EMPOWER

Empowering Teachers for Science Learning
Through Modelling-Based Approaches

The EMPOWER Framework for MbL

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Introduction

Welcome to the EMPOWER framework for modelling-based learning. This framework has been created to support you as a teacher, teacher educator or otherwise interested in designing education based on modelling. This interactive document provides background information on the tools to use, suitable domains, how to support your students and what you may expect they have learned in the end.

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Read more...

Starting questions

1. What do we know about MbL?
2. What are the expected learning outcomes?
3. Which modelling tools are available?
4. Which topics or domains are suitable for MbL?
5. What are issues for implementing MbL?

References

1. What do we know about MbL?

1

Definition of MbL
The learning goals of MbL
MbL cycles
Modelling in curricula

Definition of MbL

Modelling-based learning is a teaching and learning approach in which students engage in scientific modelling

Modelling-based learning is a teaching and learning approach in which students engage in activities of constructing, revising, comparing, testing, and using representations to understand, predict or explain phenomena.

The goal of MbL typically includes two aspects: learning about the phenomena under study as well as building modelling competence, which we can define as the ability to model as well as a higher understanding about models, often called meta-modelling knowledge.

The learning goals of MbL

MbL supports two connected goals:

Understanding the phenomenon under study, that is developing knowledge about the system or process that is being modelled. Example: when modelling the solar system, learners are expected to learn about the movement of the planets.

Developing modelling competence (the ability to engage in scientific modelling), meta-modelling knowledge (epistemic understanding of the nature, purposes, functions, strengths, and limitations of models), and metacognitive knowledge about the modelling process. More on expected outcomes regarding modelling competence can be found here.

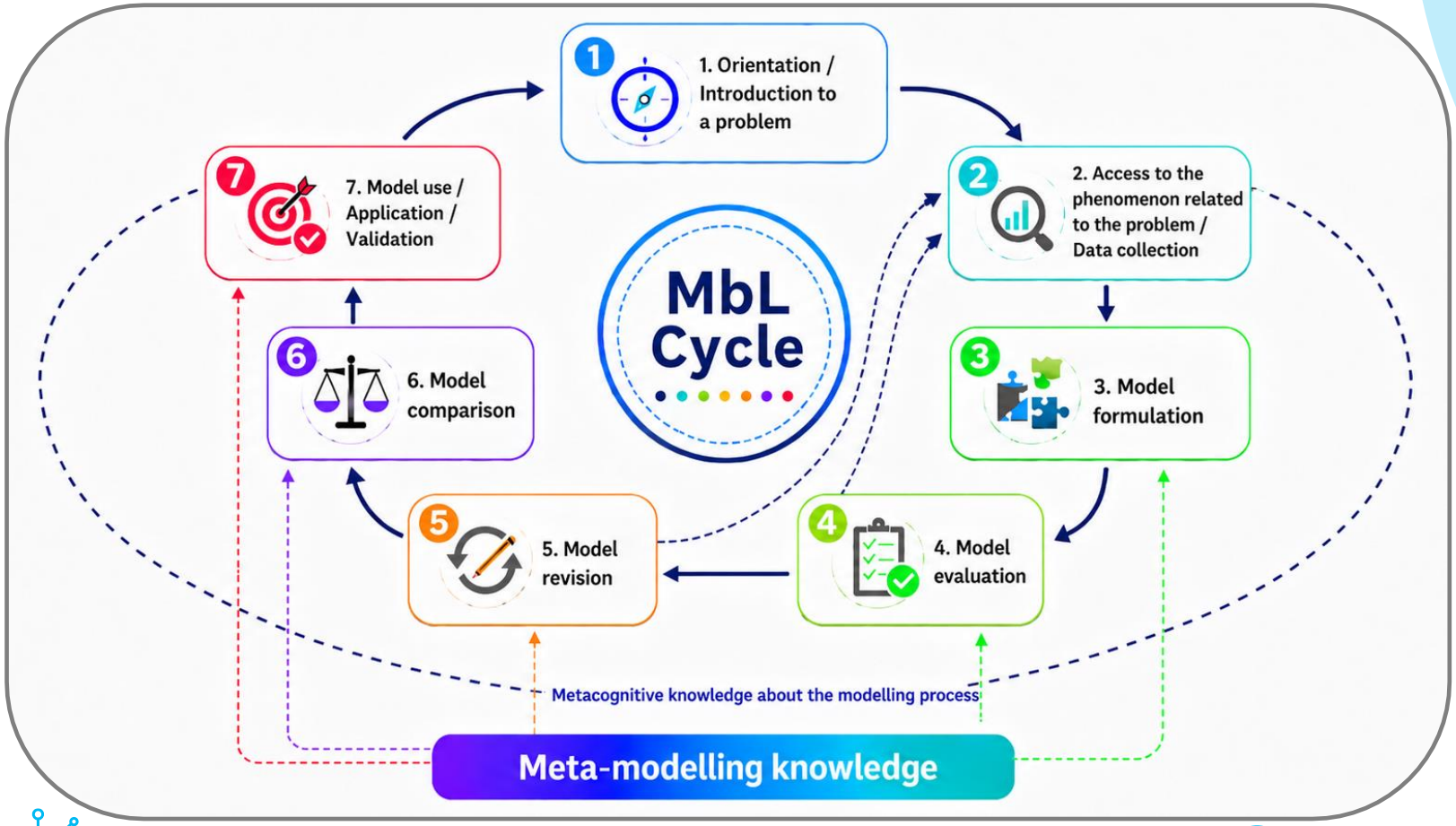
MbL cycles

Modelling is a process in which students start from initial ideas and create, test and use a model. The modelling process is often represented as a cycle, in which several phases occur such as orientation and introduction to a problem; access to the phenomenon related to the problem and data collection; model creation; model evaluation; model revision/reformulation; model comparison; and model use, application, or validation.

However, taking the cycle too literal might hinder a fruitful modelling process. In practice, modellers go back and forth between phases in the process, often to iteratively improve the model and their understanding of the phenomenon they are modelling.

On the following pages you find a graphic depiction of a modelling cycle and a description of the different modelling phases.

Graphic depiction of the modelling cycle



Phase 1: Orientation / Introduction to a problem

Students are introduced to the phenomenon, system, or problem and clarify what needs to be explained or solved. They activate prior knowledge, identify initial questions, and consider the purpose of modelling.

Phase 2: Access to the phenomenon related to the problem – Data collection

Students observe, explore, or measure relevant aspects of the phenomenon and collect data or evidence needed for modelling. They consider what information is needed to understand the phenomenon and support construction, testing, or revision of a model.

Phase 3: Model formulation

Students construct an initial model by identifying the relevant elements, variables, parameters, and relationships. They also decide what aspects of the phenomenon should be represented and recognize that the model is a simplified representation of reality (not every aspect of the phenomenon should be represented).

Phase 4: Model evaluation

Students test and evaluate the model by comparing it with evidence, observations, or reality. They may use a checklist, criteria list, table, or rubric to examine whether the model represents key aspects of the phenomenon, explains relationships or provides a mechanism that explain how the phenomenon functions, and can be used to make predictions. Such predictions can be compared with data collected from the phenomenon.

Phase 5: Model revision

Students revise the model based on evidence, feedback, evaluation results, or new understanding. They identify what needs to be changed, explain why the revision is needed, and decide how the model can be improved.

Phase 6: Model comparison

Optionally, students compare different models, including their own, peers' models, or scientific models. They examine similarities, differences, strengths, limitations, and consider which model is more appropriate for a specific purpose.

Phase 7: Model use – application and validation

Students use the model to explain the phenomenon, make predictions, solve a problem, or apply it to a new situation. They also consider whether the model is trustworthy and whether the model is valid within its assumptions and limitations.

Using the model may give rise to new observations and questions that can trigger a new modelling cycle.

Modelling in curricula

We analysed the curricula in Spain, Germany, Cyprus and The Netherlands. Across these countries, science curricula emphasize core elements such as scientific inquiry, conceptual understanding, and real-world application. However, MbL is not consistently positioned within these frameworks. The extent to which MbL is framed as a distinct scientific practice, a core competence, or a supporting instructional tool varies considerably between the countries. In some contexts, it emerges as an explicit scientific practice tied to disciplinary thinking, while in others it remains embedded within broader inquiry processes or appears as a practical teaching tool linked to specific content topics. These differences reflect not only structural variations but also differing epistemological orientations towards science education.

Modelling in curricula – ctd.

The corpus of analysed materials varied significantly across countries. In Germany, the analysis covered 67 curriculum documents from all 16 federal states, reflecting the decentralized nature of the education system, resulting in 1322 references to MbL. In Cyprus, both primary science and lower secondary biology curricula were examined through teacher guidebooks, resulting in 114 references in primary science education and in 215 references in lower secondary biology education. The Dutch report focused on the newly developed national core objectives, identifying 30 references to MbL, while the Catalan curriculum in Spain yielded only a small number (2) of relevant instances.

In the curriculum analysis we found that within the studied countries, many different types of models are mentioned.

2. Expected learning outcomes

2

MbL is a teaching and learning approach that allows to foster various skills and competencies, including students' content knowledge, communication, evaluation, and inquiry skills. Most prominently in MbL, students are expected to develop modelling competence; that is, a system of the dispositions necessary to engage in the practices of developing and using models for reasoning in science.



Dispositions

Modelling competence entails various *dispositions*. In literature, the main focus is on knowledge relevant to modelling: Knowledge about models and about the modelling process.

Knowledge about models

Knowledge about the modelling process

Further dispositions relate to the need to engage in the modelling practices and to build models of the relevant phenomenon and self-regulative abilities (e.g., volition).

Knowledge about models

Students are expected to develop knowledge about the nature and purpose of models in science
Knowledge about models can be broken down into five aspects (Figure 1). For each aspect, knowledge of models can be subdivided into three different levels: ranging from a naive understanding of models as depictions and copies of reality (Level 1) to a sophisticated understanding of models as theoretical entities and research tools (Level 3).

Knowledge about models – ctd.

Table 1. Framework of model competence by Upmeier zu Belzen et al. (2019:p. 13)

Aspects	Level I	Level II	Level III
Nature of Models	Replication of the phenomenon	Idealised representation of the phenomenon	Theoretical reconstruction of the phenomenon
Multiple Models	Different model objects	Different foci on the phenomenon	Different hypotheses about the phenomenon
Purpose of Models	Describing the phenomenon	Explaining the phenomenon	Predicting something about the phenomenon
Testing Models	Testing the model object	Comparing the model and the phenomenon	Testing hypotheses about the phenomenon
Changing Models	Correcting defects in the model object	Revising due to new insights	Revising due to the falsification of hypotheses about the phenomenon

Knowledge about models – ctd.

How to reach?

- Provide students the opportunity to explicitly discuss and reflect about models
- Address all aspects and all levels (not all within the same lesson)
- Ensure that models are discussed not only as tools for representation and explanation, but also as tools for inquiry and reasoning in science

Knowledge about the modelling process

Students are expected to develop knowledge about the iterative and cyclic process of modelling in science

While modelling, the modeler switches between the real (experiential) world and the model world (Figure 1). In doing so, the modeler follows various steps in the modelling process. These include, for example, exploring the phenomenon, developing a model, and testing a model.

Knowledge about the modelling process – ctd.

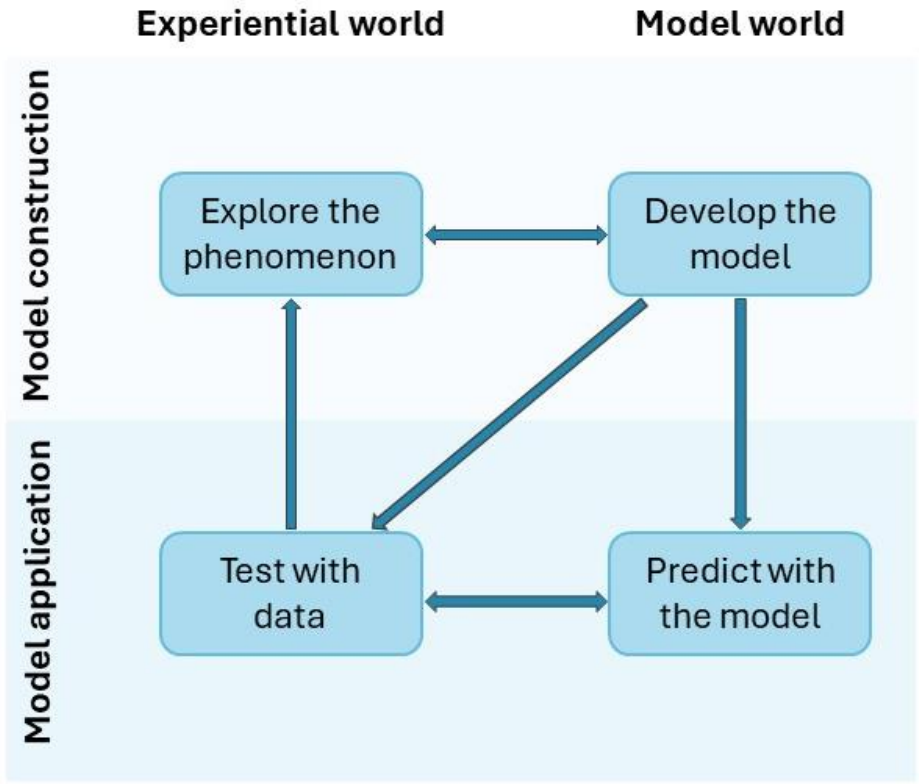


Figure 1. Framework for modelling in scientific inquiry (Engelschalt et al., 2024:693)

Knowledge about the modelling process – ctd.

How to reach?

- Provide students the opportunity to explicitly discuss and reflect about the modelling process
- Address all steps
- Ensure that models are understood as something changeable to test hypotheses (e.g., by reflecting the students' own modelling process or by using example from science (history))

Modelling practices

2

Students should be able to engage in the modelling practices of developing, evaluating, using, and revising models (see Table 2)

Modelling practices – ctd.

Table 2. Descriptions of the suggested aspects of modelling practices by Nielsen & Nielsen (2019:571)

Aspects of modelling practice	Description
***Descriptive use* of models**	Using models descriptively as a means of describing, explaining or communicating an idea or a phenomenon.
***Predictive use* of models**	Using models predictively as tools for inquiry, problem-solving, sensemaking and/or as hypothetical entities representing different ideas of the referent.
***Design* own models targeted at a specific purpose**	Students design models based on their own ideas, prior evidence and/or theories. The purpose could be related to a model's role in describing, communicating, explaining and/or predicting.
***Evaluate* own or others' models related to the usefulness decided by the purpose**	Students evaluate models based on a model's power of representation, explanation and/or prediction related to a specific question, problem or purpose. Evaluation could be based on students' empirical testing and validation of models or how a model fits with other established models or types of knowledge.
***Revise* own or others' models to improve their affordance related to the usefulness decided by the purpose**	Students revise own or other's models. The revision could change the communicative, representative, descriptive, explanatory, and/or predictive power of the model. Revision should be based on additional evidence, new findings, students' advanced sensemaking or new theoretical aspects of the target.
***Compare* models related to the usefulness decided by the purpose**	Students compare and evaluate multiple models representing the same referent to fit different purposes. The criteria for evaluation could be models' ability to represent, describe, communicate, explain and/or predict.
***Select* models for a specific purpose**	Selecting an appropriate model to solve a specific task or problem based on ability and relevance related to a model's representative, descriptive, explanatory and/or predictive power.

Modelling practices – ctd.

How to reach?

- Provide students the opportunity to practice the various steps of the modelling process

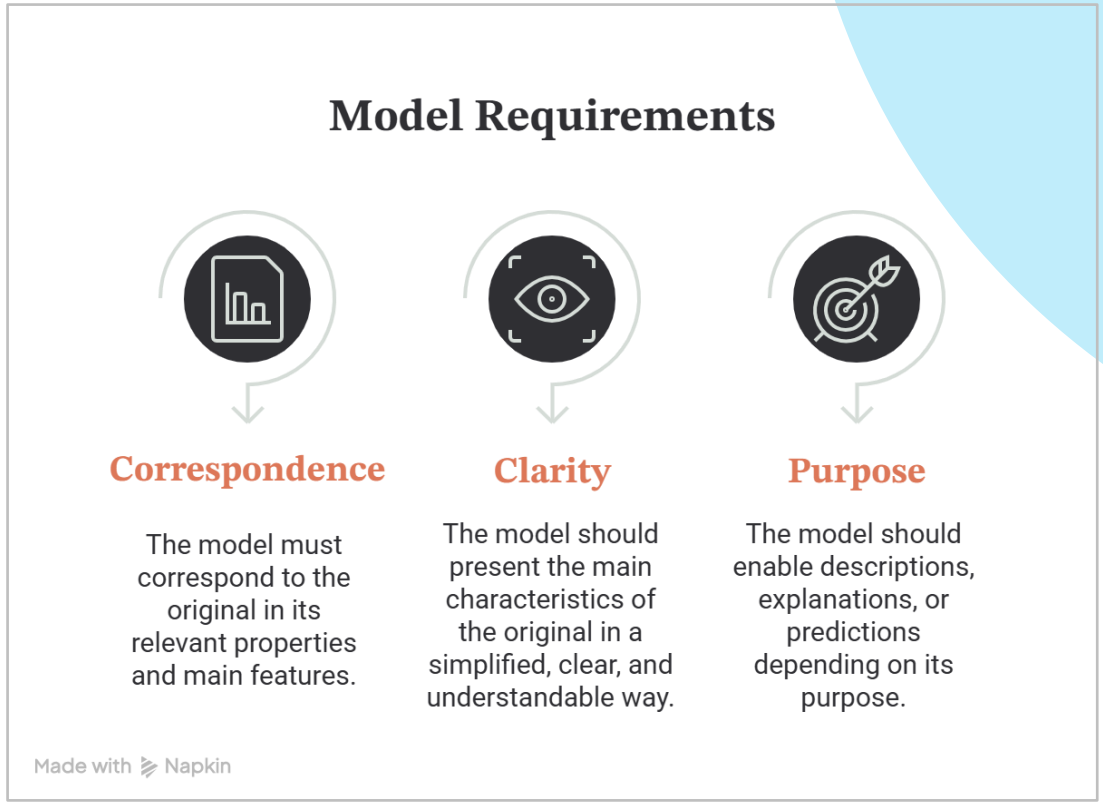
Modelling products

Students are expected to develop models that are – depending on the learning goal – scientifically accurate, explain and predict phenomena, or solve problems

The modelling products can be evaluated based on various criteria (see Table 1).

Modelling products – ctd.

Figure 4 Criteria for model evaluation by Bette at al. (2019), translated by the authors



Modelling products – ctd.

- *How to reach?*
  - Provide students the opportunity to evaluate models based on list of criteria
  - Make the evaluation criteria explicit
  - Address all aspects of model in evaluation and

3. Which modelling tools are available?

3

Types of models

Non-computational modelling tools

Computational modelling tools

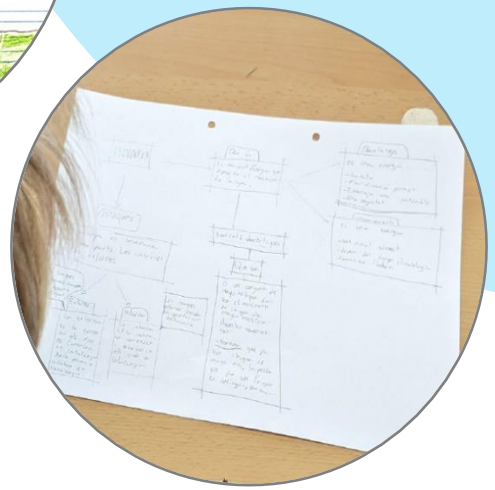
Modelling tools in national curricula

Types of models

Models come in various kinds. When analysing the curricula of four countries we encountered mentions of the following model types:

- **Mental models**, students' ideas about how a phenomenon works
- **Conceptual maps**, visual links between concepts and ideas
- **Physical models**, concrete models that students can touch or manipulate, including **models available in the school biology lab** such as organs, body systems, cells, or skeletons







Types of models

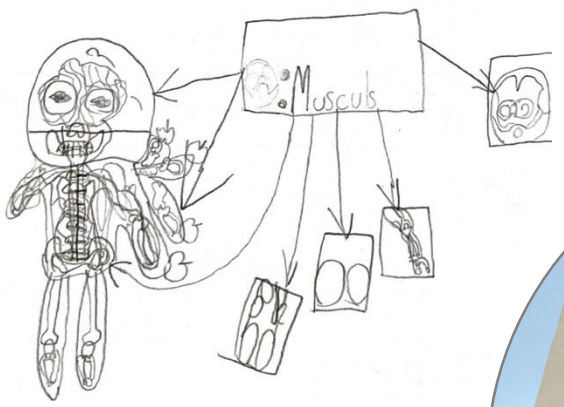
3D models, three-dimensional representations of structures or processes
Diagrams, visual representations that show parts, relationships, or processes
Drawings, student-created or teacher-provided visual representations
Computational models, that can be used to simulate the behavior of a phenomenon.

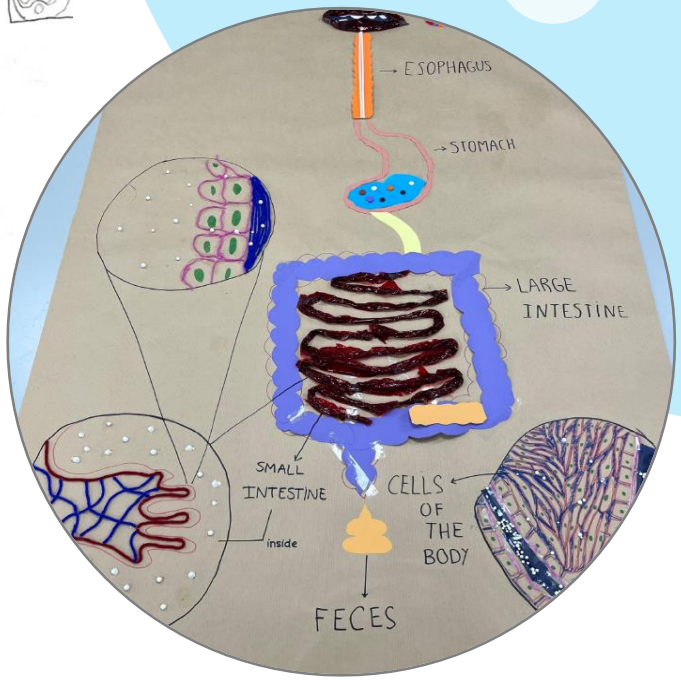
Of course, for each model, appropriate tools are needed to create these models, varying from non-computational tools, such as paper and pencil for drawings to computer tools to create computational models. Read here about how tools are explicitly mentioned in the national curricula and are used in practice.

Examples of non-computational modelling tools

Modelling tools that are not made for computational models can be classified I n several types:

- 3D Physical models, which are models that use physical materials or objects as modelling elements, for instance ball-and-stick models of molecules. The modelling tool takes shape as a collection of building blocks for the model or even raw material such as clay.



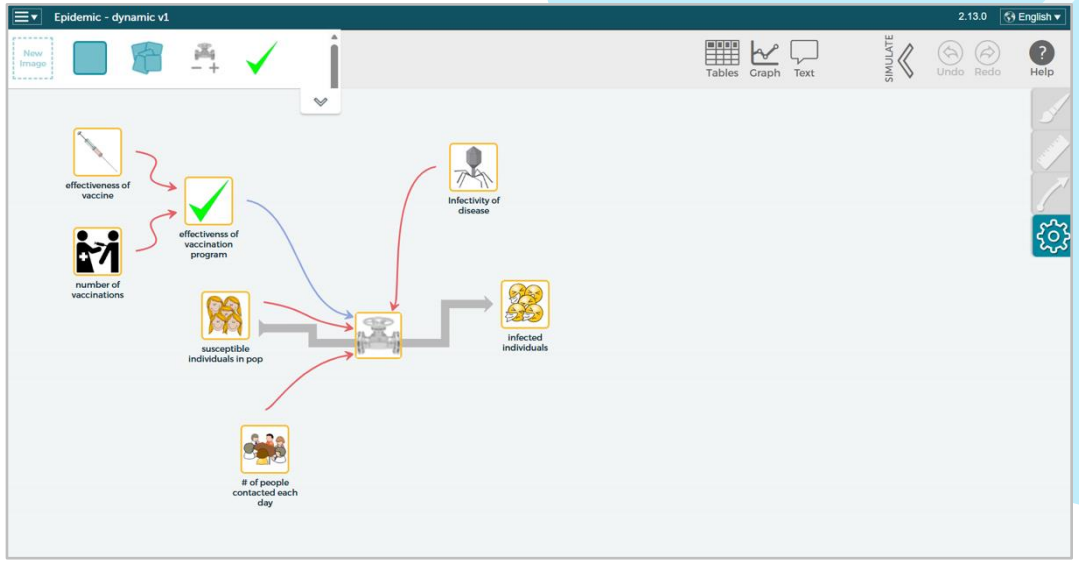


- 2D drawn models, include drawings, maps, diagrams, concept maps, etc. Tools can range from paper and pencil to computer-based drawing tools, which can be dedicated to a specific model representation, such as concept maps.

Computational modelling tools

With computational modelling tools, students can create models that are effectively computer simulations. We distinguish between several types of these:

- Tools that describe the simulation as a whole, using
  - programming code (LOGO, Boxer)
  - Mathematical equations (Modellus, DMS)
  - A graphical representation of equations (SageModeler, Model-It, Stella, Dynasim, Vensim, Co-Lab). These tools can use quantitative or quantitative methods. In the latter case, the equations are specified using qualitative expressions (“if A increases then B decreases”), drawing or selecting graphs or similar



Examples of computational modelling tools 1

- Agent-based modelling tools (NetLogo, StarLogo, Stagecast Creator) in which components of the model are represented as independent agents. Such tools are suitable to display *emergent behaviour,* such as swarming behavior by groups of birds.

Apart from these tools, some tools are made specifically for a single domain. This is most common in primary and lower secondary classes.

Examples of computational modelling tools 2

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Modelling tools in national curricula

The Netherlands - Types of modelling was only mentioned once in the Dutch curriculum, stating that in lower secondary education, students should learn to create analogue and digital 2D and 3D models within a design process.
Spain – In the Catalan curriculum, there is not explicit mention of any modelling tools or types of modelling tools.
Cyprus – The curriculum of Cyprus frequently mentioned physical models and conceptual models. Sometimes, 3D models, digital models, and diagrams were mentioned. 2D models and role-play/embodied models were mentioned once.
Germany - In the German curriculum, there was mention of digital models, functional models, feedback loop models, lock-and-key models, and structural models.

Teachers' experience with modelling tools

In a focus group we gained insights in the use of modelling tools in different countries.
The Netherlands - participants mentioned using modelling tools such as concept maps and computational modelling tools in lower secondary science classrooms, discussing both qualitative and quantitative tools. participants mentioned the need for more computational modelling tools to be introduced and used by teachers.
Cyprus - participants mentioned using drawings and 3-D constructions with early childhood and primary school learners. They report limited availability and insufficiency of tools to be used in classrooms.
Germany - participants did not discuss specific modelling tools, but mentioned they are used as explanatory and illustrative purposes. They also mentioned the challenges of finding suitable modelling tools to be used in lower secondary science classrooms.
Spain - participants did not mention many modelling tools used in primary education, the one specific tool that was mentioned was drawn diagrams.

4. Domains suitable for modelling

4

Modelling is part of all of science so many domains are suitable for teaching with and about modelling. However, in the context of school some domains and topics might be more suitable. In our scoping review we identified domains that have been used earlier. Also, we scanned national curricula for domains that were explicitly mentioned. Finally we investigated how modelling contributes to different kinds of domains and phenomena.

Modelling topics used in the literature

Physics	Chemistry	Biology	Earth science
Motion and acceleration	Molecular structures & chromatography	Plant growth	Plate tectonics
Force and motion	Chemical reactions	Cellular structures	Volcanoes
Diffusion	Chemical equilibrium	Marine ecosystems	Stream ecosystems
Temperature regulation inside a house	Acids and bases	Stream ecosystems	Global warming
Solar system and spatial astronomy	Kinetic molecular theory, diffusion, density, gas laws	Digestive system	Water quality modelling
Electrostatics	Fermentation	Ecosystems & biodiversity	Global climate change, earth's temperature
Sound	Solutions, and separation methods	Water ecology, ecosystems	Variation of Earth's mass & chemical transformations
Energy forms, transfer and transformation		Cardiovascular (Circulatory) system	Geology, space, air pollution, human health
Particle model of matter		Cells, tissues and microorganisms	External geodynamics & geological heritage
Measurement and uncertainty		Water ecology and ecosystems	Greenhouse effect, ecological footprint, energy, fossil fuels, deforestation
Buoyancy		Immune system (antigens, memory cells, etc)	Water quality and purification
Solving gas into liquids		Ecosystem dynamics	
Buoyancy, heat capacity, liquid pressure			

Domains mentioned in national curricula

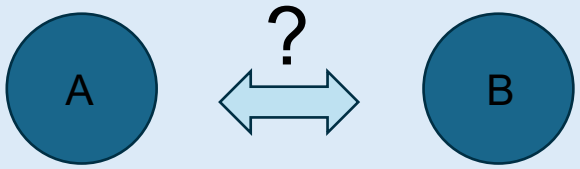
Topics mentioned in national curricula include:

- Human body
  Ecosystems
  Living beings
- Floating
  States of matter
  Electricity production and consumption
  Energy sources
  Forces and simple machines
  Light and sound
  Aerodynamics
  Water cycle and properties
  Atmosphere, geosphere and earth as a system
  Climate change

The focus is on living systems, ecologies ad technical systems, using models to make sense of how these systems function. Also particles, phase transitions, separation methods, and chemical reactions—contexts in which models help visualise invisible processes and interpret experimental results are mentioned in curricula. For the theoretical tracks, the curriculum builds on this foundation by extending
modelling to broader and more complex systems. Students develop insight into the persistence of life on Earth and use models to explore weather, climate, and water systems and their changes.

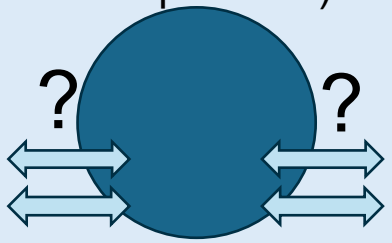
Typical kinds of modelling problems

How do things interact with each other? (forces, energy, heat, light, electricity, vibrations…)



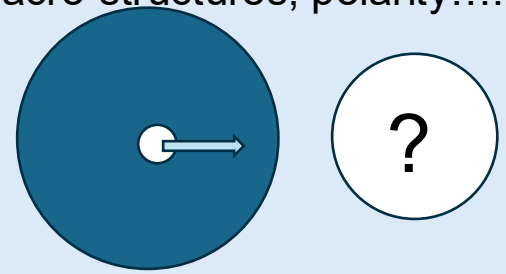
Need to think on different kinds of interaction

How living system exchange matter, energy and information with others? (nutrition, reproduction, genetics, stimulus-response…)



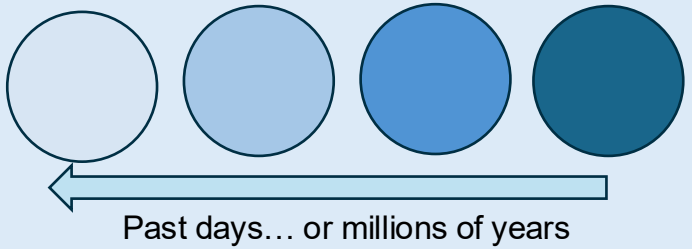
Need to think on different levels of organization

What can we imagine "inside" objects / substances / matter? (Particles, bonds, atoms' structure, internal motion, macro-structures, polarity….)



Need to think on different levels of "composition"

How can we find out how things looked before the current form? (mountains, rivers, rocks, clouds, volcanoes…)



Need to think on different time scale

5. Implementing MbL

5

Focus on models as epistemic tools
Selecting suitable modelling tools
Pedagogical tools and interventions

Models as epistemic tools

Models are epistemic tools, that is, they are part of a process of creating and using knowledge to understand phenomena. This means that we need to support students in both performing the modelling process itself and the knowledge-building or meta-modelling knowledge surrounding this. A helpful way of thinking about this support is in terms of *questions* that student (and teachers) may be confronted with, at both levels. These questions can then give rise to the use of specific interventions, supporting the student in addressing the question at hand.

Selecting suitable modelling tools

We have seen that there are are multiple kinds of modelling tools. Choosing the one for a specific modelling tasks hinges on several considerations:

1. The goal of the task: what kind of model is expected? The tool should match the expectation.
2. Required skills: some tools require skills and knowledge, such as coding or mathematical equations. The students' skill level should be such that they can use and understand the tool.
3. Curricular requirements. Some school curricula mention specific model types.

Pedagogical tools and interventions

5

Sequencing modelling activities
Questioning
Drawing and sketching
Mental modelling and simulation

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Go back Home

Sequencing modelling activities

Modelling is a process, involving various phases, often modelled in terms of a modelling cycle. In supporting modelling by students awareness of the phases is necessary, although this does not mean that always all phases need to be included in a lesson or other modelling activity. Also, the cycle does not prescribe that activities should always be strictly in the order presented, it is possible to go back and forth between phases.

In creating teaching activities being aware which phases are current at a certain stage of the modelling-based lessons helps designing timely support for students engaged in a modelling project.

Asking Questions

Modelling is mainly a mental activity, meaning that it is a good idea to prompt students' thinking processes during the modelling process. This concerns both the practical level of creating, evaluating and using the model itself and the meta-modelling aspects of learning *about* models and modelling.

Here we have listed some questions that can be used in the modelling process. They serve as inspiration and can be adapted to local needs. Other questions might prompt for elaboration and explanation of what students are doing in the modelling process.

Asking questions to prompt students' thought processes

Modelling phase	*Questions on models and modelling*	*Questions on meta-modelling*
Exploring the problem	What is the problem? What do we already know?	-
Access to the phenomenon/data collection	What aspects of the phenomenon can be observed or measured? What data or evidence are needed to develop the model?	-
Create the model	What are the relevant elements, variables and parameters? How do they relate?	What aspects need to be modelled, and which not? How is this model a representation of reality? (nature of models)
Test the model	How do we compare the model with reality?	What constitutes a good model in this case? What criteria do we have for our model? (purpose/ utility of models)
Revise the model	What changes are needed for the model? How are the changes implemented?	Which aspects of the model need revision and why?
Use the model	What does the model predict about new situations? How to set the variables/parameters to get useful outcomes of the model?	What are the limitations of the model? Can I trust its predictions, based on the modelling assumptions? (use of models)

Drawing and sketching as support for modelling

Where drawings can be models in their own right, they may also be useful in supporting the process of modelling using other tools, such as computational modelling tools.

Drawings are especially useful for qualitatively investigating structural properties of a modelled phenomenon and visualizing dynamic processes. Using drawings as a thinker tool can in this way assist in formulating the model in the language required by the modelling tool.

Mental modelling and mental simulation

Modelling is a thinking activity. This means it is important to focus both on the process of creating the model itself and on its function. In teaching materials and teaching interactions it can be very productive to ask students to predict the behavior of the phenomenon studied before actually executing the model. In a similar way, explaining what they have observed in words before making the model will help them to link the model to the phenomenon.

Such activities, using a mental representation to predict or explain an outcome is called mental simulation.

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