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A guide on models and modelling

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Abstract. A new curriculum and examination programme for upper secondary school physics was recently introduced in the Netherlands. Models and modelling play an important role here-in. But teachers need help in developing their PCK in this area. To this end we developed a modelling guide, which introduces physics teachers to the role of modelling in science and science education, the scientific base of teaching and learning routes of modelling in pre-university education, and curriculum relevant computer models. We discuss the design and contents of this guide, and teachers' first impressions when it was presented to them in workshops.

1. Introduction

In the school year 2013-2014, a new curriculum and examination programme for upper secondary school physics started. It adopts a context-concept approach to education in which models and modelling play an important role. Both computer based modelling and a modelling approach to a given problem situation are considered cognitive tools for developing scientific literacy.

There is a long tradition in Dutch physics education in using models, in having students engaged in computer modelling, and in assessing modelling in school exams. The inclusion of models and modelling in the nationwide physics exams and the introduction of new contexts for modelling has made the topic compulsory. This has stimulated teachers to update or renew their PCK. To this end, professionalization courses were organized and papers were written in teacher journals. Reports on this topic were also published by the Committee Innovation High School Physics Education [1, 2] and the Netherlands Institute for Curriculum Development (SLO) [3].

However, what seems missing is a guide that informs physics teachers about the achievement levels with regards to models and modelling, and contains suggestions and didactic advice for realizing a coherent modelling curriculum. Supported by the Centre for STEM Education in Amsterdam, a team with experience in modelling at secondary physics level, including the authors of this article, have set themselves the task of filling this gap. At the beginning of 2018, a web-based modelling guide for Dutch physics teachers was finalized, published, and officially transferred to the website of SLO: <http://handreikingschoolexamen.slo.nl/natuurkunde/modelleren> The English translation is available at https://staff.fnwi.uva.nl/a.j.p.heck/Guide_on_Modelling.

In this article we present the design and contents of this guide, and teachers' first impressions when it was presented to them in workshops. We hope and expect that this presentation informs and possibly inspire others who want to support physics teachers similarly.

2. Design of the guide

This section is organised as follows: first we briefly discuss recent changes in the curriculum and examination for upper secondary school physics in the Netherlands. This helps the reader understand



what motivated the endeavour to develop a guide on models and modelling for upper secondary physics education. Hereafter we describe the design principles used for the creation of the guide.

2.1. Recent changes in curriculum and examination for Dutch upper secondary school physics

After years of preparation [1, 2], the Dutch curriculum for upper secondary mathematics and science education was renewed both at general education level and pre-university level. In this article we will focus on the upper level of pre-university education that comprises a period of three years with school exams and a nationwide final exam. Because the new physics curriculum started in the school year 2013-2014 for all Dutch students, the physics literacy of all students at pre-university level is examined according to the new programme from 2016 onward.

The ambitions of the curriculum reform can be summarized as follows:

1. improving students' scientific literacy and covering modern physics by the introduction of contemporary and relevant content;
2. intertwining contexts and concepts in science education;
3. achieving more coherence within science subjects and across the different science subjects, physics, chemistry and biology;
4. attracting more students and preparing them better for higher education in science.

The first ambition has been realised by the introduction of new knowledge domains such as 'Quantum World', 'Theory of Relativity', and 'Life and Earth', and by the introduction of new contexts such as nanotechnology, climate, (medical) imaging, the human body, sports, modelling of dynamic processes, and so on. New contexts have been introduced to make physics more attractive, improve learning results and increase the motivation, interest, and attitude of students towards the study of physics. In the so-called context-concept approach adopted in some form in all Dutch science curricula, contexts give meaning to science concepts and to selected instructional materials, and are meant to illustrate scientific and societal applications. Concepts typify in a broad way the most important insights in mathematics and science, and they guide the teaching of science. The Innovation Committee High School Physics Education [1, 2] promoted structuring of upper secondary school physics contents via contexts and concepts. In other words, it advocated intertwinement of a context-based approach, where contexts and application of science are used as a starting point for the development of scientific ideas, and a concept-based approach, which emphasizes that scientific ideas are covered before looking at applications. The goal of bringing more coherence within and across science subjects is not only meant to improve the students' learning of science, but also to prepare them better for higher education, in which a multidisciplinary approach is more and more adopted in teaching and learning in order to reflect that modern science is often carried out in multidisciplinary teams.

Evaluation studies [4, 5] show that physics teachers in general perceive the new curriculum as new and doable in school practice and that they enjoy the physics teaching within this new curriculum, although not everyone recognizes the reform as really new because of the long tradition in the Netherlands in using contexts to teach and learn physics. Ottevanger et al [4] found that physics teachers seem to predominantly interpret this approach as a set of particular comprehensive realistic situations with particular challenging problems that can (only) be solved when the targeted knowledge is mastered. They also found that the new physics program appears to be viewed differently and enacted differently between teachers who were involved in pilot projects and teachers who were not. Pilot teachers place concepts in contexts and stimulate students to use concepts in different contexts, too. Most physics teachers use contexts in a quarter of their lessons, mainly to illustrate or introduce new content. This conclusion is in agreement with the finding of de Putter-Smits et al [6] that teachers with design experience show more competence in the context-concept approach than their nondesigning colleagues.

A new physics curriculum also means new school exams and a new nationwide final exam. Folkers [7] came in her analysis of final exams in the science subjects biology, physics and chemistry with regards to the intended curriculum innovation to the following conclusions:

- Exam designers do their best to make space for the reciprocity of context and concepts, but there is room for improvement of the quality of the contexts used with regards to clarity, authenticity, relevance for solving problems, and assessment value;
- Modern science is sufficiently addressed in the exam questions, but it is not clear whether it stimulates teachers to use them in their lessons;
- Only coherence with mathematics can be identified in the physics exams;
- There are not many exam questions about doing science, such as scientific reasoning, inquiry and modelling;
- Knowing about the nature of science is not assessed in the final exams.

Although finding the right balance between the knowledge domains in the final exams is challenging, the first exams seem to sufficiently reflect the curriculum reform. The targeted modelling competency is described in the new curriculum and examination programme as follows [2]: “the candidate can analyse a contextual problem, reduce it to a manageable problem, translate this into a model, generate outcomes, interpret these outcomes, and test and evaluate the model. The candidate can, by consistent reasoning and by use of relevant computational and mathematical skills, convert an existing model into a computer model and generate outcomes by choosing an appropriate time step.” The modelling competency is assessed in school exams and, what is new, in the nationwide final exam. The following task in the physics exam of May 2018, about the motion of a car when propulsion stops gives an impression how this is done. An schematic model is given in terms of both computer code and a graphical model (Figure 1):

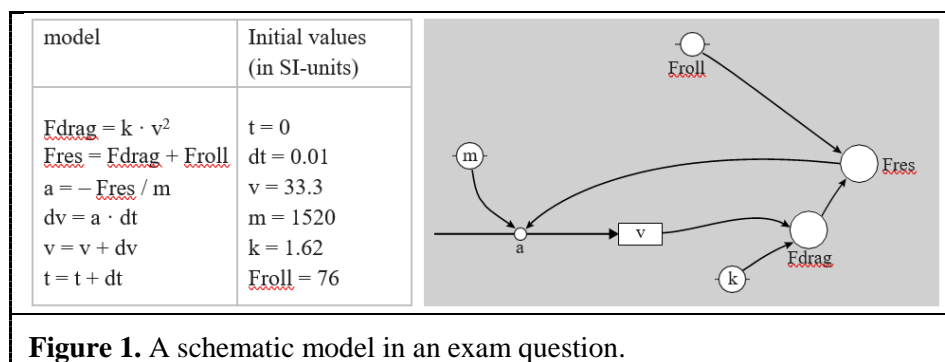


Figure 1. A schematic model in an exam question.

Two related tasks are:

1. Given graphs of measured data and model results, how can parameter values be improved?
2. Extend the computer model so that the distance that the car travels until the moment it stops is also computed.

Having such questions in a nationwide final exam simply means that physics teachers must pay attention in their lessons to computer modelling. How this is done is left to the teachers and textbook authors, but system dynamics-based graphical modelling has been advocated in the Dutch science curriculum [8] and this advice is reflected in the format of modelling questions in the nationwide final exams. Construction of computer models from scratch by students is something expected to happen in school exams in the form of practical investigations and student research projects. There is some tension between the vision of the curriculum innovation committee high school physics and the reality in the physics classroom, partly because teachers need time and experience to renew or update their PCK. To this end, professionalization courses have been developed and carried out, papers have been written about several topics in teachers' journals, and guides have been offered by the Netherlands Institute for Curriculum Development (SLO) such as the one about school examination [3]. The latter guide informs physics teachers about requirements and possibilities in assessment, and it contains suggestions and didactic advice for realizing the renewed curriculum. About computer modelling, this guide suggests for example to let students work with simplified representations of the real world and explore how change of one quantity changes other quantities, and to combine assessment with experi-

mentation in a practical investigation or student research projects. It also mentions some contexts that seem appropriate for modelling. But this is hardly enough for physics teachers to get a good view on how to incorporate (computer) modelling in their lessons. What seems missing is a guide that informs physics teachers about the role of modelling in scientific practice, the envisioned use of models and modelling in secondary school physics education and the associated achievement levels in the curriculum, and that contains exemplified suggestions and didactic advice that inspires teachers to realize a coherent modelling curriculum. The guide on models and modelling presented in this article is meant to serve this purpose, helping teacher to develop their PCK in this area.

2.2. Design principles for the guide on models and modelling

In an early discussion session of the development team it was decided that the main purpose of the envisioned guide is to help or enable physics teachers to develop and implement a modelling learning path for their students. The following requirements for the guide were set:

- The guide describes a modelling learning path that can already start in lower secondary physics education;
- The doctoral thesis of Onne van Buuren [9] is used as framework because his study is about a coherent modelling learning path that starts early, say with learners of age 13-14;
- Existing sample materials and instructions are collected, reviewed, and published in the form of semifinished resources that teachers can use to develop instructional materials and assessments;
- The guide must fit to current teaching methods and match the new physics curriculum. In particular, it must inform physics teachers in what way models and modelling are key elements of the context-concept approach;
- Attention is paid to known pitfalls in teaching and learning modelling;
- The guide is a supplement to the existing guide on physics school examination as published by the Netherlands Institute for Curriculum Development [SLO];
- The guide should be of limited size and not require much reading.

3. Contents of the guide on models and modelling

3.1. Outline

The web-based guide on models and modelling consists of four parts:

1. An introduction into models and modelling in science and technology, discussing
 - how modelling is both a way of thinking and a way of working in physics;
 - what is meant by the notion of scientific model;
 - the role of modelling in the scientific search for insight in the real world.
2. An introduction into models and modelling in science education, discussing
 - the learning objectives for modelling at secondary school level, which are assessed both in school exams and in nationwide exams of science fields;
 - a modelling cycle that can guide the learning activities and contributes to a systematic instructional approach to modelling;
 - challenges in modelling instruction, which resemble the ones encountered in inquiry-based learning and practical work;
 - the learning cycle introduced by Kolb [10] as guideline for an effective instructional approach to modelling.
3. A modelling learning path, extracted from the doctoral study of Onne van Buuren [9].
4. Overview of models and modelling equations that are most commonly used in Dutch secondary physics education.
 - Examples come from four subdomains of the examination programme: Force and Motion (see Figure 2), Oscillations, Energy and Heat, and Quantum World;
 - Computer models are presented in the form of semi-finished deliverables instead of worked-out lesson materials;

- Both text-based and graphical models are implemented in Coach [11], which is an integrated computer learning environment for STEM education and which is commonly available at Dutch secondary schools with also a home license.

In the following subsections we present details of the contents and advices for teachers in these parts.

Below are listed some dynamical models belonging to the subdomain *Force and Motion* the physics syllabus^{2,3}, with corresponding files for the Coach 7 modelling environment⁴.

1. **Constant velocity model**
2. **Constant acceleration model**
3. **Force-acceleration model**

In this general dynamical model, Newton's second law is recursively implemented for some resultant force F_{res} , i.e. the sum of all forces, considered as vectors, that are present in the given situation. The resultant force may depend on the position and/or the velocity.
Through this general dynamical model one can implement realistic dynamical systems with the resultant force, the mass, and the initial values of position and velocity as input.

Formulas in Binas:

$$F_{res} = m \cdot a$$

$$a = dv/dt \quad v = dx/dt$$

Difference equations:

$$\Delta v = (F_{res}/m) \cdot \Delta t$$

$$\Delta x = v \cdot \Delta t$$

Model rules

$$a = F_{res}/m$$

$$v = v + a \cdot dt$$

$$x = x + v \cdot dt$$

$$t = t + dt$$

Graphical model

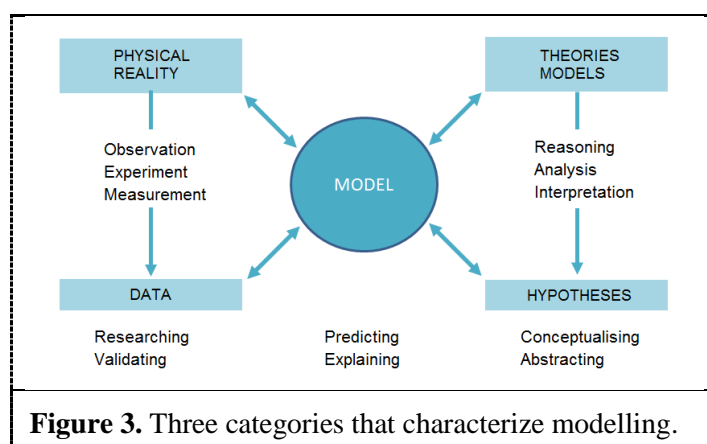
Coach 7
Example

Figure 2. Snapshot of a part of the modelling guide in the format used during its development.

3.2. Models and modelling in science and technology

Because physics teachers may not have personal experience with modelling or may not have a clear picture of its importance in modern science and technology, the first introductory chapter of the guide discusses what a scientific model is and how modelling is done by practitioners. In the guide, scientific modelling is defined in general terms as describing (mathematically) a situation in reality for the purpose of solving a problem or question in that situation. Modelling is seen as both a way of working and a way of thinking. It includes an iterative process that demands creativity and inventiveness and in which mathematical, scientific and technical knowledge is applied to describe new situations. This includes determining a strategy, analyzing or getting to the bottom of the problem, choosing variables, setting up connections, and deploying mathematical and computational tools. Figure 3, taken from the guide, illustrates that readers of the guide are exposed to the perspective of a model as a mediator between contexts and concepts. On the left-hand side are activities related to empirical research, such as collecting data that are used in the model and/or can be used to assess the modelling results. On the right-hand side are conceptual activities that must lead to the development of a model, including creative thinking and formulating hypotheses to be tested. The modelling process is from this point of view almost synonymous with the process of ‘doing research.’

Modelling is not just a tool for validating and applying theories. In science and technology, modelling is more and more a way of thinking for the purpose of creative development of theories. To illustrate this, the modelling guide contains three accounts from experts in psychological methods, theoretical ecology, and computer games development.



3.3. Modelling in secondary education

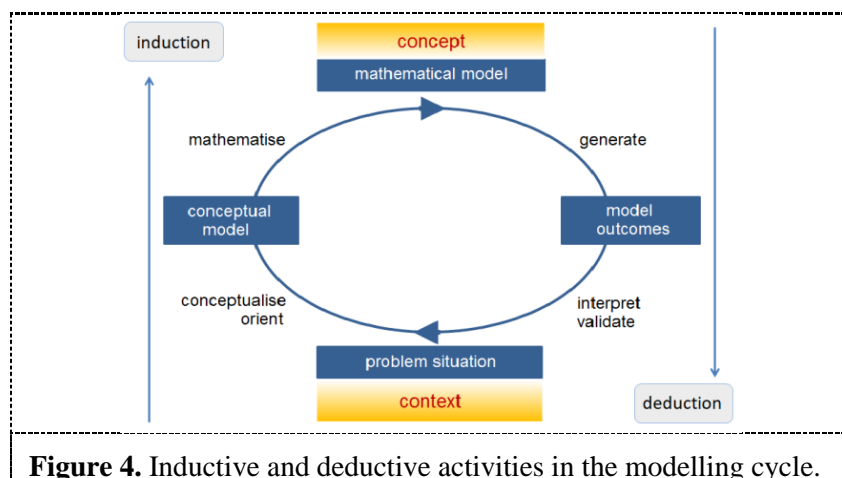
Although modelling as a skill has been part of the physics attainment levels since 1991, modelling in the physics programme focusses primarily on dynamic modelling with difference questions or differential equations, whether or not in the form of graphical modelling. Thinking in models, that is, model development as meant in the objectives of the new examination programme, remains underexposed. Readers of the guide are warned to judge the quality of a model not only with respect to its descriptive value (how well does the model describe observations and measurements?), a viewpoint that tends to emphasize that a model differs from reality and is merely an approximation, but also to look at the quality of a model in terms of its predictive power (does the model enable making prediction?) and its explanatory power (can the model explain observation or leads it to better understanding?)

To emphasize the role of modelling in education, three main learning outcomes can be distinguished [12]: (i) learning about models; (2) learning modelling; (3) and learning domain content from a model. In combination, these three learning objectives make it clear that modelling is not a separate subject in the curriculum. This is an important message for physics teachers because they may be tempted under time pressure to treat modelling as a separate subject that can be postponed.

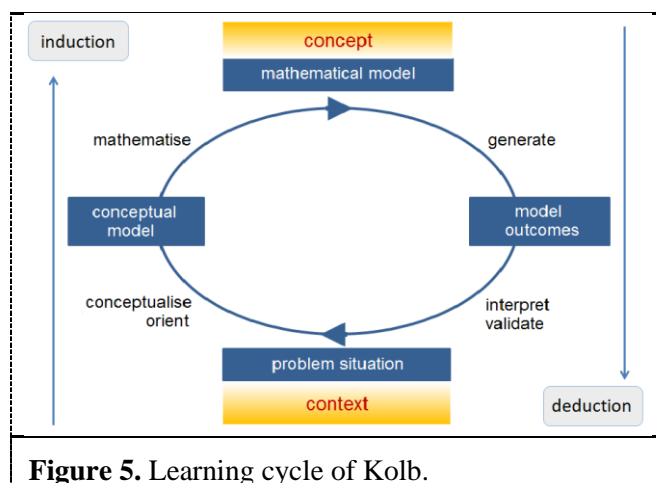
Within the framework of modelling education at secondary school level, the learning objectives are: learning to recognize situations where familiar models play a role, learning how to construct models, and interpreting model results in the light of the problem posed. These objectives can be achieved by systematically teaching students how to model. A tool to shape this is a schematic ordering of the modelling process as a cycle of activities, taken from [8] and shown in Figure 4. The following types of learning activities are distinguished in this modelling cycle: orientation, conceptualization, mathematization, generation of outcomes, interpretation, and validation. In the guide we state that research [9, 12, 14] has shown that (i) students benefit from a systematic structure of modelling instruction and from a systematic reflection on process steps and their outcomes; and (ii) that teachers benefit from the use of the modelling cycle because it structures a modelling teaching and learning strategy and its implementation in the form of a modelling learning trajectory.

In educational practice it appears that many students have difficulties in carrying out modelling activities with sufficient quality. Three important factors have been identified [13]: (i) lack of domain knowledge; (ii) insufficient understanding of the notion of model; and (iii) lack of understanding of the modelling process. Another factor is that translating a problem into a model (induction) and applying a model (deduction) are not equivalent in terms of comprehension. Induction leads from the special to the general and usually requires a greater creative effort than deduction from the general to the special. For the didactic implementation of the modelling cycle, we advise to separate the inductive and deductive modelling activities into two instructional elements with their own learning objectives: (i) thinking in models and (ii) working with models. Both should play a role in a curriculum that aims to teach physics through modelling. Figure 4 is used in the guide to illustrate how models and modelling are key elements of the context-concept approach. It is also used to show physics teachers that the didactics of this modelling cycle, in particular the phase of model development, has important characteristics in common with inquiry-based learning and practical work at school. Therefore, when

thinking about a modelling learning trajectory one can learn from findings and experiences in developing practical work for secondary physics students.



Insights about learning, for example from [10, 15, 16], may help develop a didactics of modelling. According to these insights, learning is a cyclic process that begins with concrete experiences and primary observations that subsequently lead to a connection with prior knowledge. The next step consists of a hypothesis about this connection, followed by actions with the aim of testing this hypothesis. In the modelling guide we link this and the context-concept approach to Kolb's idea of a learning cycle (see Figure 5). According to Kolb [10], there are four recognizable phases of learning: concrete experience, reflective perception, abstract conceptualization, and active experimentation and testing. Deep and permanent learning requires that all phases are completed (several times).



3.4. Modelling learning path

In the guide, a modelling learning path is described that is derived from the doctoral study of Onne van Buuren [9]. In his work it is evidenced that modelling, just like practical work, requires a lot of knowledge and skills, and takes time and effort to master. This holds for both students and teachers. Important points of attention for the teachers in modelling assignments have been identified and listed in the form of advice: (i) prepare well; (ii) limit learning goals; (iii) start as early as possible, preferably already in lower secondary level; (iv) repeat and reflect; and (v) support development of models.

A modelling learning path can be structured over time through a choice of modelling tasks with increasing degree of difficulty. Four modelling levels can be distinguished that elaborate on each other [12, 17]: (i) visual modelling; (ii) descriptive modelling; (iii) causal modelling; and (iv) dynamic

modelling. These levels of modelling as well as the inductive and deductive activities in the modelling cycle are exemplified in the guide for the motion of free fall and the quantum particle in a box.

The part in the guide on a modelling learning path ends with a discussion of the competencies needed for modelling. They include reading of diagrams and schemes, collecting and interpreting data, applying models and working with computer modelling environments, and applying specific mathematical knowledge and skills such as understanding the notions of variable, function, and difference equation, and having adequate mathematization skills. Teachers are advised to let student develop the relevant mathematical knowledge by separate instruction and practice.

3.5. Overview of models and model equations

Four subdomains, which are assessed in the nationwide final exam, have been selected for giving an overview of popular models and modelling equations in upper secondary physics education: ‘Force and Motion’, ‘Oscillations’, ‘Energy and Heat’, and (iv) Quantum World. Figure 2 illustrates how each example is organized: on the left-hand side we give a short theoretical explanation of the modelled situation and the core lines of the text-based model, plus a link to a corresponding text-based modelling activity in the Coach environment [11]; on the right-hand side we present the main formulas and the system of difference equation (differential equations are not dealt with in Dutch secondary education) as well as a graphical system dynamics-based model, plus a link to a corresponding graphical modelling activity in the Coach environment. When the reader clicks on the example button, a concrete example with initial values and graphs of corresponding model outcomes appears.

Working with quantum mechanical theory requires imagination and a lot of mathematical ingenuity. Nevertheless, the essence of the atomic structure can be clearly understood from simplified representations and models. In the modelling guide, we introduce dimensionless variables to simplify the one-dimensional Schrödinger equation. For example, in case of a quantum particle in a box with one finite wall, we reduce it to the following initial value problem

$$\frac{d^2\psi}{dx^2} + \gamma(n^2 - V)\psi = 0, \quad \psi(0) = 0, \quad \frac{d\psi}{dx}(0) = \sqrt{2n\pi}$$

where ψ is the wave function, $\gamma = \pi^2$, V is the potential of the situation with one finite well, and n is an admissible real number, that is, chosen such that the wave function does not ‘explode’. Figure 6 is a screen shot of a Coach activity, in which a concrete case is simulated.

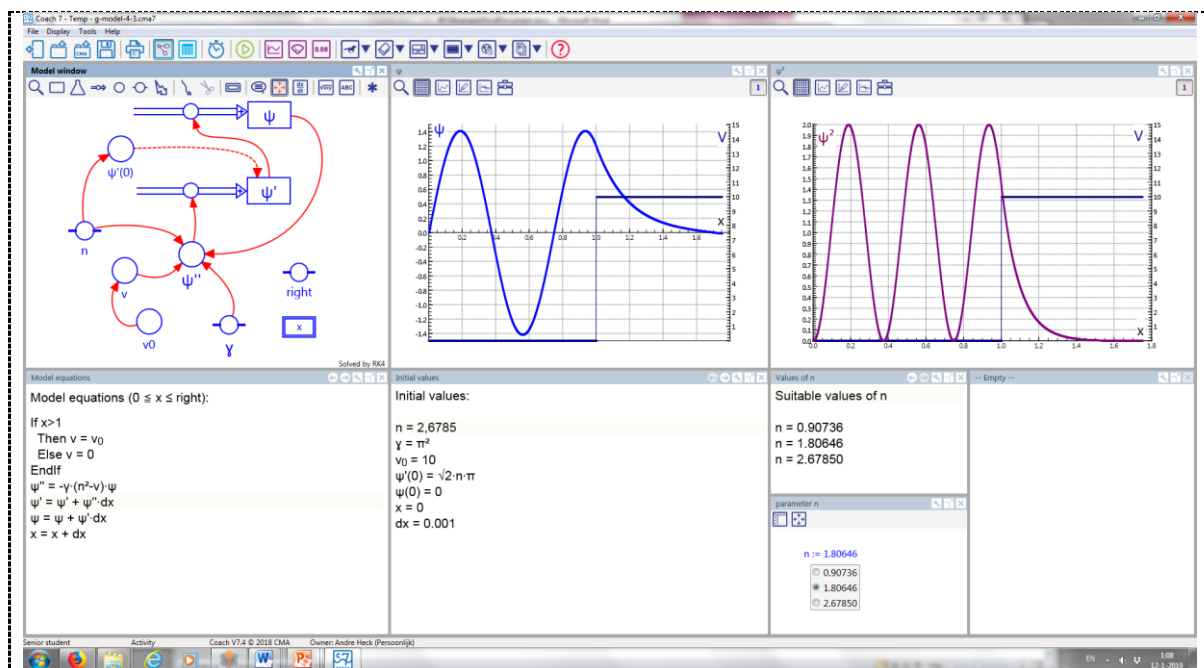


Figure 6. Screen shot of a Coach model of a quantum particle in a box with one finite wall.

Modelling examples included in the guide are always listed in increasing order of complexity. Many of them have been taken from doctoral studies [9, 14]. For the subdomain 'Quantum world' we have included the 1-dimensional Schrödinger equation of a free particle, a particle in a box, a box with one finite wall, a symmetric well, the harmonic oscillator, the hydrogen atom, quantum tunneling, and alpha decay. These are models that many physics teachers at secondary school would have difficulty with in designing the computer models themselves. The provided Coach activities help them create their instructional materials in this knowledge domain.

4. Teachers' first impressions

Despite the experience of the team that created the guide on models and modelling and the support they got from teacher educators and secondary school teachers (mostly persons who had been involved in pilot projects in the past), there is always at the end the danger of having not met teachers' expectations. Also physics teachers may have suggestions for improvement and extension. Therefore we organized a workshop at the annual physics teacher conference organized by the Werkgroep Natuurkunde Didactiek in 2018 (<https://wndconferentie.nl/conferentie-2018/>), in which we presented the guide on models and modelling to physics teachers, let them explore the four parts of the guide one at a time (in the given order), and discussed their first impressions and collected their reactions in a questionnaire. Below, we summarize the main findings.

The first two parts of the guide on modelling in science and its role in science education are generally seen as background information that is probably more useful after having obtained some personal modelling experience. Then the role of sense making of modelling in practice shows up well. Though a guide is not a piece of text that one needs to read linearly, this finding may lead to a reordering of the parts of the guide. Initially, physics teachers are more interested in the sample activities in the fourth part of the guide, followed by the part on a modelling learning path.

The third part of the guide on a modelling learning path is much welcomed, but what many teachers miss are: (i) guidelines or advice how to get started with a modelling learning trajectory in school practice; and (ii) a discussion about how text-based and graphical modelling are positioned in the curriculum and what are the advantages/disadvantages of each modelling style. This part makes some teachers with experience in modelling wonder whether they do something wrong when they use at school a somewhat different approach. This is of course not what is intended by the creators of the guide, but on the other hand it shows that the guide serves its role as giving food for thought.

The overview of models and model equations is the part that physics teachers like most for the obvious reasons that they can immediately use the resources in their own instruction and that these sample activities illustrate well a possible progression in complexity that can be built into one's own modelling learning trajectory in class. Especially the models in the knowledge domain 'Quantum World' are appreciated because these models are too difficult to create for inexperienced teacher themselves. But at the same time do these models show that the sky is almost the limit in modelling in school physics. Some teachers find the texts in this knowledge domain a bit too short; we suspect that they are wondering how to explain to their students the method of scaling to dimensionless variables. For the rest, teachers find that the guide provides them with a good collection of models for school physics.

In conclusion, it is fair to say that the guide on models and modelling is well-accepted by physics teacher and helps them get a more informed view on the subject and possibilities to implement a modelling learning path for their students.

5. References

- [1] Committee Innovation High School Physics Education 2006 *Natuurkunde leeft* [Physics lives] (Amsterdam, Nederlandse Natuurkundige Vereniging)
www.leraar24.nl/app/uploads/Visiedocument_natuurkunde1-1.pdf
- [2] Committee Innovation High School Physics Education 2010 *Nieuwe Natuurkunde* [New Physics] (Amsterdam, Nederlandse Natuurkundige Vereniging)
http://downloads.slo.nl/Documenten/Eindadvies_20Natuurkunde.pdf

- [3] Paus J 2013 Handreiking schoolexamen natuurkunde havo/vwo [Guide on physics school examination havo/vwo] (Enschede: SLO) <http://handreikingschoolexamen.slo.nl/natuurkunde>
- [4] Ottevanger W, Folmer E. and Kuiper W 2016 Context-based science education in senior secondary schools in the Netherlands *Teachers Creating Context-Based Learning Environments in Science* (Advances in Learning Environments Research vol 9) ed R Taconis, P Brok and A Pilot (Rotterdam: Sense Publishers) chapter 12 pp 213-24
- [5] Ottevanger W, Heijnen, M and Folmer, E 2018. *Monitoring en evaluatie invoering beta-vernieuwing. Eindmeting docenten en leerlingen 2016-2017* [Monitoring and evaluation implementation science education innovation. Final measurement teachers and students] (Enschede: SLO)
- [6] de Putter-Smits L, Taconis R, Jochems W and Van Driel J 2013 An analysis of teaching competence in science teachers involved in the design of context-based curriculum materials *Int J Sci Educ* **34** 701-21
- [7] Folmer, E 2018. *Centrale examens als drager van betavakvernieuwing* [Nationwide exams as supports of science education innovation] (Enschede: SLO)
- [8] Savelsberg E (ed) 2008 *Modelleren en computermodellenb in de β -vakken: Advies aan de gezamenlijke β -vernieuwingscommissies* [Modelling and computer models in the sciences: advice to the joint curriculum innovation committees] (Utrecht: Freudenthal Institute) <https://dspace.library.uu.nl/handle/1874/32409>
- [9] Van Buuren O 2014 *Development of a modelling learning path* [Doctoral thesis, University of Amsterdam] (Amsterdam: CMA)
- [10] Kolb D 2015 *Experiential learning: Experience as the source of learning and development* 2nd ed (Upper Saddle River, NJ: Pearson Education)
- [11] Heck A, Kedzierska E and Ellermeijer T 2009 Design and implementation of an integrated computer learning environment for doing mathematics and science *J Comput Math Sci Teach* **28** 147-61
- [12] Lijnse P 2016 Models of/for teaching modeling *Modeling in Physics and Physics Education* (GIREP 2016 Proceedings) ed E van den Berg, T Ellermeijer and O Slooten (Amsterdam: University of Amsterdam) pp 22-33
- [13] Ormel B 2010 *Het natuurwetenschappelijk modelleren van dynamische systemen: Naar een didactiek voor het voortgezet onderwijs* [Scientific modelling of dynamical systems: towards a pedagogical theory for secondary education] [Doctoral thesis, Utrecht University] (Utrecht: CD- β Press)
- [14] Heck A 2012 *Perspectives on an integrated computer learning environment* [Doctoral thesis, University of Amsterdam] (Amsterdam: Can Uitgeverij)
- [15] Bransford D, Brown A and Cocking R (eds) 1999 *How people learn: brain, mind, experience and school – expanded ed* (Washington, DC: National Academic Press)
- [16] Donovan M and Bransford R (eds) 2005 *How students learn: history, mathematics and science in the classroom* (Washington, DC: The National Academies Press)
- [17] Schwarz C, Reiser B, Davis E et al 2009 Developing a learning progression for scientific modeling: making scientific modeling accessible and meaningful for learners *J. Res Sci Teach* **46** 632-54