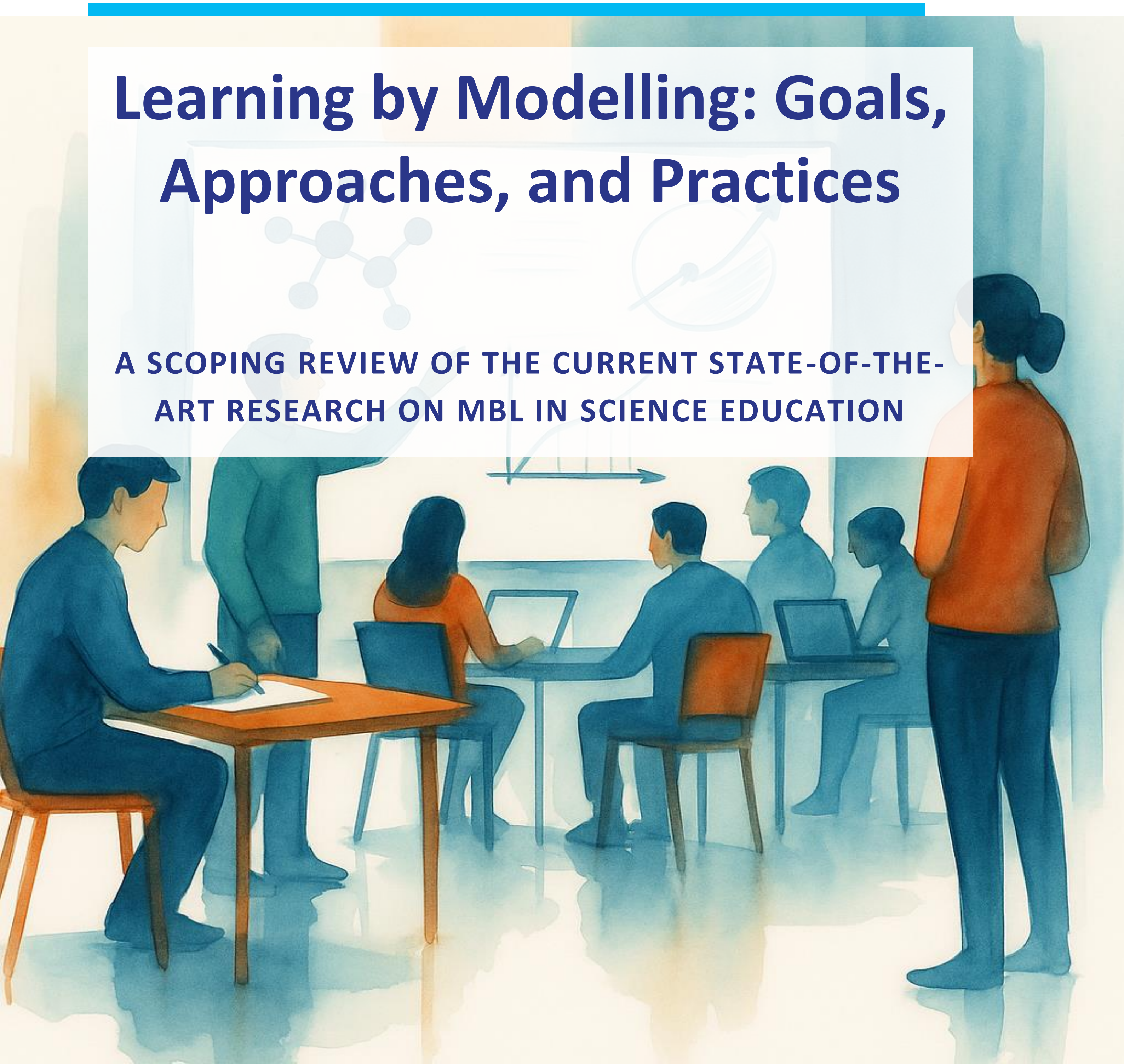
Learning by Modelling: Goals, Approaches, and Practices

A SCOPING REVIEW OF THE CURRENT STATE-OF-THE-ART RESEARCH ON MBL IN SCIENCE EDUCATION



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EMPOWER

Empowering Teachers for Science Learning Through Modelling-Based Approaches

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Erasmus+ Project EMPOWER

EMPOWERING TEACHERS FOR SCIENCE LEARNING THROUGH MODELLING-BASED APPROACHES

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Contents

1 Introduction

The current report aims to present a current state-of the art on research on modelling-based learning (MbL), related to approaches used, topics, tools used, and student ages, as well as expected learning outcomes. Modelling as a learning activity has been around since the 1980s (Gilbert & Justi, 2016), exemplified by the work of Jon Ogborn (Ogborn & Wong, 1984) and others. Since then the topic has evolved significantly, both in theoretical insights in the role of modelling and in the development of tools and practices (e.g., Constantinou et al., 2019; Louca & Zacharia, 2012).

In this report we intend to summarize the most recent developments in research on Modelling-based Learning (MbL). We focus on several aspects: the expected and observed learning goals for MbL, the (pedagogical) approaches used in setting up MbL, the modelling tools used and the domains in which MbL has been applied. We addressed these issues in the context of science education for the ages between 5 and 15, the target age group of the Empower project.

In order to set the boundaries of the project we first define the main concepts involved with MbL, starting with the most basic, the concept of *model*. We define this as:

A model is a representational tool used to understand, predict or explain a phenomenon.

This definition is a quite general description of what models entail in the context of scientific activities: objects, virtual or concrete, that scientists construct to represent the things they study. This includes scale models, pictures, schematic representations, computer simulations and more. Important is that models have a function in understanding, predicting and explaining: through the model we are able to make statements about the system represented.

From this definition we can move forward to the definition of scientific modelling:

Scientific modelling is the iterative process of constructing, comparing, testing, revising and using models in the study of phenomena.

In this definition, the word “Scientific” is added to stress that modelling is an activity for deeper understanding the phenomena studied, that is, modelling is a scientific activity. Finally, we need to define Modelling-based learning as:

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

From the three definitions together, we infer that modelling-based learning is a teaching and learning activity in which students engage in a process of constructing, comparing, testing, revising 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. In the following we will work towards a solid base for the concept of modelling competence.
As a result, this review will focus on the following research questions:

1. What frameworks for modelling competence are relevant and how do they differentiate on the development between the ages of 5 and 15?
2. What pedagogical interventions for MbL are suggested in the literature for students between 5 and 15 years old, and what is known about their effectiveness?
3. Which topics, contexts and phenomena are used in MbL activities?
4. Which tools (dedicated modelling tools, generic tools and/or AI-tools) are reported on being used as modelling tools?

2 Method

As the current study is a scoping review focussed on recent developments, we took a pragmatic approach. We started by summarizing seven recent review studies (Chang et al., 2024; Jin & Jian, 2024; Langbeheim & Bielik, 2025; Lobner et al., submitted; Louca & Zacharia, 2012; Margolin et al., 2022; Nicolaou & Constantinou, 2014a) relevant for our research questions. These summaries provided a baseline for this study. We then searched for recent literature from 2020 to 2025. The year 2020 was chosen as the period before that is assumed to be covered by the review studies we used as a basis. For each of the research questions we first summarized the state of the art as deduced from the review articles and summarized followed by results reported in the literature retrieved. We employed the following search string:

TS=(model-ba*)
AND (TS=(learning) OR TS=(education))
AND (TS=(Science) OR TS=(Biology) OR TS=(Physics) OR TS=(Chemistry) OR TS=(Geo*))
NOT (TS=(higher education))
NOT (TS=(machine learning) OR (TS=(deep learning) OR TS=(robot*)))

This search string yielded 132 results on Web Of Science. We narrowed this set down with the selection function offered by Web of Science to include only papers that addressed educational topics and excluded models in the context of AI. Finally, we scanned abstracts to select only papers that addressed primary and lower secondary education and teacher education. We ended with 49 papers in English. The search and follow-up selection procedure was repeated in German language databases, yielding 2 papers in German as well in Spanish-language databases (Enseñanza de las Ciencias and Eureka), yielding 16 papers. Each paper was assessed on its relevance for each of the research questions. Not all papers are relevant for all research questions.

3 Results

3.1 Frameworks for modelling competence

From the reviews we studied as a baseline we extracted that scientific models (hereon referred to as ‘models’) are defined as purposeful abstract representations of phenomena used as media to represent and communicate scientific ideas and as epistemic tools used to investigate and make sense of scientific phenomena (Gouvea & Passmore, 2017; Lobner et al., submitted). Scientific modelling (hereon referred to as ‘modelling’) is the iterative process of constructing and using scientific models. Modelling-based learning (MbL) refers to the instructional approaches used for learning with and about scientific models. It is a multiphase process in which students engage in constructing and using models (Louca & Zacharia, 2012; Margolin et al., 2022). This process includes engagement with practices such as developing, evaluating, revising, comparing, and using models to explain and predict phenomena (Schwarz et al., 2009). Gouvea and Passmore (2017) emphasized the importance of a cognitive agent when developing and using models, shifting from ‘model of’ to ‘model for’ heuristics. This call is manifested in the levels of the meta-modelling knowledge (Upmeier Zu Belzen et al., 2019), in which level I refers to models as a replication of phenomenon in reality and level III refers to models as epistemic tools used to explain and predict phenomenon.

Science education aims to support students’ modelling competence. Modelling competence definitions is diverse, and different modelling competence frameworks exist in the science education literature. Broadly defined, modelling competence can be viewed as “a system of the knowledge, skills, and abilities necessary to engage in the process of developing and using models for reasoning in science, including motivational dispositions to apply these capabilities for problem-solving in specific situations” (Göhner et al., 2022, p. 4). Most definitions and frameworks of the modelling competence focus on three core dimensions: meta-modelling knowledge, modelling practices, and modelling product.

Meta-modelling knowledge refers to epistemic ideas and understanding about models and the modelling process, i.e. the declarative knowledge about models and modelling (Chan et al., 2025). Nicolaou and Constantinou (2014a) suggest this includes meta-modelling knowledge about the nature of models and knowledge about the modelling process. Upmeier zu Belzen et al. (2019) describe five aspects of the meta-modelling knowledge: nature of models, multiple models, purpose of models, testing models, and changing models. They also include non-cognitive aspects such as motivation and volition. Chiu and Lin (2019) suggest that modelling knowledge includes ontological, epistemological, and methodological aspects, alongside metacognitive knowledge of models and modelling. Modelling practices refer to the observable modelling activities that students engage in. Nicolaou and Constantinou (2014a) suggest that the modelling practices includes practices such as create, use, compare, revise, and validate models. Modelling product, referring to the quality and accuracy of the resulting modelling artifacts (Chan et al., 2025; Chiu & Lin, 2019; Göhner et al., 2022).

In their review aimed at establishing an overarching definition of the modelling competence, Lobner and colleagues (under review) suggest a framework for the modelling competence comprised of four dimensions: (1) dispositions, which include modelling metaknowledge, subject-specific knowledge, and non-cognitive dispositions, (2) situation-specific skills, (3) performance modelling practices, and (4) modelling product.

While all meta-modelling dimensions are expected to be positively correlated (Chiu & Lin, 2019; Schwarz et al., 2009), the few empirical studies that set out to explore these possible correlation found weak evidence for this claim. Focusing on students, Schwarz and White (2005) concluded that higher meta-modelling knowledge can contribute to students' engagement with the modelling process, mostly when it is supported by explicit reflective discussions. Sins et al. (2009) found positive correlation between students' deep modelling processing abilities and high level of epistemic modelling understanding. Focusing on pre-service biology teachers, Göhner et al. (2022) found only weak correlation between teachers' complexity of the modelling process and the quality of their model products, with no correlation to any of the other modelling dimensions. Engelschalt et al. (2024) found moderate correlation between teachers' knowledge about the iterative nature of the modelling process and meta-modelling knowledge of models as tools to predict phenomenon. Therefore, there is a need to further empirically test the relationships between the modelling competence dimensions with both teachers and students.

There are several additional limitations that arise from current literature on MbL. As suggested by Lobner et al.(submitted), the modelling competence has subject-specific particularities that should be taken under consideration and these should also address domains beyond the natural sciences. It should also be noticed that other modelling frameworks focus on alternative terms such as skills, abilities, and practices, which overlap with most of the modelling competence dimensions but may include additional aspects. In addition, empirical studies on modelling competence in early childhood and primary school students is under-represented in the literature.

From the 49 English-language articles that were retrieved for the last 5 years, 23 were considered to be relevant for the topic of modelling frameworks. From these articles, several themes emerged regarding the main theoretical frameworks and definitions used in research studies published in the last 5 years.

The most prevalent framework in the identified literature, used in 11 of the 23 papers (e.g., Lacy et al., 2022; Peretz et al., 2023) is the modelling practice framework, originating in the Framework for K-12 Science Education (NGSS, 2012). The modelling practice framework views modelling as one of the core scientific and engineering practices that students should develop, referring to both the knowledge and abilities to construct and use models to make sense of phenomena.

A similar pattern emerges in the Spanish-language papers: among the 16 articles analysed, 7 explicitly draw on modelling practices as their main theoretical or instructional framework (e.g., Jiménez-Liso et al., 2021; Oliva et al., 2021), showing a proportion comparable to that of the English-language corpus. This convergence suggests that modelling practices have also become a central reference point in Spanish-speaking science education research, both for structuring instructional sequences and for analysing students' engagement with core modelling processes.

The second most commonly used framework was the model-based inquiry framework, appearing in 7 of the 23 identified papers (e.g., Campbell et al., 2025; Pedrera et al., 2025). This framework, initially suggested by Windschitl et al. (2008), views science learning as a system of inquiry activities and discourse that engages students with deep content learning. This is done in a process of cyclical construction, testing, revising and using models in order to develop evidence-based explanations of real-world phenomena. Based on this framework, students' ideas are represented in the form of models are testable, revisable, explanatory, conjectural, and generative. In the Spanish-language subset, we also find 3 out of 16 studies that explicitly adopt Modelling-based Inquiry, such as Guimarães & Perticarrari (2025).

Modelling competence appeared in five of the 23 papers. However, only two of these papers (e.g, Garrido and Couso, 2024) referred to the modelling competence framework associated with Upmeier zu Belzen et al. (2019), which includes aspects related to students' meta-modelling knowledge, i.e., their knowledge about the nature and purpose of scientific models and modelling, alongside their abilities to engage with the modelling practices and to produce an appropriate model product. The other three papers mentioned the modeling competence in a broader and unspecific way. In the Spanish-language review, no studies explicitly adopt the modelling competence framework. Although some papers refer to modelling abilities or the use of models, none structure their analyses around meta-modelling knowledge, modelling practices, or modelling products in the sense defined by this framework.This absence suggests that, in the Spanish-speaking research context, there is not yet a strong tradition of conceptualising "modelling competences" as a distinct theoretical construct, in contrast with the more established usage found in the international (primarily anglophone and German-speaking) literature.

Modelling-based learning appeared in 4 of the 23 papers in English (e.g., Erumit & Yuksel, 2023), which includes also socio-scientific modelling-based learning (SIMBL, e.g., Durak & Topçu, 2025), and also in four of the 16 Spanish papers (e.g., Domènech-Casal, 2020). Modelling-based explanations appeared in three of the 23 papers (e.g., Lindgren et al., 2021), and model-based reasoning was mentioned in two papers (e.g., Lacy et al., 2022),

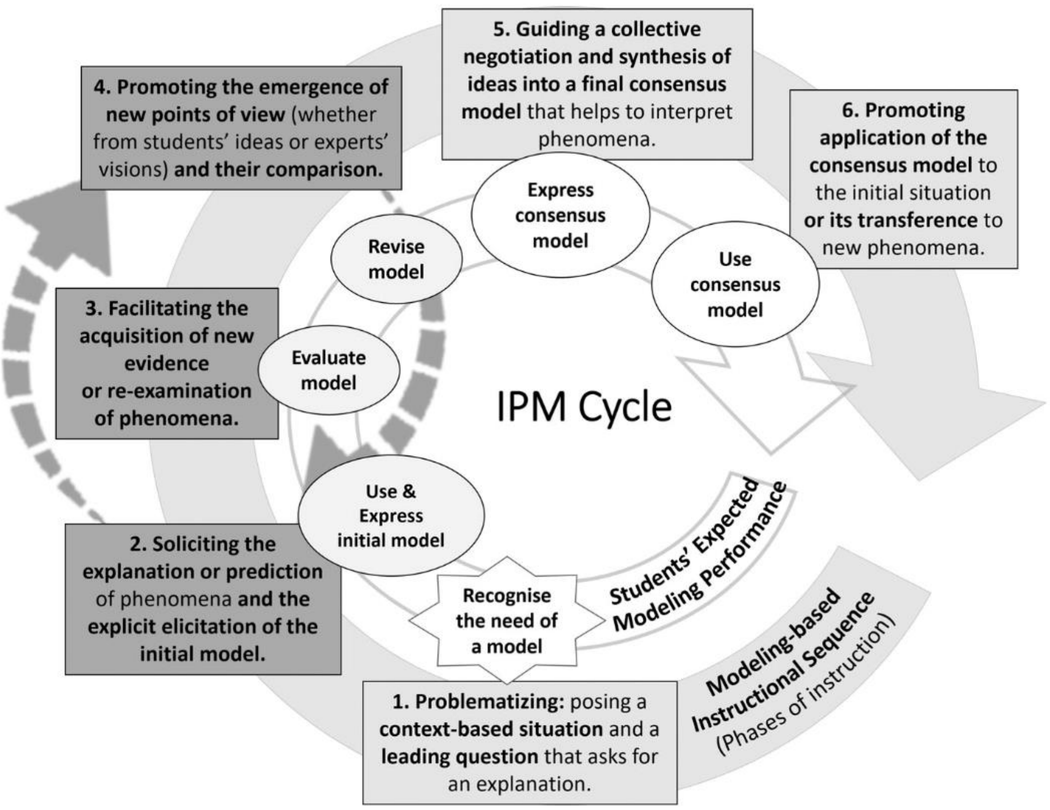
Other frameworks that were addressed only once of the identified literature included frameworks about mental models, epistemology of models, conceptual modelling, modelling skills, modelling-based instruction, and modelling performance.

In the identified literature, models were typically defined as representations of real-world phenomena and natural systems, and they include relevant components of the investigated phenomenon, their characteristics, and their interactions. In most of the identified literature, models are used to describe and explain the mechanisms and causal relationships in the system and to make predictions. Mental models are defined as models that are constructed in individuals' minds as a result of cognitive processes. Modelling is generally conceived in the identified literature as the iterative process of developing, evaluating, comparing, revising, and using models to explain and predict phenomena. In the educational context, modelling is perceived as a pedagogical tool essential to the process of developing scientific knowledge.

3.2 Supporting students' pedagogical needs for modelling

In the review studies that we used as a baseline, pedagogical approaches to modelling are often based on engaging students in actual modelling processes, that is constructing, exploring and revising models. Many authors have addressed how to introduce such modelling practices in education. For instance, Windschitl and colleagues (2008) relate the modelling practice to scientific reasoning and related "conversations", summarized as "What do we already know", "Generating hypotheses", "Seeking evidence" and "Constructing an argument". Bielik et al. (2022) define several aspects that focus more on constructing the model itself: Defining boundaries, Determining components and boundaries, Using evidence and reasoning and Interpreting the behaviour of the model. In their search to support teachers Campbell et al. (2025) base their instructional planning tool on a similar outline of the modelling process. An attempt to integrate these and many other approaches is the "Instruction Performance Modelling (IPM)" cycle (Garrido & Couso, 2025). An important feature of this cycle is that it separates the modelling performance by students and the related instructional phases (see Figure 1).

Figure 1 *The IPM cycle as depicted by Garrido and Couso (Garrido & Couso, 2025)*



Looking at the cycle, we indeed see this separation, although the instructional phases still mimic the modelling phases to a large degree. In the cycle we can distinguish three main phases, that we might label Orientation, Modelling and Application, in the IPM cycle depicted as the phases 1, 2-4, and 5-6. Still, these instructional phases describe the modelling process at an abstract level, but do not provide insights into the instructional or pedagogical intervention to support these phases of the modelling process.

Another issue is that having students perform a modelling process does not automatically mean that they will acquire (meta-)modelling knowledge about that process or about the role of models in science. The consequence is that on top of support for the modelling process we also need to support more abstract reasoning *about* models and modelling.

This means that when engaging in learning to model or learning about models and modelling, students are confronted with many different questions and issues before, during and after the modelling process. In the following table, an inventory of such questions is presented.

Table 1 *Questions relating the modelling process, modelling competence and meta-modelling competence*

Modelling phase	*Questions on models and modelling*	*Questions on meta-modelling*
Exploring the problem	What is the problem? What do we already know?	Is it suitable for modelling What assumptions need to be made? When are we satisfied with the model? What is the purpose of 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?
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?
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?

Modelling phase	*Questions on models and modelling*	*Questions on meta-modelling*
Reflecting on the model	Does the model serve our purpose?	Is there consensus about the model? Are other models possible? What would be their advantage/drawback? Is one model enough?
Reflecting on the modelling process	Did we take the necessary steps to create and evaluate a satisfactory model?	What are the reasons to trust a modelling process?

The 'questions' above provide a landscape to describe to what part of the modelling process pedagogical support can be directed. The resulting interventions can be from within the learning environment or be teacher-led. Such approaches to scaffolding align with earlier studies on scaffolding for inquiry-based learning, for instance the scaffolding qualifications by Quintana and Lazonder (Lazonder & Harmsen, 2016; Quintana et al., 2004). Highlights found in the literature reviewed here are *bifocal modelling* (Blikstein, 2014), meaning linking models directly to experiment, progressions including drawing, qualitative and quantitative modelling, the importance of high-quality representation and visualization and the use of physical interfaces to build and explore models, such as haptic feedback and physical objects with RFID tags to construct models. Finally, we collected information, if any, on the effectiveness of the pedagogical intervention.

In the reviewed articles since 2020, we only saw support for the modelling process, creating models. We did not see explicit instructional interventions on support for reasoning meta-modelling neither in English nor Spanish literature. This does not mean that the studies do not contribute to the development of meta-modelling knowledge, one can argue that participating in a modelling activity is essential for the development of meta-modelling knowledge, but no explicit measures were found.

The measures addressing the creation of models focus on various aspects of the modelling process. *Exploring the problem* has been supported by having students create drawings (Lindgren et al., 2021; Liu, 2021; Samarapungavan et al., 2023) and other student generated visualizations such as animations (Lin & Wu, 2021). For *creating the model* Arik and Topçu (2022) provide explicit explanations on the modelling formalism.

For *testing the model* prompts in the form of supportive questions to interpret data have been employed by Bhattacharya et al. (2021). Also, supporting prediction and observation using real and simulated experiments has been implemented as a supportive strategy (Bozzo et al., 2022). This relates to the idea of *bifocal modelling* as introduced by Blikstein (2014). Revising the model was explicitly supported in two studies. Bielik and colleagues used videos and experiments as triggers to extend the model beyond its current status (Bielik et al., 2022) and Lucas and colleagues found that students who revised their models after prompting score higher on a post-test (Lucas et al., 2022). Overall, the Spanish-language corpus shows a clear imbalance: all studies emphasise exploring the problem and creating the model, whereas far fewer include systematic phases of testing and revising models.

Finally, several studies did not offer support on specific phases of the modelling process but offered support for the process as a whole. Two studies base themselves on the IPM cycle (see Figure 1) and found that supporting students in following this cycle helps them to raise interest, concentration and satisfaction (Jimenez-Liso et al., 2022; Pedrera et al., 2025). Another approach is to base the modelling process based on storylines and storytelling. Lindgren and colleagues had students constructing a storyline based on an initial question (why is a pond green in summer?) and moving from this question to a modelling-based explanation of the phenomenon (Lindgren et al., 2021).

Summarizing, we see that studies try to support the modelling process as a whole or address specific parts. There is not much empirical evidence on the effects of individual support, but several studies report an overall positive outcome of engaging in modelling. The highlights that we can take from the various approaches are:

- Using visual and/or physical representations, such as drawings, manipulable objects or user created animations has been used multiple times, especially in the explorative phases of the modelling process.
- In computational modelling, learning and using the modelling formalism is crucial. Specific support is needed on this aspect. A potential support can be found in qualitative modelling techniques that allow for model creation without writing code or equations.
- What seems to be lacking is explicit support for meta-modelling, that is, reflecting on the nature of models and their role in science and beyond.

In interpreting all this we need to note that this review concerns pedagogical interventions that are built into the learning environment. This means that any on-the-spot interventions by the teacher have not been considered. Oh and Oh (2011) reviewed the international literature to delineate what science teachers need to know about scientific models (i.e., content knowledge about scientific models and modelling).

They proposed that teachers should understand the meaning of a scientific model, the purposes and uses of scientific modelling, the multiplicity of scientific models, and any changes to them. In terms of pedagogy for teaching scientific models and modelling, they emphasized that science teachers should not only take a model content- oriented approach that focuses on the delivery of the content of the models but also model-thinking-oriented and model production- oriented approaches, which engage students in the creation and use of models to explain scientific phenomena. They also proposed that teachers should develop five types of modelling pedagogies, namely exploratory, expressive, experimental (or inquiry), evaluative, and cyclic modelling, as later confirmed in a review of 81 empirical studies by Campbell et al. (2015).

3.3 Domains

The selected baseline reviews describe modelling based learning in science education. Physics and biology appear most often in the literature, while chemistry and Earth or environmental science are addressed less extensively. In **physics**, examples include motion and acceleration, force and motion, diffusion and temperature regulation inside a house. **Astronomy** appears in work on the solar system and spatially related astronomy concepts. In **biology**, studies have addressed plant growth, cellular structures, marine ecosystems, and stream ecosystems. **Chemistry** examples include molecular structures and chromatography, chemical reactions, and chemical equilibrium. **Earth and environmental science** studies cover plate tectonics, volcanoes, stream ecosystems, global warming, the water cycle through filtration activities, and developing models of water quality. Table 1 provides an overview of the topics described in the selected reviews along with the approximate age group for which each modelling activity is intended. In this tables, secondary references to the articles that were reviewed are listed.

Table 2 *Domains covered based on the baseline review papers (including secondary references)*

Discipline	*Topic*	*Age group*	*Reference*
Physics	Motion and acceleration	11–12; 16–17	(Louca et al., 2011; Sins et al., 2009)
	Force and motion	12–13	(Schwarz & White, 2005)
	Diffusion	11–12	(Louca et al., 2011)
	Temperature regulation inside a house	16–17	(Löhner et al., 2003)
	Solar system and spatial astronomy	18–22	(Barab et al., 2000; Hansen et al., 2004)
Biology	Plant growth	14	(Ergazaki et al., 2007)
	Cellular structures	4–5	(Cruz-Guzmán et al., 2020)
	Marine ecosystems	10–11	(Papaevripidou et al., 2007)
	Stream ecosystems	14–15; 21–23	(Crawford & Cullin, 2005; Stratford et al., 1998)
Chemistry	Molecular structures & chromatography	21–23	(Aalbergsjø & Sollid, 2021)
	Chemical reactions	17–18	(Dori & Kaberman, 2012)
	Chemical equilibrium	14–15	(Maia & Justi, 2009)
Earth & Environ-mental Science	Plate tectonics	12–17	(Gobert, 2000)
	Volcanoes	12–13	(Pluta et al., 2011)
	Stream ecosystems	14–15	(Stratford et al., 1998)
	Global warming	16–17	(van Borkulo et al., 2012)
	Water quality modelling	22–25	(Zhang et al., 2006)

The reviewed papers from 2020-2025 span biology, physics, chemistry, geoscience, and environmental science, sim. In biology, modelling focuses on systems such as the digestive system, ecosystems, and biodiversity. Physics units primarily focus on phenomena that are not directly observable, such as energy, sound and electrostatics. Chemistry instruction centres on particle-level explanations, such as gas behaviour, heat and pressure. Geoscience and environmental science engage students in understanding climate change, water quality, and human impacts on Earth systems.

Table 2 below presents an overview of the domains covered by the papers extracted from the selected papers. Compared to Table 2, we could include more information on the context in which the domains were addressed, due to the fact that we inspected the original papers referenced.

Table 3 *Overview of disciplines, topics, age groups and contexts addressed in the papers included in the review*

Discipline	*Topic*	*Age group*	*Context*	*Reference*
Biology	Digestive system	Middle school	Computational-thinking–supported modelling to understand complex organ interactions. Aligns with the Turkish curriculum focus on nutritional systems.	(Arik & Topçu, 2022)
	Ecosystems & biodiversity	Grades 6-8	SSI-based unit focusing on a local ecological problem ("white butterfly"); using MbL within the Turkish science curriculum.	(Durak & Topcu, 2023)
	Water ecology, ecosystems	Grades 5–6	NGSS-aligned storyline unit on algal blooms; long-term ecological investigations conducted in the US.	(Lindgren et al., 2021)
	Cardiovascular (Circulatory) system	Ages 5-6	Designed following the Mexican Preschool Program, the sequence explores veins, heart function, blood circulation, and thermoregulation.	(De Alba Villaseñor & Ramos de Robles, 2020)
	Cells, tissues and microorganisms	Ages 10–13	Study in Chilean public schools focusing on visualising cellular structures, microscopy, and representing microscopic biological phenomena	(Rodríguez Mora & Blanco López, 2020)
	Water ecology and ecosystems	Grade 7	Real-classroom implementation of a sequence built around a local environmental problem (mass fish and algae mortality caused by brine discharge)	(Jiménez-Liso et al., 2021)
	Inmune system (antigens, memory cells, etc)	Ages 11–16	Implemented in a municipal school in Praia Grande (Brazil) during the COVID-19 pandemic, exploring	(Guimarães Siles & Perticarrari, 2025)

			immune system concepts and vaccination	
	Ecosystem dynamics	Grade 10	This study uses a spreadsheet environment (Calc/Excel) to build and iteratively refine computational models of ecosystem dynamics	(Domènech-Casal, 2020)
Physics	Electrostatics	Ages 9-10	The role of hands-on experiments and PhET simulations in the development of a model and relating this to the real physical world. A primary-school physics unit aligned with Italian national science curriculum.	(Bozzo et al., 2022)
	Sound	Grade 6	Comparison of Modelling-based Inquiry (MBI) and Argumentation-Supported MBI, implemented in Turkish state schools.	(Geçgil & Akçay, 2024)
	Energy forms, transfer and transformation	Grades 4–5	Development and evaluation of the NGSS-aligned “Focus on Energy” unit, using MBI. Tested in US upper-elementary schools.	(Geçgil & Akçay, 2024)
	Particle model of matter	Kindergarten	Investigation of how technology-mediated MbL influences the development of children’s models of matter in the US.	(Samarapungavan et al., 2023)
	Measurement and uncertainty	Grade 5	A unit emphasizing measurement uncertainty, interpretation of results, and reasoning within its real-life context, in Chinese elementary science.	(Tang et al., 2024)
	Buoyancy	Grade 1	Inquiry-based activities using prediction–observation–explanation routines and guided questioning to explore causes of buoyancy.	(García-Rodeja et al., 2023)
Chemistry	Dissolution (gas in liquid)	Ages 13–14	A sequence of 14 activities linked to kinetic molecular theory; implemented in Spanish secondary science education.	(Cañero-Arias et al., 2024)

	Buoyancy, heat capacity, liquid pressure	Grades 8-9	The effect of Virtual-lab–supported MBI. The instruction units were co-designed with teachers and applied in Taiwanese junior-high science curriculum.	(Chang et al., 2024)
	Acids and bases	Ages 13-14	MBI instructional sequence that focuses on fostering students' engagement. Implemented in rural Spanish schools where acid–base chemistry is seldom taught at this level.	(Jimenez-Liso et al., 2022)
	Kinetic molecular theory, diffusion, density, gas laws	Grades 7-11	Comparison of MbL with sonified models for blind students and visual models for sighted students; implemented in Israel.	(Peleg et al., 2024)
	Fermentation	Grade 10	using a real-life context on food and health to explore fermentation and chemical reactions in Spain.	Muñoz-Campos et al., 2020
	Solutions, and separation methods	Grades 9 and 10	Secondary-school unit in Spain examining drinking-water consumption (tap vs. bottled), chemical characterisation of water, purity, separation methods, health impacts, and environmental issues linked to massive bottled-water use.	(Rodríguez Mora & Blanco López, 2020)
Geoscience	Global climate change, earth's temperature	Grade 9	Comparison of modelling-based and non-modelling-based investigations of earth's climate. EzGCM climate simulations were used for modelling. Focus on evidence, systems reasoning, and human impact.	(Bhattacharya et al., 2021)
	Variation of Earth's mass & chemical transformations	Grades 8–9	Mental-experiment activity conducted in bilingual and Spanish schools integrating Chemistry and Biology within an Earth-science context to explore Earth's mass variation and chemical transformations	(Oliva et al., 2021)

	Geology, space, air pollution, human health	Grades 1–6	Curricular analysis of the Spanish Primary Education system highlighting the marginalisation of Earth Science content by its placement within Social Sciences rather than Natural Sciences	(Achurra et al., 2022)
	External geodynamics & geological heritage	Grade 9	Teaching sequence on scientific practices and socio-scientific issues related to Spain's geological heritage, focusing on external geodynamics and landscape formation	(Paz Otero & Puig, 2020)
Environmental science (interdisciplinary)	Greenhouse effect, ecological footprint, energy, fossil fuels, deforestation	Grade 8	A unit combining SSI, scientific modelling and systems thinking, based on the SIMBL framework. Implemented in Turkey.	(Durak & Topcu, 2023)
	Water quality and purification	Grade 8	SIMBL-based instruction focusing on evidence-based reasoning in middle-school science classrooms in China.	(Jia & Ren, 2025)

From Table 2 and Table 3, we can see that modelling-based learning is mostly used with content that involves dynamic, and often invisible phenomena, where understanding depends on representing interactions, mechanisms, and changes over time. Socio-scientific issues are prominent, placing learning in real-world contexts that require students to evaluate evidence, consider multiple perspectives, and reason about human-environment interactions. Together, these studies show that modelling-based learning is applied to content where system-level reasoning, causal understanding, and engagement with societal issues are central to the phenomena under investigation.

3.4 Tools

Research on modelling-based learning shows a diversity of tools and approaches used to develop students' modelling competence. A major distinction is between non-computer based tools and computer-based tools. For both cases separately, we created a typology based on the baseline reviews and investigated the use and application of tools within the articles retrieved from our search.

Non-computer modelling tools

Chan *et al.* (2025) and Margolin *et al.* (2022) describe several non-computer modelling tools used in science teacher education. **Physical models** such as maquettes, pasta, and fan setups were used to represent molecular structures and chromatography processes (Aalbergsjø & Sollid, 2021; Cruz-Guzmán et al., 2020). **Drawings, diagrams** and **concept maps,** were used for externalizing and revising mental models (Cruz-Guzmán et al., 2023; Nelson & Davis, 2012; Torres & Vasconcelos, 2016, 2021; Valanides & Angeli, 2008). **Manipulatives** such as M&Ms and gummy bears served as analogues for cells and model types, supporting critique and playful exploration (Everett et al., 2009). **Hands-on activities, simple experiments**, and **black box setups** with ropes and tubes were used for evaluating models (Aalbergsjø & Sollid, 2021; Crawford & Cullin, 2005; Jimenez-Liso et al., 2022). **Embodied activities** and **role-play** were mentioned (Enyedy et al., 2012; Schwarz et al., 2022), as well as the use of **augmented reality** and **haptic feedback**. In the reviewed recent papers, we also see the use of drawings as well as the use of hands-on activities, e.g. in the form of energy cubes.

In the Spanish-language review, we find a similar set of non-computer modelling tools. Drawings and diagrams are commonly used to externalize and refine students' explanations (Jiménez-Liso et al., 2021; Muñoz Campos et al., 2020; Paz Otero & Puig, 2020). Hands-on laboratory activities also appear frequently, supporting the exploration of buoyancy, cellular processes, chemical change or water chemistry (García-Rodeja et al., 2023; Grimalt-Álvaro et al., 2021; Muñoz Campos et al., 2020; Rodríguez Mora & Blanco López, 2020). However, many studies additionally rely on just "paper-and-pencil work" for writing and refining models and explanations (García-Rodeja et al., 2023; Guimarães Siles & Perticarrari, 2025; Muñoz Campos et al., 2020; Oliva et al., 2021; Rodríguez Mora & Blanco López, 2020). By contrast, we found no examples of black-box activities, role-play or embodied modelling, augmented reality, or haptic-feedback tools in the Spanish corpus.

Computer modelling tools

Nicolaou and Constantinou (2014b) classified examples from the literature according to the categories proposed by Löhner (Löhner et al., 2005). Löhner distinguishes between **systems modelling tools**—including equation-oriented and diagram/structure-oriented tools—and **emergence-based tools**, which focus on interactions among discrete units.

- Equation-oriented tools include programming environments requiring coding (LOGO, Boxer) and equation-based tools not requiring programming (DMS, Modellus, Dynamo).
- Diagram/structure-oriented tools can be quantitative (Stella, Powersim, Dynasim, Vensim, Functional Blocks) or semi-quantitative (IQON, VISQ, LinkIt, ModelIt).
- Emergence-based tools include object-based tools (StarLogo, OOTL's) and cellular automata (AgentSheets, Stagecast Creator).

Some tools from the reviewed studies do not fit neatly into Löhner's taxonomy. Colab-based tools combine diagrammatic (simulation) and equation-oriented (text) elements, while Microworlds LOGO functions as both an equation-oriented programming environment and, in some cases, an agent-based platform.

Langbehaim and Bielik (2025) distinguish between **constraint-based models**, and **agent-based models.** Constraint-based models focus on the system as a whole, while agent-based models focus on representations of components or entities in a system. **System dynamics models**, the primary form of constraint-based models, use differential equations to describe

how system variables change over time and allow these variables to be adjusted to see the effects on the entire system.
Examples of computational modelling tools for constraint-based models are e.g. Model-it, Stella, and SageModeler. Agent-based models can be constructed in generic programming environments such as Boxer (DiSessa et al., 1991), Scratch (Resnick et al., 2009) and Logo (Papert, 1980). More complex models with many agents can be created in NetLogo (Wilensky & Reisman, 2006) and StarLogo (Han & Uhm, 2024; Pierson & Brady, 2020).
Apart from tools that are designed to enable general modelling, tools exist that are dedicated to modelling specific domains, such as particle systems or models of cell respiration[1]. Such tools are limited to their specific domain but can be more advanced in the sense that common behaviour for a specific domain can be built into the tool.
In the recent papers that were collected for the review we see that 13 use a computational modelling tool, of which eight use generic modelling tools and five rely on domain specific tools. The following table shows an overview of these tools. For this review we did not limit ourselves to studies

Table 4 *Overview of modelling tools encountered in the reviewed papers*

Tool kind	*Education Level*	*Domain of study*	*Topic of study*	*Reference*
System Dynamics	Lower Secondary	Earth Science	Global climate change, earth's temperature	(Bhattacharya et al., 2021)
	University	Environmental, Biology	Promotion of systems thinking and perspective taking through modelling-based learning.	(Jordan et al., 2023)
	University	Chemistry	Modelling-based reasoning in chemistry	(Khan, 2025)
Equation-based models	University	Other	Scaffolded computational modelling and simulation projects in undergraduate engineering.	(Magana et al., 2024)
	University	Biology	Cellular respiration system dynamics	(Lucas et al., 2022)
Agent-based models	Lower Secondary	Physics	Kinetic Molecular Theory and gas laws	(Peleg et al., 2024)19.08.2026 20:40:00
	University	Other	Software design evaluation using UML diagrams	(Prasad & Iyer, 2022)
	University	Other	Science teacher education. Coding-based construction of science simulations and epistemological understanding of models.	(L. Vasconcelos & Kim, 2022)

[1] **https://cellcollective.org/**

Domain-specific modelling tools	Pre-primary	Physics	States of matter and phase changes (particle nature of matter)	(Samarapungavan et al., 2023)
	Upper Primary	Physics	Electrostatic interactions	(Bozzo et al., 2022)
	Upper Secondary	Physics	Buoyancy, heat capacity and pressure in a liquid	(Chang et al., 2024)
	Upper Secondary	Chemistry	Electrochemistry (electrochemical cells, electrolysis, electroplating).	(Lin & Wu, 2021)
	University	Cross-cutting	Systems thinking and conceptual modelling (OPM/OPCloud) in cross-disciplinary contexts	(Peretz et al., 2023)

From the table we see that the generic tools are mainly used in upper secondary education and higher, whereas the target group of primary and lower secondary is most often addressed by domain specific tools by the studies that are part of the current review. This might indicate that the generic tools may require skills that are out of reach of younger children. Current literature shows some examples that may provide a lead to make generic modelling tools accessible to younger children. One example is the use of AI-based techniques to convert qualitative concept maps into computational models as is done by the MentalModeler system (Jordan et al., 2023). Other examples include the inclusion of domain specific elements and qualitative and semi-quantitative modelling techniques into system dynamic modelling tools as is done by SageModeler (Damelin et al., 2017).

In contrast with above, in the Spanish-language review the use of computer-based modelling tools is far more limited than in the international corpus. Only one study incorporates digital modelling environments: a spreadsheet-based simulations for ecosystem dynamics (Domènech-Casal, 2020). General-purpose modelling tools (e.g., system-dynamics or agent-based environments) are largely absent from the Spanish dataset, which suggests that computational modelling in this literature remains tightly coupled to concrete disciplinary contexts rather than to generic modelling formalisms.

4 Overall conclusion and discussion

For the first research question we see three frameworks dominating: the modelling practice framework (NGSS, 2012), the modelling-based inquiry framework (Windschitl et al., 2008) and the framework for modelling competence (Upmeier Zu Belzen et al., 2019). Prominent issues are the components of modelling competence, such as meta-modelling knowledge, modelling practice, domain-specific elements of modelling competence and aspects of attitude and motivation. The literature provides insights into these aspects as an input for a framework to be used within the EMPOWER project.

For the second research question, first we see a need for an elaboration of the modelling processes (to be more explicit how we can shape pedagogical support for students engaging in modelling-based learning). Various versions of a modelling cycle are present in literature, with the IPM cycle as a recent addition. While cycles are attractive means of representing processes, we must be aware that in practice the processes can be less ordered and less structured. Therefore, it might be better to focus on the individual modelling processes (steps in the modelling cycle) and the kind of support needed for each of these steps. In Table 1 we presented this approach in terms of a number of questions to provide support for each of the phases. A main feature of this table is the attention for both the modelling process and meta-modelling aspects. The reviewed articles provide several examples of means to support for various aspects of the modelling process. The main findings are:

- Using visual and/or physical representations, such as drawings, manipulable objects or user created animations has been used multiple times, especially in the explorative phases of the modelling process.
- In computational modelling, learning and using the modelling formalism is crucial. Specific support is needed on this aspect. A potential support can be found in qualitative modelling techniques that allow for model creation without writing code or equations.
- What seems to be lacking is explicit support for meta-modelling, that is, reflecting on the nature of models and their role in science and beyond.

Apparent from the complete corpus of articles, including the Spanish and German articles, scaffolds are provided for model creation, with contextualised hands-on tasks (e.g., ósmosis, buoyancy, drinking-water chemistry), and where only a few studies explicitly scaffold model testing and revision. There is an emphasis on “Exploring” and “Creating” across all studies, but substantially fewer instances of “Testing,” “Revising,” and “Using” models.

In relation to the domains, subject of the third research question, we see a variety of topics spread over the natural sciences. One trend that is visible is the rising attention for socio-scientific issues, such as climate modelling, moving modelling as something that is ‘internal’ to science to a relevant competence for all. Also visible is that modelling is applied over all ages, including 5-15, which is the target age group of the current project. Spanish-language studies are likewise anchored in authentic socio-environmental contexts (e.g., coastal management, bottled-water consumption, COVID-19 vaccination), which reliably trigger model construction yet often keep modelling tied to disciplinary content rather than to transferable modelling formalisms.

Finally, for the fourth research question we see that MbL can be supported by non-computer tools, such as physical objects, drawings, and embodied activities as well as computer tools. In the latter categories we see an abundance of the traditional approaches, system dynamics, equations and agent-based models, as well as domain specific modelling tools.

Taking the conclusions together, we see a growing trend in trying to understand modelling competence in terms of developing frameworks, but at the same time a lack in instructional support for the higher-order aspects of such modelling competences. However, for the younger age group that is the target of the EMPOWER project, we have not yet seen how modelling competence may develop with age. At the same time, looking at the domains that are often used in modelling-based teaching activities, meta-modelling is important, because the domains most often include systems that are not directly visible, meaning that understanding the model as a representational system is key. Finally, we see that generic modelling tools are more associated with ages above 15, which is older than our target group. This means that an open question if and how such tools are indeed useful for the projects target population.

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