactions between the solver step size and the equations create numerical instabilities which lead to output dynamics that is completely artificial.

The ABM simulates parallel action of agents by randomization of agent iteration order. Given that ABMS are coupled state machines, they are susceptible to chaotic behavior, where accidental but highly specific interaction order created by random mixing can become greatly amplified and create artificial outcomes.

Challenge Dealing with variability, uncertainty and noise is difficult in a single model. In a multi-model ecology, we are creating cascades and loops of variability, uncertainty and noise propagation. The effects of these can be exceptionally difficult to identify, trace and consider during sense making and interpretation, but doing so is of utmost importance.

3.7. Communicating and retaining meaning and intention

Definition Meaning and intention are the highest level aggregate properties assigned to models, that are explicitly and implicitly defined by all of the previous elements. We define the meaning as *the what* of a model and intention as *the why*. Being precise, the model itself does not have a meaning, it is "just" a machine. Meaning and intention is imbued into it by its creator who constructs in a particular way and the initial user who used it in a specific way. However, for practical purposes we do not separate the "machine" and "human" parts.

Example 7: Meaning and intention

In our example, the load flow model has the most explicit meaning : what is the current and voltage in a electrical circuit of a particular topology? The intention is also straightforward : identify situations under which the energy flows will disrupt the grid. The meaning of the ABM can be understood as : what is the result of investment behavior of a collection of firms over time? The intention can be understood as: understand how firm investment behavior affect the development of energy infrastructure.

Challenge The key challenge here is the epistemic opacity, *the what* of the model being unclear. Especially large models, that have been built over decades by many different people, such as the PRIMES model used by the EU for its energy policy are completely opaque, with nobody, or just a handful of people fully understanding them. When we start linking models in a ecology, this problem explodes. If we do not understand even a single part, how are we to understand the coupled dynamics arising from the interactions between components?

Considering the intentions, the challenge is to create insights at the multi-model level with a collection of models whose intentions fit the required role. How do we frame a modelling problem so that complex outcomes created are understandable and acceptable, which is key for acceptability, authoritativeness and usefulness of multi-models?

Finally, when used in a politicized social discourse, the validity of multi-models is easier to challenge, as attacking one component might undermine the authoritativeness of the entire multi-model. When Model fidelity, resolution, accuracy and precision are dealt with properly, this problem can be limited.

3.8. Analysis and Interpretation

Definition By analysis we mean the activity of exploring the model outcomes, quantitatively and qualitatively identifying and describing properties of the results as function of model inputs.

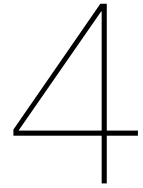
By interpretation we mean the social process of assigning meaning to identified features of model results. Interpretation is the final translation between the model world and the world of the user and their decisions and actions.

Example 8: Analysis and Interpretation

In our example, the load flow model has the most explicit meaning : what is the current and voltage in a electrical circuit of a particular topology? The intention is also straightforward : identify situations under which the energy flows will disrupt the grid. The meaning of the ABM can be understood as : what is the result of investment behavior of a collection of firms over time? The intention can be understood as: understand how firm investment behavior affect the development of energy infrastructure.

Challenge Analysing and interpreting model outcomes is hard with single models, and is at least a order of magnitude more complex with multi-models. With multi-models we are quickly approaching the so called "model comprehension barrier" : our ability to comprehend. All of the issues discussed previously culminate here, increasing the difficulty of assigning meaning to the numbers that we get out of the multi-model. As we have designed our multi-model carefully, with a specific purpose in mind, we need to extract signal from the noise, ensure that the correct meaning is preserved across all of the involved transformations and that what is left is useful and acceptable to the users.

Furthermore, when using models it is relatively easy to "game them" and "cook the numbers" in order to get the outcome that is desirable. When using multi-models, this problem becomes more complex. On the one side there is more space to game: every model can be tweaked to get better and better results. On the other hand, multi-modelling protects us from gaming the outcomes, as many if not most of the models in an ecology are not under our control, and we have limited understanding of their internal processes. Even more than with single models, analysis and interpretation of multi-models is a socially negotiated process and is really, really hard.



Interface guidelines

This section will discuss the key types of information and knowledge that should be communicated across the MMI, in order to deal with the challenges presented in section 3. As presented in figure 1.2, the interface consists of a fixed and negotiated parts.

4.1. Fixed part

The fixed part of the interface can be understood as the boilerplate, the ID card of a model wishing to take part in the multi-model ecology. It contains the metadata required for meaningful interaction and basic sanity checks. We will not discuss technical elements needed for basic communication and compatibility, such as unique identifiers for a organization, model, time stamps, unique message ids, version numbers, etc. as these are handled by the specific technical implementation.

The fixed part should help the multi-modeller to identify the right model, verify basic fitness for purpose, understand basic interaction requirements and get a sense of the uncertainty involved.

Based on the challenges identified in the previous chapter, we will describe six groups of high level guidelines for the fixed part of the interface.

4.1.1. Ontology and formalism used

In order to deal with challenges presented in sections 3.1 and 3.2 the interface should be able to make explicit and communicate the underlying model ontology and formalism used.

Ideally, a strict formal description of ontologies and formalisms used is used to make it unambiguous. However, as there are very many possible ontologies and formalism that can often be interpreted in a number of ways, a pragmatic approach would be to develop a taxonomy/tag based identification system that allows for multiple interpretations and meaning.

It would also be desirable to develop a reasoning guideline for the modellers, aiding in recognition of specific problems and viable solutions when combining specific formalisms and ontologies present in the actual ecology.

4.1.2. System boundaries, scales, assumptions and limitations

A model must be able to specify its system boundaries, if we are to start addressing the challenges presented in sections 3.3 and 3.4. Some aspects of the system boundaries can and should as much as possible be communicated precisely in a machine interpretable manner, such as the minimum/maximum spatial or temporal scale. Others, such as assumptions, limitations, artefacts may need to be communicated in a human interpretable fashion, for example through rigorous model documentation, discussed in good modelling practice white paper[6].

4.1.3. Interaction specification

Models greatly vary in how they can be interacted with. Can they be interrupted/resumed? Can a model be stepped through, or made to run backwards? What are its synchronization points? Can we run more than one instance in parallel? How long is the computation expected to last? Seconds? Months? The interface should be able to describe these in an unambiguous, machine interpretable fashion.

4.1.4. Model fidelity, resolution, accuracy and precision

In order to address challenges defined in section 3.5 and 3.6 preferably a machine readable specification should be created that describes the general levels (min/max) of fidelity, resolution, accuracy and precision for the model overall. In the flexible part, which is specific to a particular model interaction, these should be addressed again in more specific terms.

4.1.5. Input and output data

While, as mentioned in the introduction, data are out of scope for this paper, the interface must be able to specify various aspects related to input datasets. Models should be able to unambiguously communicate which data are required, their availability, quality, ownership, etc. Specifically when machine learning type models are employed, where training data are de facto part of the model, this is important.

If the interface is to rise to the challenge of uncertainty propagation discussed in section 3.6, great care must be taken when defining the input data specifications. Likewise, output data variability and noise should be explicitly specified.

Finally, part of the fixed interface should be the model output when run with standardized, public sets of reference data. This provides a baseline from which model differences can be identified.

4.1.6. Model meaning and purpose

The key piece of information that must be communicated is the meaning of the model and its purpose. It must be clear why the model is developed i.e., what kinds of questions it is meant to answer with which kinds of inputs. If possible, alternative model uses and means should also be identified, together with the conditions under which this alternative model use is possible.

Describing this kind of information in a machine interpretable manner is exceptionally difficult, if not impossible. It is however key that the users and modellers engaging in the social process can have a clear and unambiguous understanding and can negotiate the exact way how a particular model can and should be used in the MME, and maybe even more importantly when and how it should or cannot be used. Identifying the model meaning, purpose etc, is extensively discussed in the accompanying good modelling practice white paper [6].

4.2. Flexible part

The flexible part of the interface is the business end of it, where the actual communication between models takes place. It should provide the basic consistent format for expressing a wide range of information. Some of the elements it must be able to express are: variables, their values and units, uncertainties associated with them. Furthermore, control focused elements, such as model start, stop, synchronization, stepping, etc must be expressible. For many of these e.g., SI unit checking and conversion, solutions already exist, and existing open standards should be followed as much as possible.

5

Institutional embedding, continuity and evolution

As discussed in section 2.5, a multi-model ecology needs to grow/evolve, rather than be designed at once. A key component for the growth is the social structure it grows within, and the ability of that social structure to co-evolve with the technical components. There are two related but distinct parts to the social structure: The rules of engagement with and within the ecology and the institutional embedding of the socio-technical entity that the ecology is.

With the move towards a multi-model ecology, we are involved in a paradigm shift akin to the change from unconnected desktop computers in the early 90's to the fully internet connected devices today. Traditional logic, workflows and arrangements will only take us so far, and we need to prepare for, and garden the emergence of novel ways to develop models, especially in the policy support domain.

There is no single correct way to set the rules and organise the institutions that stimulate and facility a thriving multi-model ecology. There are many preferences and practical solutions available, and regardless of what is chosen, we must ensure that it can change.

5.1. Rules of engagement

The rules of engagement concern the way how models and modellers join the ecology, how they discover which models exist and can be interacted with, how the interactions between models are negotiated and how sense-making is performed.

The open source software ecology provides many inspiring examples of how this can be organized [9], models ranging from benevolent dictators, to voting processes and community consensus agreements. It is not possible to provide specific rules of engagement, given the high level of this document, other than that they must be created and must have the authority of the involvement of the community of users and modellers. Key is that we identify a (process) owner driving the growth of the ecology.

5.2. Institutional embedding

This notion of a key (process) owner brings us to the final question of institutional arrangements. The ecology is an interplay between the models/data and their owners, the model users and the infrastructure that makes interaction possible. That infrastructure can be considered as a "common" [7], such as the seas or atmosphere, a resource that is owned by everybody, and thus by nobody. It is of vital importance that this public common has a owner and a home.

Given the public and open nature of it, it makes sense that an independent body, such as the government, university, a dedicated foundation or some other entity, which has sufficient and long term funding is the process owner.

This owner has to be sufficiently staffed and able to perform the complex and hard janitorial tasks such as maintaining the software components, providing documentation and examples, advises new and existing users etc.

Next to the owner, an advisory body, user council or something of that form should exist in order to manage the growth and evolution of the ecology and the interface. That body has the difficult task of balancing stability and growth. The interfaces must be stable, and "keep the purity of the founding principles" if they are to be useful and should be against short term individual interests. However, it must also be able to grow in order to remain useful and relevant.

6

Way forward

This white paper presented a high-level vision, challenges and interface guidelines for developing and maintaining a multi-model ecology. We have specifically chosen not to discuss the technical implementation detail, fully aware that they are essential for the functioning of the ecology. The exact technical setup is highly dependent on the specific application domain, existing model, stakeholders involved and technology available at that moment. Also, while these technical details are by no means trivial, the greatest challenge lies in the conceptual and methodological aspects of multi-modelling, which is academically still a very new field with much to be explored.

Furthermore, to our knowledge there is relatively little practical experience in structured multi-modelling, with model interactions developed in an ad-hoc fashion. This is especially the case in modelling large scale societal transitions for policy support. We hope that this document is a first step in the development of a systematic and transferable vision, approach and tooling for multi-model ecologies. Looking forward, we see a number of steps that can be taken.

First, develop practical experience and methodological tooling by doing concrete projects, solving real problems. Key is that in these projects academia, industry and government closely collaborate. By treating each model coupling as a controlled experiment we can develop a greater confidence in that specific multi-model, create valuable case data for methodological development, and develop the technical infrastructure further.

Second, developing the required knowledge requires a long-term vision and commitment. We believe a joint and focused effort by government, academia and industry in forms of research and implementation programs will greatly accelerate the development of a multi-model ecology.

Finally, if a multi-model ecology is to become public and open digital infrastructure, it is essential that institutional embedding is ensured. An public interest organisation is required to manage, maintain, develop and support the ecology en enable long term sustainability of societies ability to combine models and produce insights for a greater public good.

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