Development of a modelling learning path
van Buuren, O.P.M.

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Introduction

1.1 Background of this study

In Section 1.1.1, the background and main reasons for starting this study on modelling in education are given. In Section 1.1.2, our approach to modelling, in which graphical modelling is systematically combined with experimenting, is expounded. In Section 1.1.3, our choices to integrate modelling into the curriculum and to start a modelling learning path from the initial phases of physics education are explained.

1.1.1 Computer modelling in the physics curriculum

The importance of computer modelling for education was already recognised in the early eighties of the twentieth century (see, for instance, Ogborn & Wong, 1984). Löhner (2005) distinguishes three categories of claims in favour of computer modelling. The first category concerns learning about modelling. Students should be introduced to modelling because it is a professional activity of scientists and engineers. As citizens, they must learn about the possibilities and limitations of computer models, as future professionals they should learn how to construct and use models. The second category concerns an assumed improvement of scientific reasoning skills. Modelling is supposed to help students develop higher level scientific skills, like predicting, hypothesizing, hypotheses testing, analytical reasoning, and explaining. The third category is about learning domain content. For this study, the most relevant aspect is that students are less confined by their mathematical capabilities when the computer deals with the mathematical difficulties. This enables study of more realistic subjects and solving of problems that are too complex otherwise.

Notwithstanding the claimed importance of modelling, the integration of modelling in physics curricula has been rather poor for a long time, even in the Netherlands (Lijnse, 2008). Although modelling formally became part of the Dutch physics secondary curriculum in 1991, until recently it was confined to only the highest levels (age 17-18, pre-university level) and it occurred at only a modest scale in school practice. New curricula for the upper levels of Dutch secondary physics education, with more emphasis on modelling, started in 2013 (Commissie Vernieuwing Natuurkundedonderwijs havo/vwo, 2010). System dynamics based graphical modelling is considered an appropriate candidate for
an approach to computational modelling for these new curricula (Savelsbergh et al., 2008). Henceforth, it will be referred to as graphical modelling.

Despite the claimed importance of modelling, and although positive effects of graphical modelling are reported (cf., Doerr, 1996; Van Borkulo, 2009), in practice graphical modelling in education does not go without problems. Schecker (2005) reports on a mechanics modelling project not having an overall positive effect on students’ understanding of mechanics. According to Van Borkulo (2009), graphical modelling seems to be disadvantageous for the learning of simple conceptual domain knowledge. Cronin, Gonzalez, and Sterman (2009) report on severe difficulties that students have when interpreting model output. Many authors report on difficulties that students have when designing or adapting graphical models (Tinker, 1993; Bliss, 1994; Kurtz dos Santos & Ogborn, 1994; Sins, Savelsbergh, & Van Joolingen, 2005; Lane, 2008; Westra, 2008; Van Borkulo, 2009; Ormel, 2010).

Thus, a complete, well-designed and well-tested learning path on modelling for the physics curriculum is needed. It must be found out how modelling can be implemented into the physics curriculum in an effective way. Therefore, in 2008 I started, as a member of a research and development team of the AMSTEL Institute at the University of Amsterdam, a design research project on graphical modelling. For reasons described below, a modelling learning path has been designed for lower secondary physics education. This learning path has been tested in school practice through several design and research cycles. Several student difficulties with modelling tasks have been identified and taken into account. In future, this learning path is to be expanded into upper secondary education. Outcomes of this work are presented in this dissertation.

1.1.2 Modelling

In this section, modelling is described as a comprehensive process, starting with the analysis of a realistic situation and involving the validation of the model. The role of experimenting in this process is explained and graphical modelling is introduced.

The modelling process. Modelling is much more than just constructing and running (computer) models. It involves a comprehensive process. The framework for this so-called ‘modelling process’ that has been adopted for this study is described schematically in Figure 1.1. This framework reflects the general modelling competency described in the proposal for renewal of the Dutch physics curricula (Commissie Vernieuwing Natuurkundeonderwijs havo/vwo, 2006):

“Students must be able to analyse a situation in a realistic context and reduce it to a manageable problem, translate this into a model,
generate outcomes, interpret these outcomes, and test and evaluate the model."^{1}

In our framework, a ‘real problem’ has been inserted between the ‘realistic context situation’ and the ‘manageable problem’. With this ‘real problem’ is meant a realistic physics problem that still contains too many aspects to be ‘manageable’ at once.

This modelling process is often called the modelling cycle, because for testing, validation, and evaluation of the model it is necessary to revisit the realistic context situation, while for extension of the model the real problem is revisited. Similar frameworks for the modelling cycle have been used by Blum and Leiß (2005), Galbraith and Stillman (2006), and Maaß (2006) in the context of mathematics education.

The emphasis in the learning path described in this dissertation is on computational modelling with computers, but for a clear view on models and the modelling nature of physics, students also get acquainted with other models, such as (analytically solvable) mathematical models and molecular models, each with its own benefits and limitations. The modelling process describes the creation and use of such other models too.

In mathematics and science education, sometimes the term ‘modelling’ is used in a narrow sense, limited to the translation of the manageable problem into a model and the generation of outcomes. We consider this approach to modelling as incomplete, because it lacks the necessary links to reality. Our aim is complete modelling, in which the complete modelling process is involved, not only as a learning goal for students, but also as an educational approach to the learning of physics. Complete modelling offers a better view on the methods and nature of science. By means of complete modelling, students may get acquainted with much more aspects that are important for understanding and doing mathematics and science and they may get a better view on the coherence of these aspects.

**Modelling and experimenting.** In our approach, modelling is systematically combined with experimenting and doing measurements. Three reasons for

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1 This formulation is almost equal to the formulation in the final version of the new curriculum for pre-university physics education which has been approved by the Dutch government (College voor Examens vwo, havo, vmbo, 2012).
this choice directly follow from the modelling process. Firstly, by doing experiments, students get acquainted with phenomena and concepts that appear in the realistic context situation to be modelled. They become aware of what the model is about. This is important, because a lack of knowledge of the realistic context situations is an important cause for blockages of students during the modelling of such situations (Galbraith & Stillman, 2006; Maaß, 2006). Secondly, experimenting is expected to help students familiarize with the involved concepts, analyse the realistic context situation, create the real problem, and reduce it to a manageable problem. Thirdly, measurements can provide data to be used for evaluation of models. Comparison of outcomes from experiments with model output is an important and natural way of evaluation of models. Only when students have developed sufficient understanding of relevant concepts from physics and mathematics, other approaches can be used for evaluation too, such as comparison of model output with theoretically predicted outcomes for limiting cases. Of course, experimenting is not only important for modelling. It also has a value of its own, as part of doing physics.

**Graphical modelling.** For the learning path, the system dynamics based graphical approach developed by Forrester (1961, 1968) has been chosen as approach to computational modelling. Several computer environments exist in which this approach has been implemented. Examples are STELLA (Steed, 1992) and Coach 6 (Heck, Kedzierska, & Ellermeijer, 2009). In a graphical model, variables and relationships between variables are represented by means of a system of icons in a diagram (see Figure 1.2). From a mathematical perspective, graphical modelling mainly concerns the numerical solving of (systems of) one-dimensional difference (or differential) equations. Besides difference equations, direct relations appear in these models.²

![Figure 1.2: Example of a graphical model (for the effect of solar radiation on the temperature of the surface of the earth).](image)

² By a direct relation, we mean a mathematical relationship between symbolized quantities in which at least one quantity can be isolated and written as a closed form expression of the other quantities.
The main goal of the diagrams used in graphical modelling is communication of the causal assumptions and the main features of the model in a way that is also clear to people with less mathematical education. Several authors have suggested that the visual representations in graphical models of model quantities and their causal relationships provide students with an opportunity to express their own conceptual understanding of physical phenomena (e.g., Niedderer, Schecker, & Bethge, 1991). Research has shown that students using an environment for graphical modelling can reason qualitatively and intuitively about systems (cf., Doerr, 1996) and graphical modelling seems to be effective for learning to reason with complex structures (Van Borkulo, 2009). But, as mentioned earlier, graphical modelling does not go without problems, especially not if it concerns the adaptation and construction of models by students. Doerr (1996), Lane (2008), and Savelsbergh (2008) conclude that more research is needed for successful integration of graphical modelling in education.

Modelling competencies. For mastering the modelling process, many (sub) competencies are required (see, for example, Galbraith and Stillman (2006), and Maaß (2006) for modelling competencies in mathematics education). Gellert, Jablonka, and Keitel (2001), and Galbraith and Stillman (2006) report that basic competencies, such as the mathematical knowledge of the students and their knowledge of the technological tools at their disposal, have a direct impact on how these students tackle a problem. Therefore, such basic competencies must be acquired at an early phase of the learning path by the students. We distinguish five categories of competencies for our learning path. These are competencies regarding the use and understanding of:
1. the computer environment (the modelling software);
2. graphs, as means for interpreting outcomes from models and experiments;
3. variables and formulas, for the purpose of analysing the realistic context situation and reducing it to a manageable problem;
4. the elements of graphical models and their relation to variables and formulas;
5. evaluation processes regarding models, model output, and experiments.

This requires knowledge of limitations of models, modelling, and experiments, and some understanding of the nature of models.

Each of the required competencies is a sub goal of our modelling learning path. A partial learning path has been developed for each of these sub goals.

Choice of the computer learning environment. We chose Coach 6 as computer learning environment for the learning path because it is a multi-purpose educational environment that also can be used for other activities in the curriculum, such as experimenting, doing measurements with sensors, and doing video measurements (Heck et al., 2009; Heck, 2012), it is available at most Dutch secondary schools, and in Coach animations can be coupled to graphical models. In addition, it was possible for us to adapt Coach for our research purposes. An example of such an adaptation is the possibility to couple
graphs, sketched by students, with graphical models that subsequently drive animations.

1.1.3 A learning path integrated in the curriculum, starting from the initial phase of physics education.

In the Netherlands, physics education starts in the second year of secondary education, at age 13-14 years. We decided to start the learning path on graphical modelling from this moment and to integrate it into the physics curriculum. Reasons for these choices are discussed in the following subsections.

Starting from the initial phase of physics education. We consider it advantageous to start with modelling at an early age, for the following reasons:

• It gives students more time to get acquainted with modelling.
• More students will get acquainted with modelling. Near the end of lower secondary education, each student in the Netherlands must choose a set of courses for upper secondary education. Physics needs not to be part of this set. If we start with modelling in upper secondary education, many students will not get acquainted with modelling.
• Realistic problems can be studied at an early stage of education.
• Modelling offers new ways of teaching and learning physics that might be more effective than traditional instruction.
• Traditional approaches of doing physics may not get in the way of modelling. An example is the focus in traditional education on closed mathematical solutions for special cases, such as the formula \( s = \frac{1}{2}gt^2 \) for free fall, instead of on fundamental equations. Another example is the tendency in traditional education to concentrate on problems that lead to answers consisting of one value instead of focusing on entire physical processes.

For research purposes, starting a modelling learning path from the initial phase of physics education offers an advantage too. It enables study of the coherence between modelling and the competencies required for modelling before this coherence is obscured by the conceptions and competencies that are usually developed by students in traditional lower secondary physics education. By starting with novice students, we can better distinguish what is really necessary for modelling.

There also may be disadvantages to starting at an early age. Modelling and modelling tools may be too abstract for young students, and situations that are to be modelled may be too complex when too many concepts are involved. If this is the case, not only the success rate will be low, but an early negative experience may hamper the learning process at a higher age too. Further, modelling takes time, that cannot be used for the development of traditional skills, such as performing calculations with formulas. In the design of the
learning path, care has been taken to avoid these disadvantages as much as possible.

**Integration into the curriculum.** Most research on modelling has focused on project-based modelling lessons, not on modelling as an integrated part of a curriculum. But, as Schecker (1998) points out, modelling requires a new way of thinking which takes considerable time to learn. Therefore modelling should not be limited to only one theme or subject, but should be integrated into the curriculum.

A proper integration of modelling into the physics curriculum requires adaptation of the rest of the curriculum to modelling, and vice versa. Otherwise modelling takes an unnecessary amount of extra time and misconceptions may arise (Schecker, 2005; Cronin et al., 2009). Consequently, for field testing we needed a concrete implemented physics curriculum that could be adapted as a whole. The self-designed physics curriculum of the Montessori Lyceum of the Hague (HML) fulfilled this purpose. It enabled us to develop instructional materials that address many competencies required for modelling, such as graph comprehension, correct use of variables and formulas, and an adequate notion of model, in coherence with modelling. Also, the physics content could be adapted. This enabled an integrated, rather holistic approach to modelling.

### 1.2 Educational goals and research questions

Broad educational goals of our modelling learning path are the general modelling competency corresponding to the modelling process depicted in Figure 1.1 and the learning of physics content by means of modelling. These general goals consist of sub goals. Below, the educational goals are discussed and connected to research questions (labelled RQ).

#### 1.2.1 Research questions related to the general modelling competency

Acquisition of the general modelling competency corresponding to the modelling process of Figure 1.1 is a final goal of our modelling learning path, but it needs to be reached only near the end of secondary education. Main questions for this study are what can be an effective design for such a learning path, and what can already be achieved with lower secondary students.

*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?
1.2.2 Research questions related to the learning of physics content

Woolnough (2000) notes that students tend to consider reality, physics, and mathematics as three distinct worlds, failing to make substantial links between these worlds. A reason for this may be related to the way subject matter is usually treated. In traditional physics education, students only study situations that are within the limits of their mathematical capabilities. Many of these situations are not realistic but simplified, for example, about cars moving with constant acceleration. Other situations are only limiting cases of situations that occur in daily life, such as free fall instead of fall with air resistance. Students may not be aware that they are actually studying models. Also, they may not be aware of the assumptions that have been made for these models, or to what extent these assumptions are valid. Finally, sometimes situations are studied for one specific moment, whereas many quantities in these situations actually are in a process of change. A concrete example of such a situation is shown in Figure 1.3. It is taken from a rather old textbook, but an almost identical example can be found in a recent textbook (Ottink, 2013). For these reasons, it may be difficult for students to connect school physics to reality or, vice versa, to connect their own knowledge of the real world to physics. Getting students acquainted with more or less realistic situations by means of practical work is important for students, but it is not sufficient. In school practice, students usually fail to connect their observations in practical work to scientific concepts (Abrahams & Millar, 2008).

Figure 1.3: A ship is pulled by two tugboats. Positions, velocities, and forces are changing permanently in such a situation, but in the physics textbook only the forces at the moment of the picture are considered. Students may get confused if they are not aware of this.
Modelling can be expected to help to solve these educational problems, not only because modelling enables students to study more realistic subjects, but also because students may become more aware of assumptions and simplifications in case they are involved in the modelling process. As a result, students may be less troubled by differences between their own conceptions and the conceptions as they understand them from physics at school. An important question for the design of the modelling learning path is which realistic domain content can be used for these purposes. Realistic situations can be expected to have a more general nature, involving more variables, and involving more dynamic phenomena, in which variables vary in a more complex way. Without computer models such situations are too complex. The question is, to what extent lower secondary students can understand the physics of such more complex situations. Another question for research is how the physics and mathematics content of the curriculum is affected by the modelling learning path. Which new concepts are required? What are characteristics of the new content, apart from being more realistic?

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?

Note that the second category of claims in favour of modelling, concerning improvement of scientific reasoning skills, has not been incorporated in these research questions. This category is left out, because we consider it premature to study such high level skills with lower secondary students who are still occupied with mastering basic concepts and modelling skills.

1.3 Methodology

In the subsequent sections, the type of research is described, the theoretical framework is discussed, the design process is outlined, the setting of the research is given, and the research instruments and the methods of data acquisition are presented.

1.3.1 Design research

Our research approach can be classified as design research (or developmental research): instructional materials are designed, tested in classroom, and redesigned in an evolutionary process consisting of several cycles (Van den Akker, Gravemeijer, McKenney, & Nieveen, 2006). This process of development and research can be referred to as “theory-guided bricolage”: a process that is
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guided by theory and that also produces theory (Gravemeijer, 1994). At the start, the theory is merely a global framework. During the process the theory grows and is made more specific, based on empirical input. The goal of the process is to develop a local theory on the subjects involved. This local theory is justified based on interconnected theoretical and empirical components. The cyclic process of designing and testing can occur on scales of different sizes within the same design and research project. According to Gravemeijer (1994), the cyclic process is more efficient when the cycle is shorter.

1.3.2 Theoretical framework

Nature of this study. This study can be classified as holistic, longitudinal, explorative, and formative. It can be classified as holistic, because competencies required for the modelling process, the realistic contexts to be modelled, and the relevant concepts of physics are so much interwoven that students’ modelling development cannot be understood without taking all these aspects into account. It can be classified as longitudinal, because the development of students’ understanding over a period of two years is investigated. It is explorative, because this holistic approach of graphical modelling with such young students is new, as far as we know. As a consequence, a researcher needs to keep his mind open. It is formative, because research activities have been performed during the entire development process, for both explorative and evaluative purposes, aiming at optimisation of the learning path as well as at optimisation of the design principles (cf., Van den Akker, 1999).

Because of the holistic and explorative nature, we have not used just one complete, specific theoretical framework for the design of all aspects of the learning path. Each competency and each concept from physics requires its own domain specific framework. These specific frameworks have been developed during this study, partly based on literature study, but also via experimental educational research in classroom. The only distinguished general theoretical element that was used from the beginning was the formation of bases of orientation for new concepts.

The formation of bases of orientation. As Gal’perin points out, for learning how to use and understand a new concept, students need a complete, or at least sufficiently extended base of orientation (‘orienting base’) for that concept and its use (cf., Haenen, 2001). A complete base of orientation consists of the complete set of elements that a learner needs for the execution of an action involving the concept. An insufficiently extended base of orientation is an important cause for alternative conceptions. For establishing sufficiently extended bases of orientation, we must provide students with enough sufficiently different examples. This enables them to learn distinguish between non-essential and essential properties. This eventually leads to a high degree of generalization of students’ actions and prevents the learner from attending to non-essential
For each concept in the learning path, the associated competencies are developed in small steps, aiming for the formation of the required bases of orientation. In the initial phases of this study, it was not clear yet which elements are essential for sufficiently extended bases of orientation for graphical modelling. Establishing these elements is one of the goals of this study.

1.3.3 Design process

The designer of the learning path. Parts of the design of the learning path, especially in the initial phases, have largely been based on the pedagogical content knowledge of author of this dissertation who is also an experienced instructional designer and physics teacher. He also has developed the curriculum into which the learning path must be integrated. Because of the holistic and longitudinal nature of this study, it is important that both the designer and the researcher have a good overview of secondary physics education as a whole and much practical insight in students’ conceptions, competencies, and difficulties. This requires much expertise. From this perspective, it can be an advantage for the researcher and designer to be one and the same person. In order for the design to meet criteria of objectivity, fellow researchers, other teachers, and students were regularly asked for criticism.

The design and research process. It would be premature to design an entire learning path on modelling, extending over two years of education, in one piece. Instead, the learning path initially has been developed piecewise, starting with only a few modules early in the learning path. The learning path has gradually expanded. The first cohort of students involved in this study, the cohort 2008-2010, followed an incomplete version of the learning path. The second cohort (2009-2011) worked with a more extended version. The final version has been tested with a third cohort of students, the cohort 2010-2012. Thus, since 2009, permanently two cohorts have been working simultaneously on different parts of the learning path.

In the design and research process, in general, three partly overlapping phases can be distinguished. The first phase had an orienting character. It consisted of literature study, pilot experiments (with small groups of upper secondary students), and exploratory experiments with the first modules, early on the learning path. In this phase, the focus was on exploring what is feasible, on establishing students’ difficulties and opportunities for learning, and on detecting and solving practical problems regarding the instructional materials. The second phase consisted of the designing and testing of the first elaborated version of the learning path. This design was based on experiences from the first phase. The research in this phase focussed on identifying and understanding students’ conceptions and led to more specific design principles and associated research questions. In the third phase, the last version of the
learning path was designed and field tested. In this phase, research focused on specific research questions and on educational outcomes.

These phases not only can be distinguished for the learning path as a whole, but also for the partial paths on specific competencies. For some of the partial learning paths, the third phase has not yet been reached. An example is the partial path on evaluation of models and understanding of the nature of models.

**Cycles of design and research.** Cycles of design and research took place on scales of different sizes.

Very short cycles took place within one lesson; regularly, a teaching-learning discussion with one student or with a small group of students on a subject made the teacher change his teaching approach to this subject in a discussion with a next student, or made the researcher pose specific questions to other students. Such discussions and answers to such questions were audio taped and registered in observation notes. Based on these registered observations, the design has been adapted.

A next scale of cycles has the size of a lesson. Between lessons in different classes, often small adaptations could be made to the instructional materials, to the approach of the teacher, and to the focus of the researcher.

A larger cycle is on the scale of a module. On this scale, adaptations to the design are not only based on registered observations, but also on outcomes of analysis of handed-in student materials, especially student results of computer tasks, screen recordings of students working on computer tasks, and students' answers to questions of the final test of each module. Part of the test questions have been designed especially for research purposes. Incidentally, questionnaires or tests that only served research purposes have been used as well.

The largest cycles are on the scale of the entire learning path. Based on experiences and analysis of data from one or several different modules, adaptations to other modules, and sometimes even to the design of the entire curriculum have been made. An extreme example is the inclusion of a complete new module in the beginning of the third year of the learning path.

In general, the shorter cycles prevailed in the earlier phases of design and research, whereas the larger cycles dominated the later phases. During the design research study, both the number of types of sources of data and the amount of data have increased. Qualitative data have been used in all phases, but in the course of this study the contribution of quantitative data gradually became more important.

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3 Fellow teachers were informed by e-mail and in private communication.
1.3.4 Setting

**School setting.** In practice, it is not easy to find a school that is willing to test an extended experimental curriculum, but the Montessori Lyceum of the Hague (HML), where the researcher is one of the physics teachers, offered the unique opportunity to test all instructional materials in all second and third year classes with more than three cohorts of students.

Usually at HML, there are six or seven classes in the second year, and five or six classes in the third year of lower secondary education. Each class consists of up to 30 students. Most students attend senior general secondary education or pre-university education (in Dutch: HAVO or VWO, respectively). In the Netherlands approximately 40% of all students of this age participate in these two levels of secondary education (Ministerie van Onderwijs, 2012). At HML, students effectively got physics lessons for 80 minutes per week during each year. In addition to these regular lessons, students had the opportunity to attend additional lessons if necessary.

Eight HML teachers have been involved in this project. One of them is the researcher. All classes have followed the learning path, although data from some classes could not be used for research purposes. Main reasons were incompleteness of data and cancelled classes.

Although the HML is a normal Dutch secondary school in many respects, there are some principles of Montessori education that need attention, because of their relevance for this study.

**Montessori education.** The learning path is developed for secondary physics education in general, but most of it is tested on a school for secondary Montessori education. Within the limits posed by the Dutch government to secondary education, this school strives to work according to the principles of the Italian educator Maria Montessori (see, for instance, Montessori, 1912; Lockhorst, Wubbels, & Wester, 2001). This puts additional demands to the design and has some consequences for research.

An important demand is that self-study of the instructional materials is possible. There are two reasons for this. Firstly, according to Montessori principles, students must be raised to become free, independent citizens. This means that they must learn to be in control of their own learning and must not become too dependent on their teachers. Secondly, to a certain extent students must get the opportunity to work at their own pace. This offers students the possibility to master the subject matter, which prevents them from getting stuck at later stages of their learning paths. Consequently, instructions in the instructional materials must be as complete as possible and goals of the materials must be clear to students. Also, students must be able to correct their own work and therefore must be provided with materials to do so, or the instructional materials must be self-correcting. Finally, students are used to cooperate in small groups, so they can learn from each other. Other Montessori requirements are that education must be connected to the real world and that
linkages between disciplines must be shown to the students. These require-
ments were met in a natural way on our modelling learning path.

Advantages of Montessori education for research. An advantage of Montessori education for research is that students are used to discuss freely with their teachers, and much time is available for discussions between small groups of students and the teacher. This holds even more for the additional lessons. These discussions often have the character of short in-depth interviews, in which students are invited to explain how they arrived at their questions and conceptions, and to make suggestions for improvement of the instructional materials. The fact that students are allowed to redo a test if they failed the first time also contributes to this, because usually students discuss their test with the teacher before redoing it. All discussions are valuable sources of information for research. Differences in students’ paces sometimes enabled us to adapt instructional materials after testing them with only one or a few groups of students. In this way, short design and research cycles could be carried out.

Disadvantages of Montessori education for research purposes. Apart from the problem of generalizability, which is considered below, there are some other disadvantages of Montessori education. To a certain extent, students are allowed to postpone the final test of a module. This makes it more difficult to collect all tests. Also, students are allowed to redo a test if they failed the first time; tests have a more formative character than in traditional education. Sometimes, we had to choose which attempt to use for data analysis. For practical reasons and to avoid a bias towards good results, in general we have chosen the first attempt. Other consequences are that there must be several different versions of the final test of a module, and that results of final tests are not always final results of learning: sometimes, students finished their work with the instructional materials only after the test. A last consequence of students working at their own pace is that not all students finish the curriculum completely. This may lead to a bias towards hard working students at the end of each year. As a consequence, the statistical reliability of the data decreases towards the end of the year.

Generalizability. Because the main part of the research has been carried out at only one school with some particular characteristics, generalizability of research results is an issue. In order to enhance the generalizability, a number of measures has been taken. Firstly, the first module of the learning path has been tested by six teachers at two other Dutch secondary schools as well. Secondly, important results have been incidentally checked by means of a questionnaire at several other Dutch schools. Thirdly, whenever possible, results are compared to findings in literature. Fourthly, the internal consistency of the findings and the arguments supporting them can make it plausible that results can be generalized.
1.3.5 Research instruments

Sources of data. As mentioned in Section 1.3.3, a variety of data sources have been used. They are listed in Table 1.1 and are discussed briefly below.

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<th>Table 1.1</th>
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<tr>
<td><strong>Overview of research data and instruments for registration</strong></td>
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<table>
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<tr>
<th>Data</th>
<th>Instruments</th>
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<tbody>
<tr>
<td>Registrations of students working with the instructional materials in classroom</td>
<td>• audio recordings, • computer screen recordings, • observation notes.</td>
</tr>
<tr>
<td>Short in depth interviews with students</td>
<td>• audio recordings, • field notes, • e-mails.</td>
</tr>
<tr>
<td>Interviews with and comments of teachers</td>
<td>• audio recordings, • interview notes.</td>
</tr>
<tr>
<td>Handed-in student materials</td>
<td>• results from computer tasks, • written materials (incidentally).</td>
</tr>
<tr>
<td>Final tests of modules</td>
<td>• written final tests made by students, • audio recordings and notes of discussions afterwards.</td>
</tr>
<tr>
<td>Questionnaire, specific test (incidentally)</td>
<td>• written answers of students.</td>
</tr>
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In general, two approaches have been used for registration of the way students work with the instructional materials in classroom. Goals of the first approach are to detect unforeseen difficulties and opportunities, and to get a broader overview of the students’ conceptions and competencies. The observer walks around in classroom, focussing on students’ questions and remarks. Discussions with students are tape recorded and field notes are written down. Both the researcher and the teacher usually carried an audio recorder for this purpose. In summary, participatory observation took place. The second approach aims at getting more insight in specific, task-related students’ competencies and conceptions. Here, the focus is on complete learning processes. For this purpose, more extended audio recordings, screen recordings, and/or observations have been made of small groups of students working on specific tasks (usually computer tasks). Generally, these students cooperated, which enabled audio recording.

Regularly, discussions with students resulted in interviews. Other interviews were initiated by the researcher, having specific questions for research. In order to check respondent validity, students were asked afterwards whether
the researcher’s interpretation of the content of the interview was correct, if necessary.

In addition to the observations of the researcher, use has also been made of observations of the other teachers, the teacher assistant (for practical work) and, incidentally, of upper secondary students participating in the research project as fellow researchers. For this purpose, short interviews with teachers have been made.

In order to get an overview of competencies acquired by all students, students’ materials have been collected, especially students’ results of computer tasks. Because students got help from each other and from the teacher, in general, the value of such materials is limited. Yet, they can be used to identify students’ difficulties and to study to what extent students work meticulously. This holds even more for collected written materials, because students are allowed to use materials for checking their paper work.

The aforementioned data sources have a qualitative and often explorative character. In addition to these qualitative data sources, more quantitative data sources have been used also. The most important of these sources are the final tests of the modules. Specific questions in these tests were designed especially for answering research questions. For students, these questions appeared as regular parts of a normal final test. Incidentally use has been made of other quantitative sources, such as questionnaires and tests that only serve research purposes.

**Analysis of data.** In the initial phases of this study, analysis of data has occurred in order to establish problems, to improve educational materials, and to generate research questions. For this purpose, mostly qualitative data have been used. In the later phases, analysis of the more quantitative sources, mostly handed-in final tests, has been combined with retrospective analysis of other data sources. A selection has been made, based on the expected relevance for the subject to be investigated. This expectation usually has been based on the written observation notes.

Our holistic long-term approach enabled us to combine sources stemming from different moments of the learning path in our analysis. Answers to similar test questions in different modules were compared. It made it possible to focus on relationships and processes. Our holistic approach in school practice enabled us to cope with the complexity and subtleties of situations in real life education. Because the learning path is tested in school practice, using classroom observations and regular final tests as main sources of data, the ecological validity can be expected to be high.
1.4 Overview of the dissertation

Chapters 2, 3, and 4 describe the explorative part of this study. The final design of the modelling learning path is presented in Chapter 5. In Chapters 6 and 7, two of the partial learning paths are discussed and empirical results are presented. In Chapter 8, results of the study are summarized and reflected upon.

Chapter 2.

Three pilot studies have been performed with upper level students with a focus on the problems they encountered during a variety of modelling tasks. In a fourth pilot, lower level students (age: 13-14) have studied different representations of movement by comparing video with model-driven animation. This combination appears to stimulate learning, as it acts as a mechanism for self-correction.

Chapter 3.

A first, incomplete version of the modelling learning path has been tested in classroom. After giving an overview of this path, we focus on the part in which students have to build a complete model themselves for the first time. Student’s understanding of the graphical relation structure, of the distinction between difference equations and direct relations, and of the relation between difference equations and stock-flow diagrams is investigated. It appears that students mix up different aspects of dependences of variables. We have identified a number of misconceptions which students showed when discriminating between direct relations and difference equations. Finally, we have detected a number of problems students may have when constructing graphical models.

Chapter 4.

By means of a classroom experiment and a questionnaire, the understanding by lower level secondary school students of the calculation process and the use of formulas (direct relations) in a graphical computer model has been investigated. Students could understand the calculation process on a numerical level, but had problems with the creation and use of formulas. Students did not yet have a clear notion of formula. The term formula must be defined more clearly. Suggestions are given for improvement of the learning sequence leading to the use of direct relations in a computer model.

Chapter 5.

This chapter describes one of the main results of this study, namely, the design of the modelling learning path, integrated in the first two years of the Dutch lower secondary physics curriculum, and tested in school practice. Several
student difficulties have been identified and dealt with. At the end of lower secondary education, a majority of students was able to construct and use a simple graphical model based on known equations, without assistance.

Chapter 6.

In this chapter, the focus is on students’ conceptions of formula and variable, on their ability to connect graphical stock-flow diagrams to difference equations, and on their ability to construct simple formulas independently. The design of a learning path on formulas and variables as part of the modelling learning path and the research findings of field testing of this part of the learning path with lower secondary students are presented. The main conclusions are the following. The introduction of operational definitions of formula and variable and the use of formulas in educational software contribute to a clearer notion of formula and variable, as is required for modelling. Part of the students have problems translating graphical stock-flow diagrams into difference equations and vice versa. The fact that the integration time step from the equations is not visible in graphical stock-flow diagrams seems to be related to these problems. Results with respect to students’ abilities to construct formulas are promising.

Chapter 7.

In this chapter, the focus is on students’ understanding of the relation structures shown in the diagrams of graphical system dynamics based models. Only part of the students understand these structures correctly. Reality-based interpretation of the diagrams can conceal an incorrect understanding of diagram structures. As a result, students seem not to have problems interpreting the diagrams until they are asked to construct a graphical model. Misconceptions have been identified that are the consequence of the fact that the equations are not clearly communicated by the diagrams or because the icons used in the diagrams can be misleading for novice modellers. Suggestions are made for improvements.

Chapter 8.

In this chapter, we reflect on this study, answer research questions, and give recommendations for modelling in school practice and for future research on modelling.

References


