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Models and modelling in secondary technology and engineering education

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Abstract
The common purpose of models is to provide simplified representations of other phenomena. Depending on type, they are suitable for communication, documentation, prognostication, problem solving, and more. Various types of models, such as drawings, mock-ups, flow charts, and mathematical formulae, are important tools in engineering work. An introduction to the area of technological modelling is therefore an essential component in secondary technology and engineering education, both to prepare for future studies and work, and to instil a general technological literacy. Models in the form of technical drawings and physical models are mentioned in several international curricula and standards for secondary education, but the nature of models or the modelling process are seldom elaborated upon. The purpose of this article is to investigate the 'why?', the 'what?', and the 'how?' of teaching and learning about models and modelling in secondary technology and engineering education. We discuss the roles of models and modelling and suggest a modelling framework for technology and engineering education consisting of a six-step modelling process that can be used in education with increasing level of complexity: *identification*, *isolation*, *simplification*, *validation, verification*, and *presentation*. Examples from Swedish curricula and secondary school textbooks are used to highlight the progress (or lack thereof) concerning model creation and model use. It was found that especially *validation* and *verification* are downplayed or missing in these accounts. Special attention needs to be given to the *simplification* step, where the balance between simplicity and realism often leads to difficult decisions in the modelling process.

Keywords Technology education · Engineering education · Secondary school · Model · Modelling

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Introduction

Models, modelling, and model use are fundamental to planning, communication and problem solving in technology and engineering. The creation and use of models are also among the cornerstones of most engineering disciplines. The models are of varying kinds, from architects' and builders' physical 3D models, to the mechanical engineers' drawings, and the symbolic models of molecules used in biochemical engineering. The models are used for communication, documentation, prognostication, for trying out ideas, and more (Müller, 2009; Vincenti, 1990). Being able to create, interpret, use, evaluate, and revise models of various kinds (Justi & Gilbert, 2002) should therefore be considered an important aspect of *technological literacy.* As such, it should be included in introductory technology and engineering education in school (de Vries, 2016; Rossouw et al., 2011).

In many curricula for introductory technology and engineering, models and modelling are mentioned, often explicitly, for example, in Sweden and New Zealand (Ministry of Education [in New Zealand], 2018; National Agency for Education, 2022). We have, however, yet to find a curriculum in which it is described in detail exactly what the students are supposed to learn about modelling. The purpose of students' modelling endeavours and how to implement it in teaching is thus often downplayed in curricula, as well as in standards and even in textbooks (e.g. Norström 2019). When models are discussed, it tends to be about physical models and how students can create them. Epistemological and communicative aspects of models – such as models' purposes and/or relation to reality – are seldom discussed, which means that central modelling roles and activities are generally lacking in technology and engineering education (e.g. Citrohn & Svensson 2022; Nia & de Vries, 2017).

The purpose of this article is to investigate the 'why?', the 'what?', and the 'how?' of teaching and learning about models and modelling in secondary technology and engineering education. This will be done by

- discussing the roles of models and modelling in technology and engineering education (the 'why?')
- suggesting a framework for models and the modelling process, useful when teaching models and modelling related content in technology and engineering education (the 'what?' and the 'how?').

The theoretical underpinnings are mainly from the analytical philosophy of technology and research about science and technology education. Empirical examples are provided by curriculum documents and Swedish secondary school (13–19 year old students) technology textbooks.

Models and modelling

The term model can be used in a wide variety of senses: as an ideal ('New York was commonly considered a model city concerning crime prevention in the late 1990s'), as a type ('Tatra's famous T600 model was introduced in 1951'), and more. In this article, it is used in a limited sense, derived from the fields of epistemology, theory of science, and philosophy of technology. There is no generally accepted definition within those fields, but most attempted definitions do have a common core:

A model is a simplified representation of a phenomenon.

This description has a very broad scope, and includes (but is not limited to) three dimensional physical models, mathematical representations, drawings, computer simulations, and block charts. All of which can be used and created in secondary school technology and engineering education.

No proper definition of neither *model* nor *modelling* will be presented in this article. Tentatively, by *model* we mean any kind of simplified representation of a phenomenon, intended for a particular purpose. Excluded are, however, representations that are realised exclusively through the use of natural language (spoken and written expressions), as well as models formed in an individual's mind (so called *mental models*, see e.g. Wild 1996, pp. 10–11). As we use the word, a model exists outside of the human mind. By *modelling*, we mean the process of creating models, including validation, verification, and presentation, as well as evaluation, and revision (compare Müller 2009). The strong 'design and make' tradition in technology education has led both teachers and technology education researchers to focus on models in the form of three-dimensional physical objects and two dimensional visual ones (sketches, technical drawings). The development in recent years, with revised technology subjects that apart from the traditional 'design and make' content also include information technology, electronics, infrastructure, and sustainability (e.g., Massachusetts Department of Elementary and Secondary Education, 2016; Ministry of Education [in New Zealand], 2018; National Agency for Education, 2022), necessitates teaching and learning about other types of models, such as flow charts, graphs, mathematical expressions, and computer simulations.

Models in technology, engineering and engineering science

Unlike the natural sciences, which in essence are academic endeavours, technology and engineering stem from practical traditions of knowledge. Throughout the centuries, they were developed in workshops and forges, on building sites, in factories and among engineers bent over drawing-boards. Technology and engineering did not move into the academies, universities and polytechnic institutes until the 19th century, and their applications lie mainly outside of the academic context (Mitcham, 1994; Meijers, 2009). Technology is fundamentally about solving human problems and fulfilling wishes. Technological knowledge, skills, processes and models are evaluated from that perspective. Technical models are often very context-specific. The need for generalisability is not absolute, as in the idealised natural sciences (de Vries, 2016). Complementary or even competing models can exist in parallel, if they are useful for technical problem solving in a certain context.

Throughout a typical engineering design process, various kinds of models are used. Rough sketches are made in the initial phase, drawings and physical models are used for the evaluation of suggested solutions, computer programs are planned using flowcharts, technical drawings are used for communication and documentation, mathematical models are used to determine mechanical stress and strain, etc. As has been stressed by for example Ferguson (1992), visual representations have a prominent position in the engineering toolbox. Engineers commonly present even abstract data visually, and tend to use expressions based on the visual model (e.g. talking about 'moving along the curve' rather than an abstract value changing). Knowing how to develop and interpret these varying types of models belong to the fundamental skills in most engineering disciplines.

The academic branch of technology and engineering will hereafter be referred to as *engineering science.* Work in the engineering sciences have a slightly different purpose than work in engineering. The design engineer typically aims at developing products. The engineering scientist strives for knowledge about more general technical phenomena, knowledge that can be applied in a greater range of technological problem solving (Edström, 2020; Hansson, 2007). Models are used in engineering science research, and models in the form of mathematical formulae and descriptions of design concepts constitute an important part of its output.

Modelling in secondary technology and engineering education

In technology and engineering education, the main purpose is neither to produce marketable products, nor to unveil or create new technological knowledge. Instead, it is about learning. Students should learn about the engineering process, its products, systems, processes, and roles in society.

The ability to create and use a selection of models and model kinds that are commonly used within the engineering community is necessary for the aspiring engineer or technician. But in education, models are also used for explanatory and orienting purposes that lie well off the area in which students practice engineering design. Students commonly study models of transportation systems to learn about transports. They study models of nuclear power plants to learn about nuclear power plants. This situation inevitably leads to a transfer problem: the students' knowledge about the model must be transferred and adapted into knowledge about the real phenomenon (compare Gericke 2008). Or, put in other words: Students are taught about the model but expected to learn about the real thing. Therefore, the purposes of models and modelling in engineering education should combine parts of their use in engineering design and the engineering sciences, but also add further, educational aspects. A poor educational model does not result in accidents or economic ruin, but more likely in misunderstandings or lack of learning.

Models are also commonly used to learn about the process of modelling. Students prepare models or use and evaluate models during their product development work. This can lead to situations where the very ideas of models and modelling can be illustrated. Unfortunately, this is not always done. The models and the construction of them tends to become an end in itself; the cutting of cardboard and application of glue become more important than the actual relationship between the model and the phenomenon (The Swedish School Inspectorate, 2014; Klasander, 2010, p. 221).

Technology education research on modelling has been carried out in only a handful of studies (e.g. Brink et al., 2021; Citrohn & Svensson, 2022; Citrohn et al., 2022; France et al., 2011; Gilbert et al., 2000; Haglund & Strömdahl, 2012; Hallström & Schönborn, 2019; Welch, 1998). The majority of these are teacher and/or teaching oriented. Nia's and de Vries' (2017) article is different in that it takes an explicitly philosophical stance on models. Their model typology is based on a well-established framework for describing and analysing technical artefacts developed mainly by Dutch analytical philosophers since the early

2000s (e.g. Kroes, 2012). The artefact framework relies on the view of technical artefacts having dual natures: each artefact has a physical nature as well as a functional one. Its physical nature is just that: what it is made from, its shape, weight, size, etc. It can in principle be measured using methods from the natural sciences. The functional nature, on the other hand, depends in some way on the object's purpose and/or its creator's or user's intentions. Similarly, a model has, according to Nia & de Vries (2017), an *intrinsic nature* (its form, material; how it is realised and represented) and an *intentional nature* (its purpose, what it can be used for). They apply this philosophically grounded model of models to the American standards for technological literacy (International Technology Education Association, 2007) and the New Zealand technology syllabus of 2010. While both documents repeatedly mention models and provide scattered comments about their use, none of them provides a cohesive framework for model creation or use.

Citrohn & Svensson (2022) interviewed 11 experienced Swedish technology teachers about the use of models in technology education. The responses were analysed using a thematic analysis based on Nia's and de Vries' (2017) framework. The model use in their teaching could be divided into two main categories: models as tools for 'The design process', and for 'Explaining and facilitating understanding of technological solutions' (p. 816) respectively. The models are used for communication and explanation purposes. In the design process they are also used for documentation and for prescribing e.g. a certain work-flow. The article focuses on how the teachers describe model use in technology education. It does not discuss the modelling process, how students learn about it or the place of model and modelling knowledge in a more general technological literacy. Citrohn et al. (2022) studied actual modelling processes in design projects in classrooms. They conclude that design projects with a high degree of freedom can give students the opportunity develop quite complex modelling knowledge, albeit primarily regarding physical and visual models.

Brink et al., (2021) interviewed Swedish technology teachers in lower secondary school to find out whether and for what purpose they use digital models. The twelve interviewees differ concerning details about their model use, and have no common modelling terminology. They use digital models in the form of CAD drawings, simulations, and video clips mainly to visualise technical phenomena, and to prepare the students for work and future studies. They also provide a few examples of how digital models can be used to create opportunities for cross-disciplinary collaborations, such as when students create technical drawings in technology class and use said drawings in crafts class. Judging from the article, the teachers are not used to discussion about epistemological questions concerning models' scope, or the model–reality relation.

Which models to use depend on their pedagogical usefulness, which does not necessarily correlate with their usefulness in engineering design or the engineering sciences (Norström, 2013). Haglund and Strömdahl (2012) exposed groups of students with different educational background to the same models and concluded that students' previous understanding as well as their plans for future work strongly affected how they evaluated the usefulness and 'realism' of the models. The quality of a model from a teaching and learning perspective relies on the model in and of itself, but obviously also on the context in which it is used.

Models in science and science education

Modern technologies are often to a greater or lesser degree developed using methods, models, and knowledge from the natural sciences. That, together with present day ideas about 'integrated STEM education' (science, technology, engineering, mathematics), make some comments concerning models in science education necessary. Models and model use can even function as bridging concepts between the STEM root disciplines (Hallström & Schönborn, 2019).

In idealised descriptions of the natural sciences, the overarching goal is presented as reaching knowledge about natural phenomena. To do this, hypotheses are formulated, experiments are performed, and models are created. The aim of the scientist is to create theories and models that can be used for explanation and prediction in a wide context, which is in stark contrast to the highly context dependent models commonly used in technology and engineering. The natural sciences evolve through the introduction of new and more encompassing models and theories. The phlogiston theory of combustion, introduced in the 17th century, replaced the theory of the four elements from antiquity, because it allowed for the creation of models with a greater scope and higher predictive value. When oxygen was discovered in the 18th century, the phlogiston theory was put aside. Once a theory has been falsified or a more far-reaching one (one that covers more aspects of the phenomenon and/or has greater accuracy) has been established, it is no longer considered scientific (Chalmers, 2013/1979; Popper 2002/1963).

This very strict use of 'science' and 'scientific' is seldom prominent in curricula and similar documents for primary and secondary education. On the contrary, obsolete scientific theories and their accompanying models are often used. Bohr's models of the atom and Mendel's model of inheritance are both largely obsolete within the scientific sphere. In school science, they are common, and often presented without comments about their having fallen from scientific grace. Obsolete science is used because it can be understood by the students (Gericke, 2008; Justi & Gilbert, 2002). Students can train scientific skills (doing experiments, practice measurement, write reports etc.) and learn how to draw conclusions in a scientific way, even though the underlying theories are not state-of-the-art.

Classification of models

As stated previously, models can be of many different types, kinds, and forms: physical objects, charts, mathematical formulae and more. Various attempts to divide them into groups have been made.

Representational modes

In educational studies, the most common way is to sort models according to representation: physical models, mathematical models etc. A well-known example is Gilbert's (2004) typology where he distinguishes between five different representational modes of models: the concrete or material; the verbal; the symbolic; the visual; and the gestural. These are similar to what Nia & de Vries (2017) call *types* or *forms* of intrinsic natures.

The diversity of representational modes must be taken into consideration when developing a model-based technology education, as each of these modes possesses relative representational power as well as limitations. For example, Welch (1998) emphasizes concrete three-dimensional models as one of the key factors for students to succeed in technological development tasks in school. At the same time, there is also potential in symbolic and visual models in technology education. Discerning and interrogating a model's strengths and weaknesses are conducive to solving authentic technology and engineering tasks (compare Allchin's, 1997, discussion about models in chemistry education).

From a teaching and learning perspective, the model's form, implementation or representation is important (as shown by, for example, Haglund & Strömdahl 2012). Representational modes in secondary technology and engineering education include, but are not limited to:

- *Iconic diagram* — Graphic depicting physical aspects of the phenomenon, mainly showing them as they look. Examples: exploded views of technical artefacts, and line drawings in assembly instructions.
- *Schematic diagram* — Graphic depicting physical aspects of the phenomenon, using symbolic representations. Examples: circuit symbols, field lines, force and torque arrows.
- *Technical drawing* — *Iconic* and/or *schematic diagram* adhering to certain standards and including information about measurements, tolerances, etc.
- *Sketch* — A simple *iconic* (sometimes also *schematic*) *diagram*, drawn quickly, often by hand.
- *Animation* — Similar to schematic and/or symbolic diagrams, but with added movement.
- *Network chart* — A graphic depicting abstract and qualitative relationships among different components. Examples: flow charts, decision trees, class diagrams.
- *Photograph* — Colour or black and white realistic image captured by a camera.
- *Graph* — Graphic representation of quantitative data by placement and/or size. Often includes numerical figures and coordinate systems.
- *Equation* — Symbolic expressions using algebraic symbols. Examples: Ohm's law ($V = I \times R$).
- *Physical model* — Similar to an iconic diagram, but represented as a physical object in three dimensions.

The list is inspired by Tang's (2022) list of types of visual representations in science textbooks, but adapted to include specifically technical modes and those that cannot be printed in books. The types can of course be combined.

Intentional modes

Another way of dividing models is according to their purpose, intended use, and what kind of information they represent. Models in technology and engineering can be descriptive or prescriptive (comparable to Nia's & de Vries', 2017, *model intentions*). Descriptive models describe how things are. Prescriptive models describe them as they should or ought to be. These main types can be divided further into sub-categories. Whether a particular model is prescriptive or descriptive is sometimes context dependent. If a technical drawing is used for planning manufacturing, it is a prescriptive model. If the very same drawing is later used when the finished product is presented to a prospective customer, it is a descriptive model.

Descriptive models

Descriptive models describe certain characteristics of technical phenomena (products, processes, systems). They can represent the looks of a product, how its function is implemented, or a certain characteristic such as sturdiness or resistance to corrosion. In general discussions about *models* and *modelling* in the philosophy of science, descriptive models tend to be the presumed kind (e.g. Frigg & Hartmann 2020).

In many ways, technical descriptive models are similar to those used in the natural sciences, and models from the natural sciences are commonly included as parts of complex technical models. There are however important differences, both concerning the nature of the modelled phenomena and their ontological status. In simplified terms, a model in the natural sciences describes a natural phenomenon that exists or is believed to exist. A technological model describes a human-made phenomenon that may exist, have existed or is planned to exist in the future. Amongst other things, this means that the meaning of a central concept such as validity is different. To talk about validity, in the regular sense of the word, might become absurd if the modelled phenomenon or its context does not exist. What should the model be validated against?

Explanatory models

Explanatory models make up a sub-category to the descriptive models, as an *explanation* is considered a set of descriptive statements (Hempel, 1962).

Explanation is a complex term that tends to be used differently in the theory of science on the one hand, and in technology and everyday language on the other. In theoretical natural science, an explanation is a description of why something happened. A recurring reference is Hempel's and Oppenheim's (1948) description of the *deductive nomological theory of scientific explanation* (the 'DN model', also known as 'the covering law model'). In a DN explanation, the explanans (that which is to be explained) is something that has occurred. The explanandum (that which explains) consists of a set of propositions, among which at least one natural law must be included. From a valid explanandum, the explanans can be deducted using classical logic. The rules of the DN model have been criticised for being too strict (Pitt, 2009; von Wright, 1971), but its main tenet – that explanation concerns something that has already happened and that its occurrence should be explained through cause-and-effect relations – remains very strong within the natural sciences.

In everyday language, as well as in engineering, the term 'explanation' is generally used in a vaguer sense. It includes, but is not limited to, DN-inspired interpretations. Explanation means roughly 'a description of how one occurrence depends on something else' or 'something that can be the answer to a "how?" or "why?" question' (discussed e.g. by Gilbert et al., 2000). For a model to be of the explanatory type, it must therefore include information about some kind of cause and effect. An explanatory model aspires to describe in a realistic manner at least some aspects of how or why a phenomenon occurs.

A typical explanatory model in technology and engineering education is a sketch showing how the mechanism of some apparatus works, with levers and gears that show *why* the incoming axle is faster than the outgoing one or *how* the slowing down of the rotation is accomplished.

Predictive models

Predictive models can be used to predict what will happen, with certitude or some probability. Prediction is similar to explanation in many ways, and many models can be used for both purposes. The example of an explanatory model of the inner workings of a mechanical gadget could probably be used for prediction as well as explanation. If the very same apparatus had instead been represented by a 'black box', only stating that the rotational speed of the outgoing axle is two thirds of the speed of the incoming axle, it would have been a model useful for prediction (to predict what the speed of one axle would be if the speed of the other was known) but not for explanation (as no information concerning how the speed reduction is accomplished is provided).

There are important, though at times overlooked, epistemological differences between explanation and prediction. When presenting their *deductive nomological model of explanation*, Hempel & Oppenheim (1948) claimed that the most important difference is the time scale. They proposed that explanation and prediction are essentially the same thing, but in one case concerns what has happened and in the other what will happen. This view has been criticised numerous times (e.g. Scriven, 1988/1962; von Wright, 1971). From a modelling perspective there are obvious differences. We can use an old, geocentric orrery to predict future phases of the moon or calculate historical ones. But as it relies on an incorrect, earth-centric description of the universe any attempts to explain *why* the phases of the moon change will fail. The orrery in question is a type of model that can be used for prediction, but not for explanation. It is thus not the time scale that is the essential difference between prediction and explanation, but the fact that explanation demands some kind of knowledge about causality while prediction can be based solely on the knowledge about correlation (Pitt, 1993; Scriven, 1988/1962). The validity of an instance of a prediction can be verified through observable phenomena. The correctness of an explanation cannot be verified in the same sense. The reason is the problems with identifying or detecting causality, well known since the days of Socrates (4th century B.C.) and elaborated upon by thinkers like David Hume in the 18th century (Hume, 2000).

Many decisions during the engineering design process boil down to 'Will this suffice for the final product?' which is a question about prediction. Good models are needed to answer that and similar questions with an acceptable level of reliability: Will the future bridge collapse when cars run over it? Will this motor fit into the casing? Will this class hierarchy provide a useful framework for the program development? The creation and use of models are therefore central parts of the engineering design process.

Prescriptive models

Prescriptive models prescribe how certain characteristics of technical phenomena should be. Examples include standards, safety regulations, and prescribed workflows and processes. Technical drawings for manufacturing and assembly are also included in the category. Prescriptive models are inherently normative, as they reflect the norms of their creators (compare with the concept of 'use plan', e.g. Vermaas et al., 2011).

Modelling the modelling process: a new framework for technology and engineering education

The process of modelling results in a model, *a simplified representation of a phenomenon, intended to be used for a certain purpose*. Characteristics that are not important for the purpose in question are left out. If all we are interested in is the overall look of a car, a car model for that context does not need to have an engine or be of the right size. If, on the other hand, we are interested in its deformation in a collision, it can be represented by a set of differential equations and need not have any physical representation at all (see for example, Ryberg et al., 2014). The omitted characteristics make many models' usefulness highly context dependent (e.g., Müller 2009).

In their short introduction to scientific models and modelling, Gerlee and Lundh (2012) describe a two-step modelling process: first isolation, then simplification. For the purpose of model creation in technology and engineering education, we have chosen to elaborate this, and describe a six-step process: *identification*, *isolation*, *simplification*, *validation, verification*, and *presentation*:

- *Identification* — Identify the phenomenon to be modelled.
- *Isolation* — Select the characteristics of properties of the phenomenon that are to be represented in the model.
- *Simplification* — Simplify the chosen characteristics of the phenomenon (idealization, 'black boxing', …).
- *Validation* — Validate the simplified model. Is it a good enough representation of the chosen characteristics of the phenomenon for the intended purpose?
- *Verification* — If possible, verify the model using known or experimental data describing the phenomenon. Can the model be used to predict the behaviour of the phenomenon? What are the limits for the model's use?
- *Presentation* — Present the model in a suitable form (physical object, graph, block chart, diagram, …).

In real life, these steps tend to be intermingled. Choices in one step may affect another. Which simplifications that are necessary depend partially on which presentation equipment that is available, for example.

As is obvious from this process, a model cannot be 'true'. Instead, it represents a sub-set of the phenomenon's characteristics, each with a certain accuracy.

When creating educational models, the curricula and similar documents tend to influence the *identification* and *isolation* steps strongly, while to some extent the *simplification* and to a great extent the *representation* are left to textbook authors, teachers etc.

Why should students learn about models and modelling in secondary technology education?

For students to be able to become active agents in a technologically advanced society, they need fundamental understanding of models and their limitations. Without some knowledge about simplifications, limitations, and context-dependence, it is very difficult to evaluate the reliability of prognoses concerning future infrastructure, risk assessments for nuclear power, or what a planned city block will look like. Technical models are important for many kinds of political decisions and debates.

During the last decades, the collaboration between or the unification of school subjects in the form of STEM (science, technology, engineering, and mathematics), STEAM or STEMM (with art or medicine added to the mix) has become prevalent. As has been pointed out e.g. by Hallström & Schönborn (2019), models and modelling can serve as uniting epistemic concepts in STEM education. Models originating from the natural sciences are used in engineering and represented in mathematical form, for example. Models can however also be used to mark the differences between the root disciplines, as they play different roles: the descriptive models of the natural sciences represent the world as it is while the prescriptive models of engineering can represent future products or systems.

Learning about models and modelling is also necessary as a preparation for future education and careers in technology and engineering. To understand the modelling process and model use (including the limitations of all models and the inherent normativity of prescriptive models) are important building blocks in a general understanding of engineering processes.

What should students learn about models and modelling in technology education?

As described above, curricula in Sweden and elsewhere describe students as users and creators of models. In both these roles, they need to be aware of models' essential characteristics: they are simplified representations and are therefore context dependent and have limited scope.

Models can be used to gain understanding, to communicate, to guide actions or more. As model creators, students should learn about the modelling process, in this article described as *identification*, *isolation*, *simplification*, *validation, verification*, and *presentation*. This is necessary for many types of design or product development processes, whether the model is a problem-solving tool along the way, a way of presenting an idea, or the final product of the project. Dividing the modelling process into these distinct phases allows students to practice and show various types of modelling knowledge and skills. Modelling work in Swedish schools commonly has a strong focus on physical models and the *presentation* phase (Citrohn & Svensson, 2022; The Swedish School Inspectorate, 2014). For modelling activities to be occasions for multi-faceted learning, even the other phases should be included. From our analysis of curricula and textbooks (see below), it is particularly noticeable that the verification and validation parts of the framework are missing.

How should students learn about models and modelling?

Students are model users and – in many cases – model creators whether they know it or not. A first step towards better understanding could be to make them aware of the limitations of the models they encounter. Which details have been omitted from the drawing of the electrical motor in the textbook? How does the model house differ from a real house? The reduced size is easy to spot, but apart from that? Can the model be used to determine the house's suitability for cold climates?

The 'learning by doing' doctrine is strong in technology and engineering education, and well suited to the process of model creation. Decide what the model shall be used for: *description*, *explanation*, *prediction*, and/or *prescription*. Follow the steps of *identification*, *isolation*, *simplification*, *validation, verification*, and *presentation*. Validation and verification are difficult, especially for models of objects that do not yet exist in the real world, as was noted above. However, including these steps in learning modelling might lead to an understanding of this difficulty in the process of engineering design.

Applying the framework: Modelling in curricula and textbooks

Technology curricula for primary and secondary school

In several international syllabi for technology and engineering in primary and secondary school, models and modelling are mentioned. According to the New Zeeland curriculum, students should ‘learn how functional modelling is used to evaluate design ideas and how prototyping is used to evaluate the fitness for purpose of systems and products’ (Ministry of Education, p. 2). On key stage 3, English students should be taught to ‘develop and communicate design ideas using annotated sketches, detailed plans, 3-D and mathematical modelling’ (Department for Education [in England], p. 2). In the National Science Foundation’s standards for K–12 engineering education, modelling is included in a list of important engineering ideas, and we learn that ‘engineers use modeling [*sic*, American spelling] to understand how a product or component may function when in use.’ (p. 7). Obviously, models and modelling are identified as an important area of study within technology and engineering for primary and secondary school internationally. Different countries do however focus on different aspects of descriptive models and their use (communication in England vs. evaluation in New Zeeland, for example).

For the rest of the article, examples are mainly from the Swedish technology subject. In Sweden, technology is a mandatory subject for all students in the so-called pre-school class (6–7 years) and the nine years of compulsory schooling (7–16 years). From 2022, the curriculum is based on three supposedly generic skills: (i) reflection on technology and society, (ii) knowledge about technical solutions, and (iii) design and construction. These skills are applied to the core content, which includes classical engineering areas such as materials, solid mechanics and electronics, but also automatic control and the history of technology (National Agency for Education, 2022). In upper secondary school (16–19 years), technology is a subject within the technology programme, which is chosen by a few per cent of the students.

Swedish lower secondary education

Models are explicitly mentioned in the national curriculum document (syllabus) in the core content for compulsory school. In years 7 to 9 (the last three years of compulsory schooling, students are 13–16 years old), under the heading ‘Working methods for developing technological solutions’, the document states that students should learn about ‘documentation of technical solutions: sketches, drawings, physical and digital models …’ (National Agency for Education, 2022, p. 260). All these would fall under our broad definition of model, and the aim, according to the curriculum, is to learn to document technological solutions, i.e. using descriptive models for communicative purposes.

In the assessment criteria, the need for knowledge about models and modelling is more distinct. For the highest grade (A) students should ‘carry out development and construction work in a well-structured way. During the work process, the student methodically tries and re-tries ideas for solutions and choses ways that lead towards a working solution. The student documents their work so that its intention is clear.' (p. 6). Well-structured development work, evaluation and testing, as well as documentation all imply the necessity for knowledge about modelling, even though the term is not used.

Swedish upper secondary education

The curriculum of technology (National Agency for Education, 2012) in upper secondary school is based on nine key abilities that students are to develop. Of these, models and/or modelling is explicitly mentioned in only one:

5. Ability to use models and tools for analysis, calculations, reasonable estimates, documentation, presentation, and information.

This covers a wide range of model use, explanatory (*analysis*) as well as predictive (*reasonable estimates*) and purely descriptive (*information*). Note that the explicit focus is on model use, not on creation, validation, or verification of said models. In the descriptions of two other abilities, the use of models can be presupposed, although the term itself is not employed:

3. Ability to solve technical problems.
4. Ability to use methods, concepts and theories from the technological sciences.

Models of varying kinds, from simple sketches to advanced simulations, are absolutely necessary for many types of technical problem solving. Models are involved in many of the methods used in engineering, they are used to present theories, and they form many important concepts in the technological sciences.

Technology education in upper secondary school is divided into three courses: *Technology 1* (an introductory course that includes e.g. project planning and technical drawing), *Technology 2* (with a stronger emphasis on applied mathematics and natural science; intended for students who plan to study engineering on university level), and *Technology – specialisation.* The last one is an umbrella concept for all kinds of more specialised content, such as solid mechanics, materials science, mechatronics, the history of technology, and more (National Agency for Education, 2012).

Use as well as creation of two-dimensional descriptive models, such as sketches and technical drawings, are explicitly mentioned in the syllabi. For other types of models, what students are expected to learn is open to interpretation. Throughout the syllabus text, there is, for example, no explicit mention of the ability to create mathematical models, only to use them.

In the grading criteria, models and modelling are mentioned explicitly only in *Technology 2*. For grade A (the highest grade), the student (among other things) ….

> … solves advanced technological problems, choses and uses in collaboration with a supervisor suitable methods and documents the work and the results. In the work

process, the student uses technological concepts, theories, and models confidently and correctly.

Assessment of modelling in secondary technology and engineering education curricula

According to the Swedish technology syllabus for lower secondary school, for the highest grade (A) students should manage to systematically test and retest possible ideas for solutions and chose methods that lead forward. They can also in a well-developed way describe how parts of technical solutions work together, and document their work in ways so that the intention is clear (National Agency for Education, 2022, p. 260). 'Well-developed', 'systematically', and clear intentions ought to imply in-depth knowledge about model use and the modelling process, including (but not limited to) recognition of the models' characteristics and creation, from *identification* through *validation*, *verification*, and *presentation*.

If the modelling process in technology and engineering is to be taken seriously, all the phases of the modelling process should be practiced and assessed during technology education. Judging from the Swedish Schools Inspectorate's (2014) report about technology education in compulsory school, this is not always done. There are some examples of planned and reflective modelling processes, e.g. one school where students plan playgrounds and outdoor recreational areas and use *physical models* and *iconic diagrams* to communicate their ideas to local politicians (p. 23). In other examples, the so-called modelling focused strongly on the presentation phase. Students in one of the studied schools (p. 18 f.) built physical models of bridges, where the purpose of the modelling was not stated. According to the students' stories, they started in the simplification phase and spent most of the time in the presentation phase. As the model had no explicit purpose, validation became impossible. According to our interpretation of the assessment criteria, the students did not have a chance to reach the upper grades. The task provided no opportunities to practice planning or to show the ability to create a 'well planned' model; good planning demands a purpose or goal to be evaluated against. The presented framework offers a structured way of making sure that the modelling is 'well planned', based on research on modelling in technology and engineering education and philosophy.

Models and modelling in Swedish secondary technology and engineering education textbooks

Five textbooks for the subject of technology in secondary school (Citron & Lovén, 2022; Frid, 2011; Frid, 2017; Nyberg, 2011; Svensson et al., 2018) are studied to find examples of model use for descriptive and prescriptive purposes, how students are taught and encouraged to use and develop models, and for how the modelling process has been performed when creating the educational models found in the books. Four of the books are intended to be used with the curricula introduced in 2011, i.e. National Agency for Education (2011) for lower secondary school and National Agency for Education (2012) for upper secondary school. The fifth, Citrohn & Lovén (2022) is intended to be in line with the revised curriculum for compulsory school (National Agency for Education, 2022), used from the autumn semester of 2022 onwards. From a models and modelling perspective, the differences between the old and the new curricula are miniscule. All books include models intended to teach the reader about technical phenomena, such as machines, systems and processes. They also include at least rudimentary chapters about sketching and technical drawing.

Tang (2022) showed that certain types of illustrations are used with certain types of text in science textbooks. Stories and descriptions use mainly photographs, explanations and descriptions of procedures use diagrams together with photographs, and 'experimental accounts' (procedures and results of scientific experiments) use diagrams together with tables of numerical and text-based data. Roughly the same division applies to the studied Swedish technology textbooks, which we analyze below.

Identification

The technical phenomena that are modelled in the studied textbooks are mainly physical artefacts. Some phenomena are most likely chosen because they are among the listed examples in the syllabus. The core contents for lower secondary school includes technical solutions for solid and stable constructions, as well as programmable electronic equipment. (National Agency for Education, 2022, p. 260). In all the lower secondary school textbooks (Citrohn & Lovén, 2022; Frid, 2017; Svensson et al., 2018) types of beams, reinforcement, and simple electronic circuits are included. In the secondary school textbooks, inspiration also seems to have come from a very detailed syllabus that was used for the technology subject between 1970 and 1994 (National Agency for Education, 1970). Core content from that syllabus, such as properties of steel and testing of materials, frequently show up in Nyberg (2011) and to some extent in Frid (2011).

The prescriptive models are few, with flow charts describing the engineering design processes, or parts thereof as the most prominent type.

Isolation

The aspects of the studied phenomena that are chosen for representation are mainly physical artefacts' appearances and how their main functions are implemented. A vast majority of the models provided by the textbooks are of a purely descriptive nature.

In the books for upper secondary school, there are some models that can be used for prediction, but they are absent from the lower secondary school books.

Simplification

In the studied textbooks, the provided models have been simplified mainly according to the following principles:

Idealisation

Materials are homogenous, electric conductors and power sources lack resistance, friction is omitted, etc.

3D to 2D

Three-dimensional objects and phenomena are studied in two dimensions only. Movement and physical extension along the axis perpendicular to the paper are omitted; the model is flat even though the phenomenon is not.

Black boxing

A component or sub-system is described only with reference to its input and output. The implementation of the function is omitted (Klasander, 2010).

Removal

Certain sub-systems or components are removed. They might be absolutely necessary for the operation of the equipment, but not to show the characteristics that are studied at the moment. E.g. earth wires and fuses are omitted from electrical equipment, synchronisers are omitted from gearbox models, and both cooling and lubrication systems are omitted from engines.

Context elimination

The phenomenon is shown without context. This eliminates problems with vibrations, precipitation, noise etc. Electricity, water and similar resources provided by the context are taken for granted.

Exaggeration

Small changes in shape, size, electrical current or the like are vastly exaggerated to be clearly discernible. Typical examples include beams' bending under stress or a construction element's elongation due to increasing temperature. These changes are often not drawn to scale but exaggerated by several hundred per cent in textbook illustrations.

Presentation

As the models are printed in books, they are two-dimensional, static, and of limited size. Modelling by students is mentioned. This is mainly in the form of *technical drawings*, but also to some extent about the creation of three dimensional *physical models*. In Frid's (2011) book for upper secondary school, life size models to try out ergonomic characteristics are mentioned. In the lower secondary school books, there is a strong focus on visual appearance. Citrohn & Lovén (2022, p. 89) provide an exception to the rule in the form of an exercise where the students are to design and model a holder for a mobile phone or tablet to be mounted on a bus or train seat. They suggest that the model could be made from rubber bands, ice cream sticks, cardboard, and hot-melt adhesive. Interestingly, there are no instructions or even suggestions concerning the modelling process.

Depicting models – *photographs* or iconic diagrams – are the most common. *Symbolic diagrams* and *network charts* are used to describe circuits in the chapters about electricity and electronics in both lower and upper secondary school.

Mathematical models in the form of *graphs* and/or *equations* are absent from the lower secondary school books, but exist in the chapters about electricity and solid mechanics in the upper secondary school textbooks. Frid (2011) has a short section about measurement errors, based on a short case study of a temperature measuring device which measures temperature indirectly through the variation in a measuring probe's electrical resistance at different temperatures. A model in the form of a graph, where temperature is plotted as a function of resistance is presented. The graph can be used to interpret measurements, and also to predict the expected resistance at a certain temperature or vice versa (p. 82). There is a reminder to calibrate measuring instruments, but no further discussion about important issues such as the limited scope of the model (it will not work for temperatures above the melting point of the probe, for example) or how measurement errors can lead to insufficient precision (hopefully detected during the *verification* phase).

Progression in modelling: solid mechanics and engineering mechanics

Examples from solid and engineering mechanics have been chosen as they are included in all five textbooks. The mechanics chapters tend to include explanatory as well as predictive models. Here, *engineering mechanics* refer to movement, mechanical equilibrium and similar concepts from Newtonian physics applied in a technical context. *Solid mechanics* concern the mechanical tension and deformation of solid objects exposed to force, stress, and torque. Especially in the lower secondary school books, this distinction is not made. Instead, everything mechanical is grouped together.

In the books for lower secondary school (Citrohn & Lovén, 2022; Frid, 2017; Svensson et al., 2018) the area of solid mechanics is approached from an experience-based, intuitive, rather than scientific angle. The concept of force, presumably known from physics class, is used, but neither torque nor pressure/stress. A typical example of a lower secondary school mechanical model is a combined *iconic* and *symbolic diagram* showing a balcony with a boy standing on it (Citrohn & Lovén, 2022, p. 28). The balcony floor bends, and arrows indicate how its upper surface is stretched while the lower is compressed. The model is simplified mainly through *3D to 2D*, and *exaggeration*. The bending of the balcony's floor compares to the distance between the floor and the boy's ankle, which is far more than a regular balcony made from concrete can bend without breaking.

The engineering mechanics chapters in the books for upper secondary school, Nyberg (2011) and Frid (2011), consist of rules for mechanical equilibrium, reaction forces, resulting forces, determination of mass centres, etc. Everything is highly idealised: forces are either applied to points without extension or uniformly spread over circular or square-shaped areas, friction is either 0 or well known, etc. It is fundamental Newtonian mechanics that could just as well be included in a physics textbook.

Nyberg (2011) has separate chapters for engineering mechanics (statics only) and solid mechanics. Frid (2011) have integrated them in one chapter. The models and examples they use are almost identical and of well-known types: beams resting on two supports and affected by vertical forces; beams fastened horizontally in a wall, bent by vertical forces; and calculation of bending resistance to show how the shape of the beam's intersection affects bending.

The progression is from common sense knowledge in lower secondary school to science-based or science-like knowledge in upper secondary school. This is reflected in the types of models used. In both upper secondary school books, the solid mechanics chapters include mathematical models in the form of *equations* and *graphs*. The models are mainly *predictive*, they can be used to predict what will happen when for example a certain force is applied to a beam. The solid mechanics chapters are based on calculation. This is in stark contrast to the studied books for lower secondary school (Citrohn & Lovén, 2022; Frid, 2017; Svensson et al., 2018) where no mathematical models at all are involved when sturdy constructions are described and discussed. Instead, concepts like hardness, elasticity and bending are described in everyday language and common ways to increase stability are described: reinforced concrete, corrugated metal, sandwich materials, shape (mainly the triangle), and how they affect artefacts' mechanical characteristics.

The *identification* process has been conducted differently on the two school levels. In lower secondary school, examples that students are likely to have experienced are chosen, such as bridges, concrete floors, and roofs made of corrugated sheet metal. In upper secondary school, the examples are mainly beams. These are presented with little or no context. The lower secondary school examples are intended to raise an interest, and be discussed using everyday language. The upper secondary school examples are most likely chosen because they lend themselves to *simplification* (*idealisation* and *3D to 2D*) which results in problems that can be analysed using simple mathematical models.

Conclusion

The 'why?', 'what?', and 'how?' questions are largely left unanswered in the curricula, and teachers' model awareness and interest in working with models and modelling on a conceptual level is often low (Brink et al., 2021; The Swedish School Inspectorate, 2014). Citrohn & Svensson (2022, e.g., pp. 821–822) describe how the experienced technology teachers that they interviewed would benefit from better knowledge about both model use in the design process and also the differences concerning model use in technology compared with the natural sciences. As shown above, the aid and support offered by technology textbooks for lower and upper secondary school are, at least in Sweden, inadequate. Models are used, but taken for granted. Neither their epistemological status nor the modelling process is discussed.

This study suggests a framework for teaching, learning, and analysing modelling in technology and engineering education in a fruitful way. The framework was applied to Swedish technology and engineering education curricula and textbooks for secondary education, and it was found that especially *validation* and *verification* are downplayed or missing in these accounts. *Simplification* is also an underdeveloped aspect of the process, even though it is an essential aspect of the model's nature. At the same time, the simplification has to be done with utmost care. Otherwise, the model might lose its validity. Students ought to know about common simplification strategies (idealisation, 3D to 2D, 'black boxing', removal, context elimination, and exaggeration), their advantages and limitations.

All the parts of or steps in the process, presented as a framework – *identification*, *isolation*, *simplification*, *validation, verification*, and *presentation* – are important building blocks of a solid understanding of models and modelling in technology and engineering (education). Therefore, the framework could serve as a blueprint for improving teaching and learning about technological and engineering modelling, both in curricula, textbooks and in technology and engineering classrooms.

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