Development of a modelling learning path

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Towards a learning path on computer modelling*

Abstract

Although the use in teaching of computer modelling and of measuring with video and sensors is promising, results are not always as good as expected. More insight is needed into the way students can develop an understanding of mathematical and physical concepts and methods by means of modelling. Our aim is to develop a learning path on which students not only can learn how to model, but also develop such an understanding by combination of modelling and experimenting. Three pilot studies were done 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 (13-14 years) studied different representations of movement by comparing video with model-driven animation. This combination appeared to stimulate learning, as it acted as a mechanism for self-correction.

2.1 Introduction

Modelling is a key activity in scientific enquiry and engineering. Therefore it might be expected that in education explicit attention should be paid to it. According to Hestenes (1987, 1992), it should be the central theme of physics instruction. But until recently, explicit attention to models and modelling in educational practice has been rare, at least in the Netherlands (Lijnse, 2008). During the last decades of the twentieth century however, educators in science and mathematics started to realise that modelling on computers could be useful in education. Educational researchers began to make suggestions in

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favour of computer modelling as a learning activity. Within these suggestions, three categories can be distinguished (Löhner, 2005). The first category concerns learning about modelling. Students should be introduced to modelling because it is a professional activity of scientists and engineers. They have to learn about the possibilities and limitations of computer models and should learn how to make and use models themselves. The second category concerns an expected improvement of scientific reasoning skills. Modelling might encourage higher level skills, like predicting, developing hypotheses, testing hypotheses, analytical reasoning and explaining. The third category concerns learning domain content by modelling. Because the computer can deal with a great part of the mathematical difficulties, students should no longer be confined by their mathematical capabilities. This should make it possible to study more realistic subjects and to solve problems that would be too complex otherwise.

Almost without saying, our focus has shifted from modelling in general towards the type of computer modelling mostly used in physics courses. This type of modelling is often referred to as ‘dynamical modelling’. From a mathematical point of view, this mainly concerns the numerical solving of differential equations, especially initial value problems and boundary value problems. In this study, the focus will be on this type of modelling.

The importance of computer modelling has now been recognized in many countries, but the integration of modelling in the curricula is still rather poor. Until recently, Dutch secondary students were not involved in modelling activities until they reached the highest level of secondary education (age 17-18, pre-university level). Even at this level, computer modelling only occurs at a modest scale in the curriculum. At this moment, the situation is changing. New curricula are under development for the upper levels of Dutch secondary education for all sciences. Modelling is meant to be part of all of these new curricula (Savelsbergh et al., 2008).

In spite of all promising suggestions, educational results of modelling activities do not always meet expectations. Students do not automatically connect models, experiments and underlying theories and concepts with each other (Doerr, 1996; Hodson, 1993; Schecker, 2005). Claims on positive learning effects are proven only occasionally (Hwang, 2006; Löhner, 2005). But as the importance of modelling in education is clear, the question is not whether, but how we should use modelling in teaching. We need to develop a learning path into modelling. Therefore we need more insight into the way students can develop modelling skills and an understanding of mathematical and physical concepts and methods by means of modelling (Hwang, 2008; Lijnse, 2008).

A related question is at what age such a learning path may start. So far most research has been focussed on the highest levels of secondary education and on modelling lessons on a project base, not on modelling as an integrated part of a curriculum. As far as we know, little research has been done on the learning of students with modelling activities extending over a longer interval of
time. Nevertheless, it might be advantageous to start with modelling at an earlier age, based on the following assumptions:

1. It gives students more time to get acquainted with modelling.
2. More realistic problems can be tackled at an early stage of education.
3. Modelling makes it possible to study traditional subjects in a different, possibly more effective way.
4. More students will be acquainted with modelling.
5. Modelling might turn out to be a more natural activity for students if they are introduced to it in the initial stages of their science education, when they are not yet used to the standard approaches of doing physics.

Possible disadvantages of starting with modelling at an early age may be, that

1. modelling and modelling tools may be to abstract for young students. In that case not only the success rate will be low, but an early negative experience may also hamper the modelling learning process at a higher age.
2. students do not have the required skills and knowledge yet.
3. modelling may have a negative influence on the development of traditional skills such as calculating with formulas. Not only does modelling take time which cannot be used for traditional exercises, students even might become ‘spoiled’, because they might not see the relevance of doing traditional calculations any longer.
4. the situations that are to be modelled may be too complex for young students when too many concepts are involved
5. with computer models, an additional representation of physics will be added to the curriculum. This may take extra time and can be an extra complication.

Research by Mulder, Slooten, Uylings, and Wieberdink (2008) has indicated that it is possible to involve students in quantitative modelling at the age of 14-15 years. Schwarz and White (2005) did some research with seventh grade children (age 12-13 years), but their software was domain specific and limited, as children had to express their ideas qualitatively by answering multiple choice questions. Their answers were translated into a quantitative, hidden model, used for simulation. Lawrence (2004) describes a strategy for modelling using VnR-software, based on his experiences with 11-14 years-old children, but his approach is semi-quantitative. We want to examine if starting a learning path into quantitative modelling in the Netherlands is possible in the year in which students get their first lessons in physics. At most Dutch secondary schools, this is the second year (age 13-14 years).

### 2.2 Theoretical framework: the modelling process

The question for us is which skills and knowledge are required for modelling. To answer this question we will examine the modelling process more closely. The requirements proposed by the commissions for renewal of the Dutch science
curricula form a general description of the modelling skills a science student must possess after finishing secondary school (see, for example, Commissie Vernieuwing Natuurkundeonderwijs havo/vwo, 2006). The proposal offers a framework that can be useful for describing the modelling process:

"The student 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."

This has been represented schematically in Figure 2.1. In this figure the modelling process is represented as a sequence of six 'states' and six 'transitions' between states.

**Figure 2.1: Modelling process**

Similar descriptions can be found elsewhere, especially in research on mathematical modelling (Blum & Leiß, 2005; Galbraith & Stillman, 2006; Maaß, 2006). The process is often called the modelling cycle, as for the evaluation of the process it is necessary to revisit the realistic context. If the outcome does not prove to be appropriate, particular steps or even the entire modelling process need to be revised.

In practice, the process is far from linear and not unidirectional (Galbraith & Stillman, 2006; Haines & Crouch, 2009). This is not surprising. As we will see below, during most transitions knowledge of subsequent transitions and stages is required, and vice versa. The advantages of the description are that it can serve as a map on which to put the required skills and knowledge, and that it gives direction to the process, not only for the researchers, but also for students (Maaß, 2006).

Sometimes, the term 'modelling' is used in a narrow sense, limited to the translation of the problem into a model and the generation of outcomes. We consider this approach to modelling as 'incomplete', as it lacks the necessary links to reality. Our aim is 'complete' modelling, in which the whole modelling process is involved.

We shall examine the stages and transitions of the process more closely below.

### 2.2.1 The realistic context situation

Without sufficient knowledge of the realistic context situation, neither analysis and reduction nor interpretation, testing and evaluation will be possible.
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Students’ understanding of this situation can be a major hurdle (Galbraith & Stillman, 2006; Hwang, 2008; Maaß, 2006).

Therefore, this situation must first be studied. Doing experiments can be an appropriate way to get a better understanding of the situation and to collect data on which analysis, reduction, interpretation and evaluation can be based.

2.2.2 Analysis and reduction

Some basic knowledge of the domain content is required or must be learned at the beginning of a modelling task, because the situation must be analysed in terms of its possible applicable theories and because variables, and relations between them, must be determined. Part of the analysis can be an estimation of magnitudes of variables on which a proper reduction can be based. Estimations and predictions can provide a base for evaluation during the whole process.

In order to reduce the situation to a “manageable” problem, the modeler must recognize that problem as manageable. This requires some experience and sufficient skills concerning the subsequent steps of the modelling process. This is congruent with findings of Galbraith & Stillman (2006) and Gellert, Jablonka, & Keitel (2001). They found that the mathematical knowledge of the students and the knowledge of the capabilities of the technological tools at their disposal have a direct impact on how these students tackle a problem.

For more advanced students, part of the reduction can be the splitting up of the problem in partial problems, which can be solved subsequently (Lijnse, 2008).

2.2.3 Translating the problem into a computer model

For the translation of the problem into a computer model, students must be able to manipulate the relations between variables, in order to adapt them for the model. They must understand some principles of numerical modelling, e.g. iteration processes. They must know how to use their tools and how to build models. It is recommended that they learn to recognize standard patterns in order to use these patterns as building blocks (Lawrence, 2008; Lijnse, 2008). In case of graphical modelling tools based on the stock and flow approach developed by Forrester in the early 1960s, such as Stella or PowerSim, some understanding of this approach is required. The software we have used, Coach 6, offers a mode based on this approach (Heck, Kedzierska, & Ellermeijer, 2009).

2.2.4 Interpreting, testing and evaluation

Without interpretation, the model cannot be tested or evaluated. The output of a model usually consists of tables and graphs. As graphs provide the best
overview, we consider the ability to read and interpret them as one of the most important skills.

In Figure 2.1, evaluation is positioned at the end of the process. However, in practice competent modellers constantly evaluate intermediate result during all stages of the process. The inability to do so can form a blockage for students (Galbraith & Stillman, 2006).

When evaluating a model, a modeller must compare model outcomes with their counterparts not only in the realistic world, but also in the ‘manageable problem’. The values of key variables often will be somewhat different in these different stages, as a result of simplifications and the numerical method. There can be even more different values corresponding to each variable when the model is developed in multiple cycles with an increasing level of complexity. For an appropriate evaluation, students must be able to keep all approximations and corresponding values of variables apart.

2.2.5 Concluding

More can be said about skills and knowledge required for modelling. For example, for most skills, levels of increasing abstraction and difficulty can be distinguished. Much is yet to be uncovered. The description given above provides us with a first overview.

Summarizing, we conclude that basic skills and knowledge for modelling are: knowledge of the realistic situation, some content knowledge and the skills to use this knowledge, some knowledge of the modelling tool, and the ability of interpreting graphs.

2.3 Research questions

Our final goal is the development of a learning path into modelling. As mentioned above, students do not automatically connect reality, experiments, models and underlying theories and concepts with each other. Therefore, our first research question is:

*How can a combination of measuring and modelling help to bridge the gap between realistic contexts and the relevant mathematical and physical concepts and methods in school practice?*

The development of basic skills and knowledge is part of a learning path. Related research questions are:

*What is a good sequence of steps on a learning path on modelling?*
*Which conditions must be fulfilled for each step?*
*Which problems and which new opportunities for learning are encountered by students and teachers on a learning path on modelling?*
2.4 Four pilot projects

We did four pilot studies. Three of them involved upper grade students. These pilots will be summarized below. The fourth involved lower grade students. This pilot will be described in more detail in Section 2.5. As an educational tool we mainly used Coach 6. This integrated computer working environment is used at the majority of Dutch secondary schools. It integrates the facilities required for doing experiments with sensors, video analysis, modelling and model driven animation, thereby making it possible to combine these activities (Heck et al., 2009).

2.4.1 First pilot project

In this pilot we observed two upper grade students (age 16-17 years) with little experience on modelling, doing a multiple-cycle modelling research project (60 hours) on celestial mechanics. We wanted to investigate which blockages occurred. Blockages reported by the students were analysed and discussed. We encountered 4 kinds of potential blockages:

• Blockages caused by a lack of knowledge of the realistic situation. Students were not able to evaluate some of their results because they could not perceive if their results were realistic.
• Blockages caused by misconceptions about the realistic situation. In some cases students did not perceive that their outcomes were correct.
• Blockages caused by a lack of experience with debugging. Especially in cases where two or more bugs occurred simultaneously, debugging turned out to be very difficult.
• Blockages that had to do with the differences in perspective between traditional teaching and modelling. Models are mainly built on fundamental equations, such as the definitions of velocity and acceleration, and Newton’s second law. In traditional teaching, much emphasis is put on solutions of fundamental equations for special cases, such as \( h = \frac{1}{2}gt^2 \), which is only valid for free fall with zero initial velocity in a constant gravitational field. Another example is the supposed circularity of planetary orbits. The students tended to use these solutions as laws on which the model was to be built, instead of using the fundamental equations.

The first two of these kinds of blockages stress the importance of a careful introduction of the realistic situation. To the third, explicit attention must be paid on a learning path. The last blockage might be overcome by an early introduction of modelling, prior to or simultaneously with exact solutions for special cases.
2.4.2 Second pilot

In this pilot we involved a class of 16 upper grade students (16-18 years) in parts of the modelling process. Most of them had not been involved in modelling activities before. The lessons were part of an experimental course on weather and climate. The pilot concerned the first chapter, in which the pressure in the atmosphere was modelled in a few cycles with an increasing level of complexity. In the last cycle, the students had to change an existing computer model, after an introduction of the iteration process, in which a few iterations had to be calculated by hand. Partial research questions were:

1. Can these students understand the iteration process?
2. Can these students separate the effects on key parameters of the different approximations and assumptions connected to successive steps in the modelling process?

From classroom observation, analysis of their exercise-books, and a questionnaire among the students, it appeared that most students were able to understand the iteration process. However, from an analysis of their exercise-books and a test it appeared that most of them had great difficulty in separating the effects of the different approximations and assumptions. This may be considered as a cause for blockages during evaluation.

2.4.3 Third pilot

The third pilot was with the same group of students as the second, and the lessons were part of the same series of lessons. A given graphical model, for the temperature of the surface of a square meter of the earth during a day, was used as a tool for simulation. The graph for the surface temperature was to be matched to experimental data, provided in written material. Therefore some of the model parameters had to be adjusted. Model output consisted both of the graph of the surface temperature and graphs of two underlying quantities. Partial research questions were:

1. What do students learn about the underlying model from a simulation in which parameters must be adjusted?
2. How do students use the model and the underlying quantities in their reasoning?
3. How do students use the realistic context in their reasoning?

From a post-test it appeared that most students were able to reproduce the main structure of the model. They also succeeded in qualitatively describing the influence of a change of the key parameter on the target, the graph of the surface temperature. However, most of them failed in describing the influence
of this key parameter on underlying quantities, and in describing the effects of other parameters on the target. Apparently, they had not learned much more than the direct influence of the key parameter on the graphs they had to match, in spite of the fact that the entire model had been introduced to them in the preceding lessons.

From classroom observations, screen recordings and sound recordings, it appeared that during the task students did not use the underlying model for reasoning and did not pay attention to the graphs of underlying quantities.

It also appeared that few students used the realistic context in their reasoning. Even more, some students were seen adapting their view on the realistic context instead of questioning their model input after making some mistakes. Apparently, an orientation on the realistic situation by reading about it is too weak for these students.

2.5 Fourth pilot project: combining video analysis and model-driven animation in the second year of Dutch secondary education

2.5.1 Partial research questions

Research questions for this pilot study are:

- Is it possible to involve students of 13-14 years into complete modelling?
- Can a combination of video analysis and model-driven animation stimulate students to interpret and evaluate their models?
- Can this combination stimulate students to use or acquire new domain skills?
- What differences in behaviour are there between well skilled and poor skilled students?

2.5.2 Set up of the experiment

**Choice of a starting point for a learning path.** In accordance with Section 2, in order to make a start on a learning path on modelling, students must at least be able to interpret and evaluate graphs and they must know how to use formulas. At the school at which we planned this pilot project, these skills are usually taught in the middle of the year. During a first course on kinematics, graphs of distance versus time ($x,t$-graphs), graphs of velocity versus time ($v,t$-graphs) and the formula relating mean velocity to displacement and time are introduced. Therefore, this seems to be an adequate starting point.

**Research method.** As we wanted to integrate modelling into the curriculum, we developed a series of lessons on kinematics for this purpose. These
lessons were to be tested and are to be improved in subsequent cycles. This approach can be indicated as educational design research (Plomp & Nieveen, 2009; Van den Akker, Gravemeijer, McKenney, & Nieveen, 2006). We tested the materials in two different groups of 30 students each. After testing in the first group, it was possible to adapt part of the materials for the second group. Therefore we went through two research cycles.

**Design of the lessons.** The 5 lessons of 80 minutes each consisted of the following topics:
1. Reading & interpreting \(x,t\)-graphs
2. Formula for mean velocity
3. Video analysis: start of a runner
4. Reading & interpreting \(v,t\)-graphs
5. Combining video analysis & model-driven animation

In the first two lessons, basic skills were introduced. In the third lesson, the realistic context was introduced by means of a video which was to be analysed by the students. Also, in this lesson Coach was introduced. The fourth lesson was meant for basic skills (\(v,t\)-graphs). In the fifth lesson modelling was introduced. The design of the third and fifth lesson will be described in more detail below.

**Design of the third lesson: video analysis.** As a context we chose the start of a runner. We used an already existing video, not only for logistical reasons, but also because this made it possible to adapt the modelling activity and the video measurements to each other, as we shall see later.

In this lesson Coach had to be introduced. Whereas higher grade students usually do not have problems working with Coach for the first time, younger students can have some problems if too many new features have to be learned. Therefore, we only introduced the features we considered most important. These were: starting the measurement; measuring by clicking on the target in the video; scaling the video; scaling diagrams; scanning data in a graph; and saving results. We consider scaling important, because scaling confronts students with real magnitudes in the real situation. In addition, a wrong scale can make effects in graphs invisible. Coach offers the option to scale graphs automatically, but if data are not correct, automatic scaling can put students on a wrong track.

All instructions were on screen, and instructional pictures were added (see Figure 2.2). Because results of this approach were poor, as we shall see later, we replaced these instructions by a short (2 minutes) instructional video.

The measurements of the students resulted in an \(x,t\)-graph. The students had to study qualitatively the relation between the velocity of the runner and the slope of the graph. They also had to determine quantitatively the mean velocity of the runner over different intervals of time.
Design of the fifth lesson, combining video analysis & model-driven animation.

**Set-up of the lesson.**

In the last lesson, modelling was introduced. The start of the video runner was to be modelled in a simple way. The model should have the same starting place and the same mean velocity as the video runner. The students had to determine the right values for these parameters from the $x,t$-graph of the video runner, just as they had done in the lesson on video-analysis.

The targets of this lesson were: introduction of modelling, improvement of understanding of graphs, and clarification of the difference between the concepts of mean velocity and velocity as a function of time. Students often have difficulty with these concepts, as could be seen in tests in the years before this pilot. Even higher grade students often make mistakes with these concepts. One cause for this is the confusion of distance with position. Therefore, we did not use $x = 0$ as the starting place of the runners.

As we wanted to put emphasis on interpretation and evaluation, the model drove an animation which we wanted to run simultaneously with the video. Because of problems with timing, this was not possible. Instead, we used the data of the video as input for a second model, which drove a second animation. Now, we had two models which ran simultaneously. We told the students about this trick, but the second model itself was kept hidden. While
the models were running, $x,t$-graphs and $v,t$-graphs were drawn. In this way, the runs of both the video and the model were represented in three ways. A screenshot, made during the run, can be seen in Figure 2.3.

![Screenshot during the run.](image)

Figure 2.3: Screenshot during the run.

By means of questions and tasks the students were invited to compare video and model in each representation, and to compare different representations with each other. A fourth representation was offered by the formula, which the students had to use to determine the mean velocity of the video runner. This velocity had to be entered into the model. The run of the model provided them with feedback on the results of their calculations.

**Choice of the modelling mode.**

Coach offers three modes for constructing and viewing models: the graphical mode, the equations mode and the text mode. Only the graphical mode permitted us to drive an animation while keeping the second model hidden. A disadvantage of this mode at this stage might be that it would take considerable time and effort to explain the stock and flow approach to our students, especially because this approach is quite abstract in the case of kinematics. Because no numerical knowledge is needed to understand this simple model, forcing students to learn the numerical method would not stimulate them. Therefore, we decided not to explain the numerical method yet. Instead, we offered a ready-made model, in which the initial values had to be adapted. This model can be seen in the upper left corner of Figure 2.3. Although the model was used
as a simulation, in this case the difference between simulating and complete
modelling is rather small, because the students still had to use the basic relation
for the model in order to determine the mean velocity. An advantage of our
approach is that it provides the students with a first orientation on graphical
modelling. We used an instructional video of a few minutes in order to intro-
duce our students to the required features.

Extra activity.
Finally, an extra activity was added for the fastest students. In this activity,
students were asked to change the model. We let them use an if-then condition
for this purpose, as their mathematical skills were not suited for other ways of
changing the model. By means of an if-then condition the movement of the
runner can be split into two parts, each with a different velocity. The students
were asked to keep the distance between the two runners as small as possible.

2.5.3 Data acquisition
We did classroom observations during all lessons and analysed a number of
exercise books and some of the questions in the post test. During the fifth
lesson, six pairs of students were observed more closely. In addition, audio
recordings were made.

2.5.4 Results

Results of the third lesson, on video analysis. For organisational reasons
the lesson on video analysis in the first of the two groups was started earlier,
halfway the second lesson. This first group appeared to have great difficulties
using features of Coach. Much scaffolding was required and students didn’t
finish this activity in time. The main reason appeared to be poor reading. After
this lesson, we decided to make an instructional video in which the use of the
software was demonstrated. Attending this video took only two minutes. We
showed it at the start of the next lesson. This video solved most of our prob-
lems. Students who still had difficulties after seeing the video could easily watch
it again. Students became far more enthusiastic about the activity.

Most students were able to answer the qualitative questions about the
relation between the slope of the $x,t$-graph and the velocity of the runner. The
determination of mean velocities over different intervals of time proved to be
more difficult.

Results of the fifth lesson, combination of video-analysis and model-
driven animation. Most students were able to finish the greatest part of the
activity in time. After watching the instructional videos, students had few
problems using the modelling environment. They clearly favoured video
instructions above written ones. However, even with video instruction, we
observed that students who don’t like to read encountered more blockages and used more trial and error. On the other hand, some of these students discovered and used more features of Coach.

In the first group, not being able to use the formula appeared to be a major reason for blockages. Therefore, in the second group, the students were briefly reminded of the formula at the beginning of the lesson. We observed fewer blockages in this group.

The activity stimulated students to interpret and evaluate their model. The combination of animation and video acted as a debugging tool. Students still made mistakes in determining the mean velocity, but they clearly detected these and other mistakes by watching the animations and the \(x,t\)-graphs, and they were able to correct these mistakes. Therefore we conclude that the combination of video and model-driven animation can act as a mechanism for self-correction. However, the ways students corrected their errors were different. Some of them discovered and understood the cause of their errors themselves, other students invoked the help of the teacher, but others corrected their errors by trial and error.

The activity stimulated students to use or acquire new domain skills. We observed students
- comparing representations in order to get a better understanding of the more abstract ones;
- discussing different representations of the same movement;
- making and testing hypotheses about different representations;
- getting a better understanding of the relation between velocity and slope of the \(x,t\)-graph by experimenting with different values of the velocity.

Differences were seen in behaviour between well skilled and poorly skilled students. Poorer skilled students more often made use of the animations and their own experience with running. They seemed to avoid the more abstract and new representations. They also made more use of trial and error. After making a mistake, better skilled students still used all representations in order to correct their error, whereas poorer skilled students showed some regression to the less abstract representations.

Many students worked fast enough to accomplish the extra task. These students were able to use the if-then condition. However, as far as we could observe, they mainly used trial and error to fulfil the task. This is not surprising, as this is actually an efficient method for this purpose.

Test results on qualitative reasoning with both \(x,t\)-graphs and \(v,t\)-graphs were good. 76% of the students scored adequately on questions. 40% of the students could determine a mean velocity from an \(x,t\)-graph. As this was a major hurdle in preceding years, this can be considered an improvement. However, this number dropped to 19% when the students were offered a choice between an \(x,t\)-graph and a \(v,t\)-graph to determine the mean velocity from. 17% chose the \(x,t\)-graph but did not correct for the starting position. 40% of the students tried to use the \(v,t\)-graph. Among this last group, three different
types of answers were given. 12% used the velocity at the end of the $v,t$-graph, 10% divided the end velocity by the time, and 19% took an average of velocities from the $v,t$-graph.

2.5.5 Fourth pilot: discussion and conclusions

Our main result is that it is possible to involve students in this modelling activity.

The combination of video and model can be used to acquire new domain skills and does stimulate students to interpret and evaluate their model more than video analysis alone. The combination acts as a mechanism for self-correction. However, attention must be paid to the way students correct themselves.

Students still had difficulty in determining a mean velocity when offered a choice between an $x,t$-graph and a $v,t$-graph. This might be because we did not pay explicit attention to the relation between mean velocity and $v,t$-graph in our modelling lesson, and the paper lesson on $v,t$-graphs was near the end of the course, so probably not all students had enough time to understand it sufficiently. In the next version of the course, more advantage can be taken of the mechanism for self-correction to improve students’ understanding of $v,t$-graphs.

A question is, if the different behaviour of poorer-skilled students is caused by a lack of knowledge. We observed students who, having the formula written down and filled-in, still hesitated to use their results in the model. In many cases, encouraging students to use new representations was enough. Therefore, the different behaviour may also be caused by a lack of confidence or a lack of experience. Another question is who learned the most from the activity, the better-skilled students of the poorer-skilled ones.

2.6 Conclusions

To our main research question, how can a combination of measuring and modelling help to bridge the gap between realistic contexts and the relevant mathematical and physical concepts and methods in school practice, we can say, that, in the case of video-analysis and modelling, this combination stimulates students to compare the results of the measurements in the realistic context with the outcomes of the model, thereby acting as a mechanism for self-correction.

Regarding the sequence of steps and the conditions to be fulfilled for each step on a modelling path, we can say the following:

- The realistic situation that is to be modelled is to be introduced carefully before, or at the beginning of the activity, because a lack of knowledge or
misconceptions about it can cause blockages. An introduction by means of written material only is possibly not effective.

- A lack of basic domain knowledge and skills can be a cause for blockages. At the beginning of a learning path this knowledge and these skills must be developed to a sufficient level before the modelling activity commences.

- The integration of modelling into the curriculum may have consequences for the way physics is taught, because modelling needs more emphasis on fundamental equations instead of emphasis on exact solutions for special cases.

To the learning problems encountered by students and teachers, much has already been said above. We add to this:

- A lack of debugging skills can cause blockages;
- Students may have difficulty in separating the effects of different approximations and assumptions on key variables.

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