Development of a modelling learning path

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Conclusions and discussion

8.1 Introduction

Main goal of this study

The main goal of this design study was to investigate how modelling can be implemented into the physics curriculum in an effective way. Therefore, we have started a design research project in which a learning path on system dynamics based graphical modelling has been developed for the first two years of physics education, integrated into the physics curriculum. With the term modelling the entire modelling process is addressed, a comprehensive process starting with the analysis of a realistic context situation and ending with evaluation of the model (Figure 8.1). Doing experiments and measurements contributes to this process. Therefore, modelling has systematically been combined with experimenting. For mastering this modelling process, many (sub) competencies are required. We have distinguished five categories of competencies for the modelling learning path. The modelling learning path as a whole can be viewed as consisting of five intertwined partial learning paths, one partial learning path for each of these categories. The partial learning paths focus on:
1. the computer environment (the modelling software);
2. graphs;
3. variables and formulas;
4. the elements of graphical models;
5. evaluation and the nature of models.
This learning path has been tested in school practice in several design and research cycles.

Figure 8.1: Schematic representation of the modelling process
Educational goals of the learning path and research questions

Broad educational goals of our modelling learning path are the general modelling competency corresponding to the modelling process depicted in Figure 8.1 and the learning of physics content by means of modelling. In Section 1.2, two research questions are posed related to the general modelling competency and two research questions related to the learning of physics content. The research questions related to the general modelling competency are:

RQ1: What are characteristics of an effective learning path on graphical modelling in lower secondary education?

RQ2: To what extent do students learn to model when they follow this learning path?

The research questions related to the learning of physics content are:

RQ3: To what extent can students understand the physics of the more realistic and more dynamical phenomena in the modelling learning path?

RQ4: How is the mathematics and physics content of the lower secondary physics curriculum affected by the modelling learning path?

These research questions are answered in the next section. In the last section, I reflect on the presented and future work: I reflect on choices made for the design, go into limitations of this study, make suggestions for further research and development, discuss implications for physics education in school practice, and reflect on my experiences as being both a teacher and a researcher.

8.2 Answers to the research questions

8.2.1 Research question 1 – characteristics of an effective learning path on graphical modelling in lower secondary education

Modelling is a complex and comprehensive process, requiring a multitude of connected competencies and sub competencies. As one of the students, working on an early version of a modelling activity of the module Sound, sighed: “One has to know so much for this.” These competencies are connected to each other and to other parts of the curriculum. An effective modelling learning path must deal with all competencies and connections. The cyclic research and development efforts underpin the following general characteristics of an effective learning path on graphical modelling in lower secondary education:

- each sub competency is regarded as a separate learning goal;
- the number of learning goals per learning activity is limited;
the learning path contains checks to verify whether vital competencies have been acquired by the students and such vital competencies are addressed repeatedly, because progress on the longitudinal learning path is blocked if students have not mastered them;

different types of learning goals are approached in different ways; for instance, for equipment skills, a cookbook approach suffices, but conceptual learning goals require a conceptual point of view and reflection must be stimulated;

modelling is tuned to the curriculum and vice versa. Many of the modelling competencies are necessary for other parts of the curriculum too. Examples are graph comprehension, formula comprehension, and competencies with respect to practical work; some of these competencies must be addressed before they can be applied for modelling, but the development of some of the competencies can also be supported by modelling. Examples are the development of student conceptions of variable and formula (Chapter 6) and the development of graph comprehension by means of modelling in combination with video measurements and animation (Chapter 2);

modelling is integrated into the curriculum. Two reasons are:
- students must apply modelling to a multitude of different subjects for developing a sufficiently extended base of orientation, in order to enhance transfer;
- an integrated modelling approach offers a different, more comprehensive view on physics and physics concepts. When modelling is only offered on a project base, the remainder of the curriculum will not benefit from modelling. Furthermore, specific modelling competencies are easily forgotten if they are not regularly repeated by the students;

modelling is combined with experimenting and doing measurements. Doing experiments and measurements is an effective element of a modelling learning path, because it helps getting students acquainted with the realistic context situations and with the use of physics concepts in these contexts, and it supports model evaluation. In addition, the combination of modelling and experimenting offers students a more comprehensive view on the nature of science.

the mathematical meaning of the graphical diagrams is addressed explicitly, because this meaning is not clear for novice modellers. This mathematical meaning cannot be circumvented by using some metaphor, because such metaphors are not easily grasped by novice modellers and because graphical modelling must be connected to physics education, in which formulas are commonly used;

cross-disciplinary elements are used. The use of models taken from other disciplines facilitates the development of a sufficiently extended base of orientation. It also shows the value for other disciplines of concepts learned in physics class.

In the presented modelling learning path, these general characteristics have been accommodated (1) by the use of modelling learning sequences on the
scale of a module and (2) in the design of the five partial learning paths that are embedded longitudinally in the curriculum and intertwined in modules.

The general modelling learning sequence is based on the identified analogy between modelling and practical work; it is described in Section 5.5.1. The five partial learning paths are described in Section 5.6; the partial paths on variables and formulas and on the elements of graphical models are treated in more detail in Chapters 6 and 7, respectively.

Arguments for the effectiveness of these general characteristics can be found throughout this dissertation, especially in Chapter 5 in which the design of the most recent version of the learning path and its evaluation in school practice are described. The effectiveness of the characteristics became clear in cases in which they had not yet been adequately implemented. In such cases, this turned out to be a cause for students’ blockages. Such blockages subsequently were taken away by carefully making use of the given characteristics.

8.2.2 Research question 2 — the extent to which students have learned to model

In this section, students’ progress is considered from the perspective of both the relevant partial learning paths and the modelling process.

**Progress from the perspective of the relevant partial learning paths**

**Graph comprehension.** Results of tests at the end of the modules in the learning path and classroom observations indicate that the attention for graph comprehension as offered in the learning path is sufficient for enabling students’ progress on the learning path. Therefore, in this study more attention is paid to other partial paths. Nevertheless, the level of graph comprehension that has been reached is high for lower secondary education. In our learning path, lower secondary students have learned to understand and use tangent lines and have developed a notion of the meaning of the area under the graphs of flow variables (velocity, and energy flows). Students turned out to have difficulty with certain advanced aspects of graph comprehension (such as the ability to infer from diagrams of the in- and outflow what happens to the stock as described in Section 5.6.2, and the addition of mathematical functions in the module *Sound*). These difficulties did not impede progress on the modelling learning path in lower secondary education, but they make clear that graph comprehension still needs to be addressed in upper secondary education.

**Variables and formulas.** In Chapter 6 is shown that much progress has been made within the partial learning path on variables and formulas. Blockages have been overcome regarding students’ conceptions of variable and formula. These conceptions have now reached a level that is required for modelling and that is higher than generally found in lower secondary education and, probably, also higher than usually found in the first year of upper second-
ary education. Students have developed basic understanding of difference equations at this early age too. The progress in the students' ability to construct simple direct relations and simple difference equations is promising when compared to studies of modelling in upper secondary education, but students' abilities to construct formulas need further development.

**Graphical models.** For this partial learning path, I refer to Chapter 7. Students have successfully worked with several graphical models, have shown to understand the process of numerical integration, and have developed an adequate understanding of structures of direct relations as shown in the graphical diagrams by connectors. The students who have followed the learning path can construct a graphical model to a given mathematical model consisting of one difference equation and one direct relation without assistance. They are also able to construct more complicated graphical models based on known formulas if some guidance is offered. There are still difficulties with students' understanding of the relation between difference equations and stock-flow diagrams concerning the roles of the time step and the initial value, and with respect to the interpretation of the relation between stocks and outflows. Apparently, it takes time to get a more complete view on graphical models.

**Evaluation and nature of models.** Students have got acquainted with several types of models: molecular models, mathematical models, and graphical models. They have learned that models (and experiments) have benefits and limitations and can be criticised. They have developed an understanding of science as a combination of experimenting and modelling, and students have shown in discussions that they can understand the idea of falsification. It is very plausible that all students have understood the importance of modelling for physics, as one of our students spontaneously exclaimed: “physics appears to be all about modelling!” These results must be considered preliminary, though. In the explorative phases and in the design of the learning path, attention has been paid to this partial learning path, but in the final phases of this study, we have focussed on more problematic parts of the modelling learning path.

**Progress from the perspective of the modelling process**

In our learning path, all students have become acquainted with all stages and steps in the modelling process depicted in Figure 8.1. The steps have not only been presented to them, but for sufficiently simple cases students have also mastered the steps separately. In this respect, our goal has been reached. This does not yet mean that students already can go through a complete modelling process without assistance. For probing students' ability to go through a complete modelling process from scratch, at the end of the second year of the learning path, a pilot project (part of the *Dune* project described in Chapter 5) has been performed with students who had completed our modelling learning path. After doing measurements for getting acquainted with the situation to be
modelled, without any guidance these students managed to construct a simple model that fitted the experimental data, but their model was not correct. These well-motivated students stated that much perseverance was required for this task, but they also felt excited when, after some assistance, they had managed to construct a better model. Modelling competencies clearly need further development, but the students seem to be prepared for the next steps in the modelling learning path planned for the upper level.

8.2.3 Research question 3 – students’ understanding of more realistic and more dynamical phenomena

Several ways and levels of understanding of a phenomenon can be distinguished. The more realistic and more dynamical phenomena have been studied both by means of experiments and by means of models. Here, three ways of understanding are considered:
1. understanding from an experimental, empirical point of view;
2. understanding of the model separately;
3. understanding the connections between the empirical phenomenon and the model.

Examples of student difficulties with making connections between models and phenomena have been found that can stay concealed in traditional physics education but that are addressed by the explicit use of more realistic and more dynamical phenomena. In the module Velocity in the first year of the learning path for example, students investigated realistic movements, such as the start of a real runner. Students certainly understood the movement of the runner from an experimental, empirical point of view. They understood the movement qualitatively. They could also analyse this movement more quantitatively, by determination of positions and of velocities in the position, time-graph, and they were able to recognize the diminishing acceleration in the changing slope of this graph. But students initially had some difficulty making the connection between a realistic movement and a model in which the velocity had the same average, but constant value: some students stated that they did not completely grasp the concept of average velocity. Students in previous years seldom discussed this concept, but in these years average velocity was never explicitly compared with realistic varying velocity. By comparison of these movements in a modelling activity, this difficulty was successfully addressed.

In general, students have few problems accepting many realistic phenomena. They have no difficulty understanding that the acceleration of a realistic car is not constant. But some have difficulty with simplifications, as follows from statements such as: “but cars do not accelerate at constant

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1. These students actually refused the guiding instructional materials; they felt challenged.
acceleration, do they? They can doubt such simplifications. As a consequence, it may be more difficult for students to understand the simplified situations used in traditional education than to study more complicated phenomena.

Reached levels of understanding differ among students, but in general, students applying for physics in upper secondary education performed well on test questions about more complicated phenomena. There are just a few exceptions. The most clear example of a case in which the intended level of understanding of a phenomenon has not been reached is a question in the final test of the module Sound about the phenomenon of beats of sound caused by two tuning forks. In this question, a diagram was shown containing graphs of two sine functions representing sounds with slightly different frequencies. Students were asked at which moments these two sine functions would interfere constructively and when destructively. Most students answered this question incorrectly. Although this may be disappointing, it was not problematic. It did not impede further learning, because subsequent learning activities do not depend on this understanding. Furthermore, most students did grasp several other aspects of beats, especially on a more empirical level. They have developed a first, qualitative understanding of interference and most students have been able to determine the beat frequency from a graph. Thirdly, although the intended level of understanding of beats from the viewpoint of physics has not been reached, from the viewpoint of musicians, the most important learning goal has been reached: most students have learned to apply their knowledge of beats for tuning musical instruments (at least theoretically).

An important conclusion for the design of a learning path is that a lack of understanding of the most difficult aspects of complicated phenomena must not impede progress. This is the case if subsequent steps in the learning path do not depend on students’ understanding of such difficult aspects. If this condition is fulfilled, such more difficult subjects are useful for differentiation, because they can be challenging for some of the students.

Regarding the more dynamical character of the phenomena, indications have been found for the following students’ difficulty. In their answers to questions in the final test of the module Force and Movement in which one instant from a fall with air resistance was considered, some of the students took values of variables corresponding to other instants into consideration. Apparently, these students insufficiently realised that in such a movement the values of variables are changing in the course of time, and that distinctions must be made with respect to the instant that is considered. This problem can also be observed with upper secondary students who have followed more traditional education. Apparently, more attention must be paid to the varying nature of

2 Later, indications have been found that this is caused by an unexpected difficulty with graph comprehension. It requires more research.
quantities. Modelling more dynamical phenomena may turn out to be an effective way to do so.

8.2.4 Research question 4 – affection of the mathematics and physics content of the curriculum by the modelling learning path

First of all, modelling takes time at cost of other subjects from physics, because specific concepts must be learned that are not present in a traditional curriculum. Yet, the contribution of modelling to the development of traditional competencies, such as graph comprehension, offers some compensation. The modelling learning path has affected the mathematics and physics content of the lower secondary curriculum in other sense too, namely by:

1. the introduction of modelling learning sequences;
2. the introduction of more complicated subjects from physics;
3. a change of the mathematical content, necessary for modelling; and
4. a shift in the view on physics.

They are discussed below.

**Introduction of modelling learning sequences.** Because of the modelling learning sequences, situations are studied more intensively, because at least two approaches are used for studying situations: an approach in which experiments are used, and an approach in which models are used.

**Introduction of more complicated subjects from physics.** As explained in Section 1.2.2, modelling in education is expected to help students develop a better view on physics and on the relation between physics and reality. The main argument is that modelling makes it possible to study more realistic phenomena and problems at an early stage of physics education. Such more complicated phenomena are usually not studied in a traditional lower secondary curriculum, or only at a qualitative, superficial level. In Section 8.2.3, it is argued that it is possible to study such phenomena using a modelling approach. An effect of adding such phenomena to the curriculum is that some domains of physics have been studied much more extensively, because several related new concepts must also be introduced. An example is the force for air resistance, which traditionally is studied only superficially, even in upper secondary education. Getting acquainted with such new concepts takes time, although this effect can be reduced by choosing concepts that also can be used for development of traditional skills. An example is the use of quadratic functions. In traditional education, the formula \( s = \frac{1}{2} gt^2 \) is used for this learning goal, but the formula \( F_{\text{air}} = k \cdot v^2 \) can serve this purpose as well.

Finally, in a modelling learning path, more complicated phenomena not only can be studied, but, for three reasons, they are even necessary. Firstly, by using only the idealized phenomena that are usually studied in traditional curricula, the connection between reality and physics is not clarified for
students. Secondly, for students, there would not be a need for modelling. Thirdly, some more difficult phenomena are necessary for learning to deal with specific aspects of the models. The type of phenomenon that must be incorporated in the curriculum is related to the essential feature of system dynamics based graphical modelling, namely, that it is used for numerical integration of difference equations (represented by stock-flow diagrams). Therefore, in the curriculum a number of situations must be incorporated that can be modelled by means of one-dimensional difference equations. Quantities are required that can take the roles of flows and of stocks; parameters for regulating the flows are also necessary. Resistors and capacitors in electrical circuits are examples of such parameters. Such a circuit would therefore be a useful subject for modelling, but capacitors are not included in the current Dutch physics curriculum. The vacuum pump is another example of such a system. Such systems demand a deeper study of the fields of physics to which they belong.

**Change of the mathematical content.** One of the claims in favour of modelling is that students can study phenomena that would be otherwise beyond their mathematical capabilities, because the computer deals with the mathematical difficulties. This is true as far as it concerns the technical mathematical skill of solving equations. But, as is shown in Chapter 6, modelling demands a higher level of conceptual mathematical understanding. Examples are the required conceptions of difference equations and of variable and formula. Other examples are the principle of addition of functions in the module *Sound* and principles of numerical integration in several modules. In Chapter 6 is described how the curriculum has been adapted for developing the required notions of variable and formula. In addition, mathematical abilities with respect to graph comprehension have become more important in the curriculum. Students must be able to interpret graphs in terms of changing slopes and in terms of areas under curves. At this stage of students’ development, this cannot yet be compensated by paying less attention to calculation skills. Students still need such skills, at least for the development of proper conceptions of variable and formula, and for evaluation of model results.

**Shift in the view on physics.** The modelling learning path has led to a shift in the view on physics in the lower secondary curriculum. There is more attention for time behaviour of systems and less for calculations leading to isolated outcomes. Also, there is more attention for fundamental equations and for construction of models of more general and more realistic situations, and less for working with only a few mathematical solutions for a limited number of special cases. A more scientific view on physics is used, in which attention is given to critical reflection, especially with respect to assumptions and limitations of models and experiments. This attention is stimulated by the combination of modelling and experimenting, because this makes limitations and the value of assumptions become clear in a natural way. Generally speaking, the relation between reality and physics has become more important.
Further discussion. The aforementioned adaptations require time at cost of attention paid to subjects from other fields of physics. In the presented curriculum, more attention has been given to the molecular theory of matter, to sound, to dynamics, to mathematical competencies, and to specific modelling competencies, at cost of attention for parts of heat, optics, and electricity. This raises the question what is the more effective and useful for lower secondary students: development of competencies that are useful in other disciplines as well and of deeper insight into a smaller number of fields from physics, or development of a more superficial insight into more fields of physics. I think that students benefit more from the first option. A deeper insight into fewer fields may facilitate the development of insights in other fields of physics in future. A second interesting question is whether modelling should be confined to the physics curriculum. Integration of modelling into the entire lower secondary curriculum offers more opportunities to create sufficiently extended bases of orientation and can stimulate a more interdisciplinary view. In practice, such an integration will not easily be established, because of the differences in interests and nature of the disciplines, and of the limited abilities and affections of the involved teachers.

8.3 Reflection on the presented and on future work

8.3.1 Reflection on choices made for the design of the learning path.

For the design of the modelling learning path, a number of choices has been made. The choice to integrate modelling into the curriculum is discussed in Section 8.2.1, and the choice to combine modelling and experimenting is discussed in Sections 8.2.1 and 8.2.3. In the current section, choices to start with modelling in lower secondary education and to use system dynamics based graphical modelling as a modelling approach are discussed.

Starting in lower secondary education. Presumed advantages and disadvantages of starting with modelling from the initial phases of secondary physics education are listed in Section 1.1.3. The first two of these presumed advantages are definitely true: it gives students more time to get acquainted with modelling, and more students get acquainted with modelling. As is shown in this dissertation, the third and fourth presumed advantages are also true: more realistic problems have been studied, and modelling offers a new way of teaching and learning physics. The last presumed advantage, traditional approaches of doing physics may not get in the way of modelling, could not yet be established, because we have not done a comparative study. With respect to the presumed disadvantages, the modelling learning path must be developed carefully, otherwise modelling can indeed be too abstract for young students. Also, there is a risk that situations to be modelled are too complex when too
many concepts are involved. To avoid this risk, modelling learning sequences have been developed, and the development of modelling competencies has been distributed over the curriculum. Finally, modelling does take time, but, as discussed in Section 8.2.4, this time is well spent.

A question is, whether it would be more effective to start with modelling at a higher age. The advantage would be that students may have already developed some important competencies and have got acquainted with more concepts from physics. This may be true, but a condition is that the preceding curriculum prepares for modelling. Among the competencies that must be developed in a preceding curriculum are competencies regarding graph comprehension, a notion of difference equations, and proper notions of variable and formula; closed mathematical solutions for special cases are preferably avoided. By starting at a higher age, students would have less time to develop other required competencies. In addition, as is argued in Section 8.2.1, modelling can support the development of competencies that are important in traditional education as well. Finally, modelling competencies may be more useful for all lower secondary students than some of the subjects from physics that are studied usually.

System dynamics based graphical modelling. As is shown in Chapter 7, we have not yet managed to solve all difficulties concerning students’ understanding of the graphical diagrams. This raises the question whether we should not use another approach to modelling, for instance text based modelling. In order to get a decisive answer on this question, a modelling learning path based on such another approach should be developed and learning effects should be investigated. Here, I only give some arguments to take into consideration. First, the diagrams used in graphical models do provide students with an overview of the system that is modelled, and its ability to act as a mind map (or, using a more adequate term, a relation map) can be useful for students for comprehension of the situation that is modelled (if used carefully). Another advantage of graphical modelling is that more sophisticated algorithms can be used without a need to change the graphical diagrams and without the necessity for students to understand the details of such algorithms. Finally, it can be expected that in future the identified difficulties with respect to students’ understanding of the elements of graphical models can be solved. In Sections 7.14.4, recommendations are made how this can be done. Firstly, the relation between difference equations and stock-flow diagrams may be clarified by showing the corresponding difference equation in the dialog window for the stock. Also, an option can be implemented into the modelling software to permanently show all equations to the relevant icons. Another way to clarify the meaning of the diagrams is to show how the diagram can be translated into a text-based model at an early stage of the modelling learning path. In Coach 6, an option is available for this translation. Finally, the icons can be adapted to show their meaning more clearly.
8.3.2 Limitations of this study

For this study, a holistic and longitudinal approach has been chosen, in which the learning of the multitude of modelling competencies and their connections to the entire curriculum have been studied on a detailed level, whenever necessary. I felt that in many research projects on graphical modelling the difficulties of upper secondary students with respect to basic competencies may have been underestimated, at least in the initial phases of these research projects (see, for instance, Löhner, 2005; Westra, 2008; Ormel, 2010). For detecting and exploring such difficulties, and for exploring the opportunities for learning offered by a modelling approach, it was an advantage that we were in control over the content of the entire curriculum and that we could monitor students’ progress with respect to all competencies over two years in detail. By making several adaptations to the curriculum and by tuning the modelling learning path and the curriculum carefully, modelling competencies have been developed in a more effective way. Students’ difficulties could in some cases clearly be related to omissions in earlier parts of the learning path. As we have shown, students’ understanding of concepts from physics and mathematics has been developed effectively by means of modelling and more realistic phenomena have been studied. The longitudinal approach enabled regular repetition of vital competencies, in a way that is not possible in a modelling course on project base.

As a consequence of this holistic and longitudinal approach, this research project has become very extended. We have collected much more data than could be analysed in sufficient detail within the limitations of this study. We have chosen to investigate in detail only specific aspects that turned out to be the most critical for the modelling learning path. This selection has mainly been based on preliminary results. These preliminary results have mainly followed from classroom observations, from discussions with students, and from preliminary analysis of all test results: as a teacher, I always went over all answers of my own students to the final tests of all modules, and so did my colleagues. The most critical aspects turned out to be comprehension of variable and formula, and the understanding of the elements of graphical modelling. Research on these aspects is described in Chapters 6 and 7, respectively. The validity of the findings described in these chapters is high; they are based on careful analysis of multiple data sources. Other important findings concern the design principles described in Chapter 5. These findings are generally based on the type of preliminary results mentioned in this section and on arguments from research literature. The most important example is the general modelling learning sequence. The idea that such sequences are necessary is the result of many findings throughout the entire research project and distributed over the entire modelling learning path; it is theoretically supported by the analogy between modelling and practical work. Finally, some aspects have not yet been investigated thoroughly, because other aspects demanded higher priority. Although data on such less deeply investigated aspects need
more detailed analysis, preliminary results about these aspects are occasionally presented in this dissertation, because of their importance for a coherent view on the modelling learning path. The nature of these results must yet be considered as explorative.

With respect to generalizability, almost all research has been carried out at only one secondary school, the Montessori Lyceum of the Hague (HML). The instructional materials have not been designed especially for Montessori education, but in some cases specific aspects of Montessori education have influenced research outcomes. In this dissertation, such cases and this influence have been indicated, but we have reasons to believe that research outcomes would not have been much different if the research would have been carried out at other secondary schools. One reason are the preliminary results of the try-out of the first module of the learning path at two other schools. In addition, research outcomes with respect to students’ notions of variable and formula are supported by results of a questionnaire given to students of 23 classes at seven secondary schools. However, in general, for establishing the generalizability of our findings, in future the learning path must be tested at more secondary schools.

Finally, it is noted that I have not only been the designer and the main researcher in this study, but I was also one of the teachers. Although I am aware of the risk of subjectivity and although care has been taken to meet criteria of objectivity by regularly asking fellow researchers, other teachers, and students for their opinions and for criticism, in order to increase the validity of our findings, these findings need to be tested in future by means of independent research.

8.3.3 Recommendations and suggestions for future research and development

In this study, several difficulties are still left unsolved and some competencies need to be investigated more closely:

• The relation between stock-flow diagrams and difference equations need to be clarified for students; attention given in our learning path to this relation turned out to be insufficient. In Section 8.3.1, suggestions for improvements are summarized.

• The students’ abilities to construct formulas must be further developed. Suggestions are made in Chapter 6. Paradoxically, these construction abilities may be less important for physics education, where many formulas are already available to the students, than in biology education, whereas physics students can be expected to possess better mathematical skills than biology students.

• Student competencies with respect to interpretation and evaluation need to be investigated.
• Abilities with respect to the general modelling process need to be developed further. Students must yet learn to analyse and reduce a realistic context situation into a manageable problem from scratch.
• Effects on the learning of students of physics content by means of modelling need more attention.

These difficulties and competencies can be addressed in a follow-up to this study. As expected, the modelling learning path has not been finished yet. The broad final learning goal of mastering the general modelling competency has not yet been reached, and the possibility of learning physics content by means of modelling must be investigated more closely. For achieving these goals, the learning path must be extended into upper secondary education.

8.3.4 Implications for physics education

Adaptation of the curriculum. For an effective implementation of modelling into the physics curriculum, the goals and the content of this curriculum need reconsideration. The content must be adequate for the development of modelling competencies, as is described in Section 8.5. We have shown that modelling offers possibilities for the introduction of new domain content, that can have more value for students but that until now has been left out of the physics curriculum because it surpasses students’ mathematical capabilities. Therefore, we need to reconsider which physics content is really worthwhile for students.

Implementation into the curriculum: getting teachers acquainted. A difficulty for introduction of modelling into the curriculum is that many teachers are not familiar with computer modelling in general and graphical modelling in particular. Several teachers that have been involved in our design and research project initially had difficulties with graphical modelling that are similar to reported student difficulties. The time it takes for teachers to get acquainted with modelling must not be underestimated, especially because secondary teachers in the Netherlands have little spare time. Teachers must get acquainted to a modelling approach at three different levels. Firstly, teachers must learn to model and all schools must be equipped for modelling. Secondly, teachers must get acquainted with modelling pedagogy and need support for organizing modelling in classroom. Only as a last step, the shift in view on physics can be made: from teachers who have not yet mastered the first steps, it cannot be expected that they all have full overview of the possible consequences of a modelling approach for physics education. Therefore, it seems wise to integrate modelling into the curriculum gradually.

Adaptation of the exams. Exams must be developed in which modelling competencies can be tested; as we have shown in this research project, many modelling competencies can be tested without a computer, using only pen and
paper. Also the rating of students’ answers on exams needs reconsideration.

Students can answer a question by making use of models with different degrees of approximation. These approximations should be rated differently, but differences must be gradual. For example, students can be asked to determine from a velocity-time graph the average velocity over some interval of time for a realistic accelerating object. From a modelling point of view, taking the average value of the initial and final velocity must not be rated as right or wrong, but as a first order approximation. A better approximation makes use of the area under the curve. Such a better approximation must be rated higher.

8.3.5 Being both teacher and researcher

This study has been enabled by a scholarship of the stichting VO Haaglanden, the foundation for secondary education in the region of the Hague, in which HML, the school at which I am one of the physics teachers, is one of ten participating schools. For five years I have been given the opportunity to do educational research in school practice. This has had consequences for myself as a teacher, designer, and researcher, and for the school at which I work and where most of the research has been carried out, especially for my near colleagues. In this final section, I discuss the relation between educational research and educational practice from a personal point of view, and try to sketch the implications that this project has had for myself and for the school.

During this study, I have worked with several teachers, and I have come to appreciate the great practical pedagogical content knowledge (PCK) of experienced teachers. But from a scientific point of view, there can be problems with this PCK: much of it is based on practical experience, and in case it is scientifically well based, often the teacher has forgotten how and where this knowledge comes from. This knowledge is very valuable and often correct, but not always: teachers can become trapped in their own viewpoints and educational habits. For me, being both a teacher and a researcher, it sometimes was hard to determine whether my own knowledge was scientifically well based, although this research project would hardly have been possible without my PCK. On the other hand, for this research project I occasionally read scientific papers that seemed to be theoretically well founded, but I doubted the interpretations of the data by the researcher: as a teacher, I felt that this researcher had missed many things that had happened in classroom; there were clear indications that this researcher had little experience with the behaviour of real students in school practice. There certainly exists a gap between research and school practice. From this point of view, being both teacher and researcher is definitely advantageous.

Being part of two worlds, it was amusing to notice that incidentally teachers considered my work as merely theoretical (and therefore not applicable to their own situation, that was certainly different), whereas I also incidentally have met scientists who questioned this project because they expected
it to be merely practical and of limited theoretical value: they seemed not to expect me to find anything that was not already known (to scientists). Fortunately, I also have met teachers and researchers who showed enthusiasm for this combination of teaching and research.

An interesting question is whether this study has contributed to bridging this gap. Personally, I think that I have become a better teacher. I have had more time and opportunity to think over the design of my lessons, to reflect on my own teaching, and on learning effects for the students. I had the opportunity to learn by observing fellow-teachers. It was inspiring to work at the former AMSTEL Institute, meeting educators from all over the country and all over the world. I have learned from reading scientific articles about education. I have become a better designer too: as it is shown in this dissertation, the quality of the instructional materials has gradually been improved during this design and research project and more effective design principles have evolved. I leave it to the reader of this dissertation to judge whether my achievements as a researcher have been worthwhile, but if they are, one reason is their ecological validity.

The project enabled cooperation between the physics teachers (and the teacher assistant) at HML; generally in school practice, physics teachers do not have much time for efficient cooperation. Most of my colleagues have cooperated constructively, as critical friends. I am grateful for their cooperation: for them, there was no extra time available for participating in this project and it has not always been easy. The fact that modelling has become a more important part of the curriculum has been an important argument for participating. My colleagues certainly have learned from this project. They had the opportunity to try out new materials and insights, and because of my presence there was a connection with the scientific educational community. In this way, collaboration between researchers and practitioners can be an effective way for bridging the gap between research and school practice. Because parts of this project have been carried out at other schools, there is a similar effect for teachers of those schools. But transfer of knowledge would have been better if my colleagues would have had more time. Therefore, I would plead for more projects like this one, but in such projects, attention should also be given to the facilitation of the participating teachers.

References

