System Dynamics in High School Physics

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Abstract

System dynamics has a strong didactic potential for physics education. The use of modeling systems like STELLA in the physics classroom creates new opportunities to:

- accentuate the basic structures of physical theories,
- investigate more complex and realistic phenomena,
- improve the possibilities for students to bring in their own ideas.

Conventional physics instruction is often dominated by a bulk of special equations (gimmicks) for special cases, like $s=v \cdot t$ for linear motion on an air track. System dynamics models help students to realize that the core of physics can be expressed by a limited number of power tools like Newton's laws _p=F·_t, which are applicable to a wide range of topics, including realistic motion with friction. Once the students have become familiar with the modeling process and the graphical modeling language, they can use system dynamics as a tool to solve problems from nearly all domains of physics, starting from the motion of bodies to the decay of nuclei.

Empirical research carried out by the University of Bremen has documented case studies about the use of STELLA over three years of high school physics courses. A comprehensive selection of modeling examples ranges from the motion of meteors over electromagnetic vibrations to Rutherford scattering. Our empirical findings show a) that using systems dynamics methods is feasible in normal physics classes, and b) that content, methods and results of physics teaching are improved. The paper presents the didactic rationale and selected examples.

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1 Introduction

The application of the system dynamics approach in physics education is a small but blossoming flower in German high schools. System dynamics tools are being used in physics in several high schools in the State of Bremen. Teacher students at the University of Bremen are introduced into the SDM approach for physics education. Training courses for in-service teachers are taking place regularly in Bremen and other States of the Federal Republic.

From 1988 to 1992 a pilot project "Computers in Physics Education" (CPE) situated at the University of Bremen under a federal grant developed a large number of curricular materials and carried out empirical research in schools in the State of Bremen (Niedderer et al., 1991). Physics models for a great variety of topics ranging from mechanics to nuclear physics were published in a book on *Materials for Modeling and Simulation in Physics Education* (Bethge and Schecker, 1992). A follow up project starting in 1992 spread the ideas to other federal states of Germany and to other subjects. The North-Rhine Westphalian Institute for School and Adult Education (ISAE) has started a system dynamics curriculum project for sciences and mathematics (e.g. Goldkuhle, 1993).

While CPE worked with the software tool STELLA, which limited the applicability of the materials to schools equipped with Apple computers, in 1992 and most recently in 1993 new graphics oriented system dynamics tools for the IBM-PC platform became available (MODUS, PowerSim).

Hard- and software and concrete modeling examples are the prerequisites for introducing system dynamics viewpoints into physics education, but the essential issue is to outline a clear pedagogical framework—the German term is *didactics*—for the use of modeling systems in *physics* education. The questions are Why?, How?, What? and What are the results? General considerations about the value of systems thinking for effective teaching (cf. Forrester, 1990) have to be sidelined by concrete arguments why system dynamics modeling contributes effectively to *learning physics*.

The CPE project has put much weight on formulating such a didactic framework. This paper outlines the didactic rationale before examples for system dynamics modeling in high school physics are given.

2 Why? — Didactic rationale for system dynamics modeling

International research of the past 20 year into the outcome of physics education has arrived at a number of well-founded and common results which cast some doubt on the effectiveness of traditional physics teaching. With respect to central physical concepts like *force*, *energy*, or *heat*, students tend to keep their pre-instructional ideas even after instruction (cf. Duit and Pfundt, 1991).

Students look upon physics knowledge as a bulk of specific formulas for specific problems, rather than as a limited set of widely applicable concepts and principles. They may learn textbook physics for the next exam but they hardly apply physical concepts to everyday phenomena outside the physics lab.

Students regard physics as one of the most difficult and least attractive subjects in school. Statistics show that in German schools enrollment in physics courses is steadily decreasing.

Physical topics are often chosen under *mathematical* aspects. In the physics classroom *quantitative* problems, where students have to fill in numbers into equations to arrive at an answer, dominate over *qualitative* phases where students have to engage in conceptualizing a phenomenon based on their own ideas. Thus students are not encouraged to develop a conceptual understanding.

In most *exams* students get high marks for manipulating equations and making calculations. As long as we do not include qualitative examination questions and support conceptual understanding by good scores, students will not appreciate these abilities as *important* for physics (learning).

While students have the chance to develop and try out own experiments by modifying the setup of apparatus, their opportunities to *experiment with ideas*—i.e. to work out and test theoretical approaches—are limited. The necessary analytical operations exceed in most cases their level of mathematical competence.

Looking at the deficits of physics education and their origins physics educators arrive at the following proposals (e.g. Labudde, 1993):

- Shift the focus of instruction from *quantitative* calculations to more *qualitative* and *semi-quantitative* discussion of hypotheses.
- Give students the chance to explore their *own ideas* about relevant physical problems and ways to tackle them.
- Cut back on highly idealized laboratory phenomena, like feathers in a vacuum tube, and change to more realistic cases, like parachutists in the sky.

Computer-based modeling under the system dynamics approach can make important contributions to these aims.

2.1 System dynamics accentuates physical concept structures

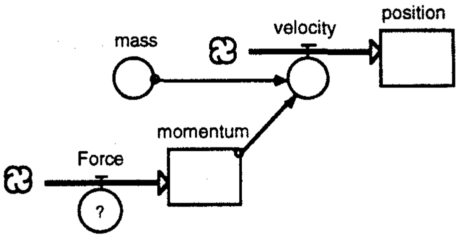
The concept structure of a physical domain consists of a number of interrelated quantities and rules for their use. Newtonian mechanics can be broken down to a small set of definitions and general principles. The most important are:

- definitions:

  velocity eq. rate of change of position: $v= \Delta s/\Delta t$
  acceleration eq. rate of change of velocity: $a=\Delta v/\Delta t$
  momentum is the "quantity of motion": $p=m\cdot v$
  force eq. rate of change of momentum: $F=\Delta p/\Delta t$
- main principle:

  In all interesting motions there are forces acting on a body. If you want to predict the motion of a body then find the forces, find out what they depend on and sum them up.

For physicists some of the definitions may seem unusual. They make use of the system dynamics term *rate of change*. But *rate of change* is also a very appropriate *physical* term, because it refers to the *dynamics of change*. Textbooks and students often speak of velocity as "displacement per time", but these words do not underline the central feature of velocity namely being related to a *process* of change. Acceleration is for most students mainly "increase of velocity" the aspect "per time" is disregarded. Simply introducing the definition "acceleration is the rate of change of velocity" in physics lessons has frequently stimulated fruitful discussions with students about a proper understanding of acceleration.



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☐ momentum(t) = momentum(t - dt) + (Force) * dt
  INIT momentum =  0 {kg*m/s}
  INFLOWS:
      Force = ?
☐ position(t) = position(t - dt) + (velocity) * dt
  INIT position =  0 {m}
  INFLOWS:
      velocity = momentum/mass
○ mass = 1 {kg}
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Figure 1. Newtonian standard model.

Figure 1 shows a simple STELLA model built from the definitions. This model is sufficient to describe and predict a large group of phenomena from classical mechanics to nuclear physics:

- parachuting, including investigations of the opening phase of the parachute (Schecker, 1993)
- meteors entering the atmosphere (Schecker and Bethge, 1991)
- mechanical oscillations: string and spring pendulums with small and big elongations (Bethge and Schecker, 1992)
- cycling under realistic conditions (Bethge and Schecker, 1992)
- planetary motion, two- and three-body problems
- Rutherford scattering (see below)

The solutions to all these problems can be based on the same core model (see Figures 1 and 2). The students have to follow the principle "Find the forces; find out what they depend on and sum them up". The model can be duplicated for two-dimensional motion or for two-body problems. The relationships between velocity and friction force may take different shapes. Still, the core remains the same. More typical core structures exist for electrodynamics, nuclear physics, and other domains. Students can thus learn that physics is "easy"—in the sense that many different complex examples can be explained with the same small set of conceptual instruments.

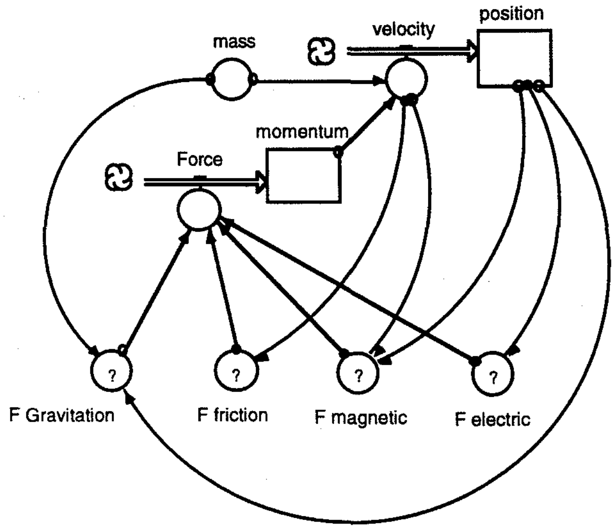

Figure 2. Feedback loops in the Newtonian standard model.

2.2 System dynamics removes mathematical boundaries

Let us look at two laws of motion:

(1) $v(t)=g\cdot t$

(2) $v(t)=\sqrt{\frac{g}{k}}\cdot\tanh\left(\sqrt{g\cdot k\cdot t}\right)$

g: gravitational acceleration
k: constant
t: time

Equation (1) describes the fall of a body under uniform gravitational acceleration, i.e. a constant force, while (2) refers to motion under a so-called Newtonian friction force, where friction depends on velocity ($F_{friction}$ µ velocity^2). One can easily understand why dynamic friction forces are often excluded from the investigation of motion in physics courses: It takes a lot of analytical expertise to arrive at a law of motion that describes the trajectory.

The two equations look completely different from each other, suggesting that their physical backgrounds differ. The simulation diagrams however show on the graphical level that the difference only lies in one additional link between velocity and force. The rest is mathematics.

The investigation of motion with friction can be done on the students' physical level of competence. *Formulating* the (difference) equations becomes the main task instead of *solving* them—and here is where *physical* competence can be proven and extended. The tedious job of integrating the equations system is taken over by the SDM software. Afterwards physical discussion goes on by evaluating the predictions given in the form of graphs or tables. The students have to work out whether these predictions are in accordance with their expectations or experimental results. Differences between the model output and the students' ideas either lead to a revision of their expectations, e.g. stimulating new experiments, or to a revision of the model, i.e. changes in the model structure. Both activities are genuinely *physical.*

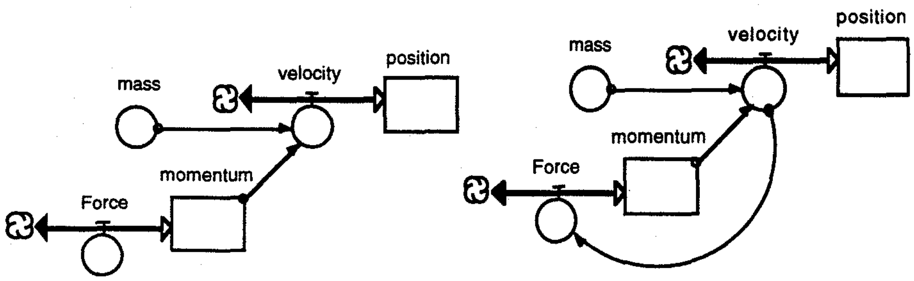

Figure 3: Constant and dynamic forces.

2.3 SDM helps to investigate more complex phenomena

Phenomena from the real world are more complex than laboratory experiments that were designed under the aspect of simplicity. With the help of SDM-tools many interesting effects can be dealt with that are usually excluded. This does not only refer to the mathematical problems already discussed. SDM supports the investigation of complex physical problems in more ways:

- The simulation diagram gives a graphical overview that shows the interrelationships between the quantities more directly than a set of equations can. This is particularly important for complex phenomena with many quantities involved and a high degree of interdependency.
- Complex model structures can be built up from simple models stepwise by a succession of *local extensions*. The students do not have to bother with the correct order of the equations.
- Changing the names of quantities in order to clarify their meaning is no problem because all the equations affected are automatically altered.

By working on more complex and realistic examples for which standard solutions fail, students can realize that it is essential to have a *qualitative* understanding of physical concepts and principles because simple formulas learnt by heart will not help.

2.4 System dynamics fosters learner-directed learning

Learning is an active process of self-organized construction of meaning. This so-called *constructivist perspective* has become the paradigm of research about learning processes. The teacher cannot cannot *transfer* information into the students' minds. All he can do is create adequate learning environments where students have the chance to further develop their ideas by constructing meaning from experiences and observations.

If we want the students to construct qualitative physical ideas we have to create environments fostering this process. Why does the SDM method help to achieve this aim? Mainly because it forces the students to engage in a qualitative, principle oriented analysis of the problem before they can work on the equation level. Prior to a definition of special functional relationships the relevant quantities have to be defined and the structure, i.e. the conceptual features of the model, must be formulated. The students are introduced into the strategy of expert solvers.

In the process of model development students explicate their ideas. They transfer their internal mental models into external ones (Webb and Hassell, 1988). SDM prompts the students to bring their vague ideas into a precise form, so that they can be explicitly discussed. The simulation diagram serves as a stimulus for discussion in student groups or in a class forum about the ideas behind this graphical concept map.

Computer aided modeling allows students to *experiment with ideas*. Theoretical assumptions become visualized by iconic representations. The consequences of the students' assumptions for the predicted behavior of the system become clear. The confrontation of intuitive model structures with physically accepted descriptions can help students to become aware of differences between the scientific view and their informal preconceptions.

3 How? — Methodological issues

The proposed contributions of system dynamics modeling to the improvement of physics education are not achieved automatically, simply by using computers and SDM-tools in the classroom. Information technology has to be connected with new teaching strategies which we call *contrastive teaching* (Schecker and Niedderer, in press) and Forrester (1990) calls *learner-directed learning*. These strategies see the student in the center of the teaching/learning process—instead of the teacher as the dominating factor. Their aim is to activate students to leave their conventional role as *consumers* of instruction to become *contributors* to the teaching/learning process.

Whenever possible, the models should be developed in class—either in group work or in a class forum. Simple student-made models have more meaning for the class than any elaborated model prepared by the teacher. If there is only one computer available, it should be operated by students. Our field research shows that students are more willing to contribute to the construction of a model if one of their peers is in charge of the modeling software. At the same time the teacher is relieved from practical tasks and can concentrate on the discussion.

It takes time to work out and understand a simulation diagram. Not all of the students actively contribute to the model formation. They have to construct meaning for a model structure proposed by others. The teacher should prompt the students repeatedly to explain why certain quantities are introduced and why certain relationships are drawn. The graphical concept map is at least as important as the graphs and tables produced by the model. Due to the fact that students' preconceptions often differ from scientific theories it happens that models proposed by students are inadequate. The teacher should refrain from interfering with the students' ideas too soon. He or she should rely on the process of comparing the predictions of the model with data from experiments or the text book.

System dynamics modeling must be connected with other forms of physical knowledge acquisition, like experimenting or deducing. It is important to have at least some vague idea about the behavior of the system to be modeled. Ask the students to explain their expectations before a simulation run starts. Otherwise they cannot judge whether a model makes sense.

4 What? — A case study from nuclear physics

Case studies about the long-term use of SDM in upper secondary physics courses are published in Bethge and Schecker (1992), Schecker (1993) and Vol. III of Niedderer et al. (1991). The physical domains are mechanics and electrodynamics. This chapter shows a brief example from an advanced level physics course on nuclear physics with 14 students (average age about 18 years). The class was equipped with a Macintosh Plus and an overhead panel. All the models were developed interactively in a class forum. SDM units covered about 15% of the total lesson time (14 weeks, 6 lessons per week). The class was experienced with using STELLA.

4.1 Overview

The sequence of models covered the following topics:

- *b-radiation in a magnetic field.* Experimental data were evaluated with the help of STELLA used as graphing tool and a function plotter. This use of STELLA is not strictly in the system dynamics sense but helpful.
- *Rutherford scattering* (presented below).
- *Energy of an electron in the hydrogen atom.* The model integrates over the Coulomb potential.
- *ß-particles in a homogeneous electric field* . The model compares the classical definition of force as $\Delta p/\Delta t = m \cdot a$ and the relativistic definition as $\Delta p/\Delta t = m \cdot \Delta v/\Delta t + v \cdot \Delta m/\Delta t$. with respect to conservation of energy.
- *Radioactive decay* (presented below).
- *Physical and biological half-lives of Tritium.* Dynamic saturation level of Tritium incorporated by drinking water.

Any model developed in school has some idiosyncratic features that make it difficult to understand it by "outsiders". The original models have been revised for this paper without changing their physical meaning.

Presenting models in a textbook way is problematic because teachers tend to stick very closely to pre-fabricated model structures—particularly as novice SDM-modelers—thus rejecting useful proposals made by students when they deviate from the prototype provided in the teacher materials. But there is always more than just one appropriate structure for modeling a phenomenon. Students will at least propose other names for the components.

4.2 Rutherford scattering

Rutherford scattering means that a-particles (nuclei with two protons and two neutrons) are deflected by inert gold nuclei because of repelling Coulomb forces. For the Rutherford model the class could draw upon mechanical models developed some time before (see the standard mechanical model shown in Figure 1). Force is the rate of change of momentum Æ momentum (and mass) determines velocity Æ velocity is the rate of change of position. This chain is duplicated for the x and the y component. The Coulomb force depends on the distance between the a-particle and the gold nucleus, and the charges.

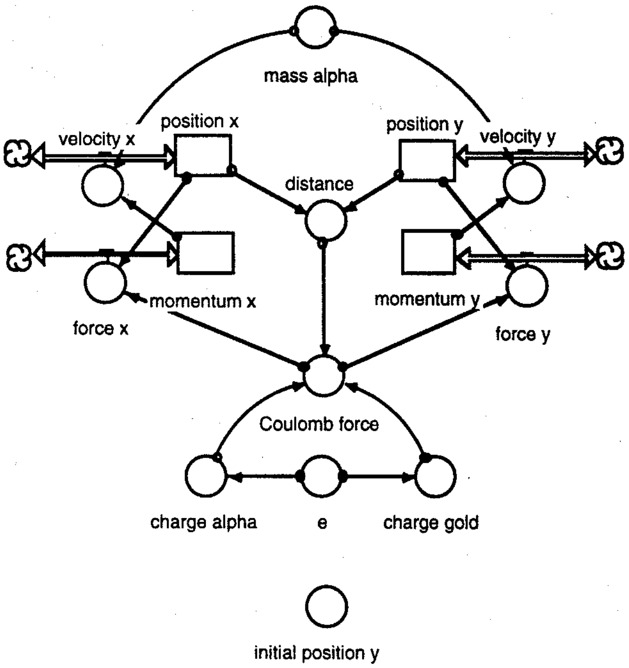

Figure 4. Rutherford scattering model.

The simulation run in Figure 5 assumes that the a-particle initially only has momentum in x-direction. The trajectories mainly depend on the initial y-position. This parameter is altered in the sensitivity run. The graphs show how forward and backward scattering result form different initial values of the y-position. Although there are only 10 runs, it becomes clear that backward scattering is very rare.

The Rutherford model stays almost unchanged for the description of planetary motion, e.g. the orbit of the moon round the earth. Only the force law has to be changed from Coulomb to gravitational force. The two masses take the place of the two charges.

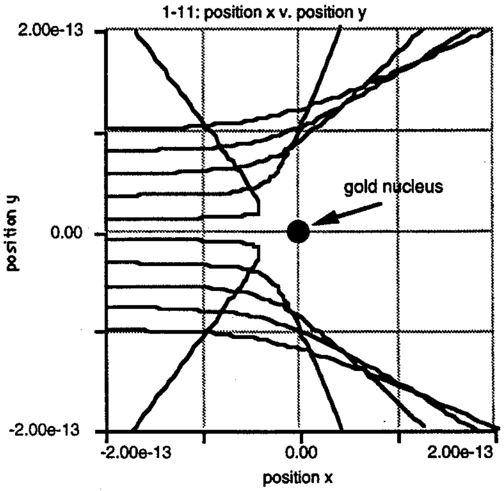

Figure 5. Rutherford scattering, sensitivity run.

4.3 Decay series

The modeling phase was preceded by measurements of radioactive decay. The decay law was gained from the experimental data. $N=N_0e^{-lt}$ is for most students just another "formula". A deeper understanding of its qualitative meaning—per time unit a *certain percentage* of nuclei decay—was developed by applying the concept of decay to a more complex series of decays.

The decay series model in Figure 6 is constructed by connecting two simple decay part models that are structurally identical. The students again learned how complex processes are broken down to a simple physical core structure made up by the following assumptions:

- Activity is the rate of change of undecayed nuclei.
- Activity depends on the number of undecayed nuclei and a certain constant called *decay constant.*
- A more illustrative quantity than decay constant is half-life. The decay constant can be directly derived from half-life.

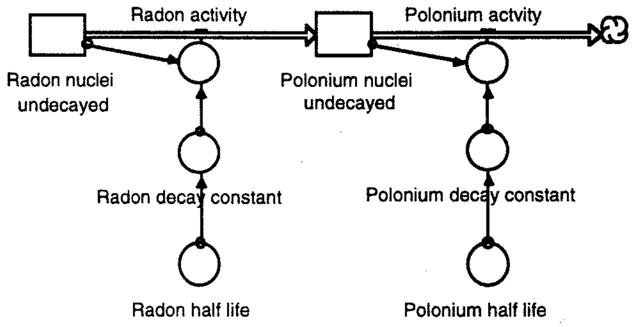

Figure 6. Decay chain model.

By combining two simple decay models to a mother-daughter-decay interesting investigations can be undertaken. The graphs produced by the model e.g. show that although the numbers of Rn nuclei and Po nuclei are different in orders of ten the activities of the two radioisotopes soon become equal, so that the ratio of Rn to Po nuclei is constant.

The decay model was later slightly changed and applied to the incorporation of Tritium into the human body by drinking water. In this case the biological half-life of Tritium had to be considered instead of the physical half-life. The incorporation is constant if we assume that a person drinks a certain amount of liquid per day. The biological outflow depends on the stock of water in the body. Both effects result in a dynamic saturation of Tritium.

5 What are the results? —The effects of system dynamics modeling on teaching and learning

Research on the use of SDM-tools in physics education has been carried out by the Computers in Physics Education project on the basis of classroom observations, lesson protocols, and audio recordings of physics courses in advanced level high school physics courses over periods of two weeks up to several months. Before some of the results are presented a short review of studies from physics and other subjects is given.

5.1 Review

The effects of using SDM-tools in teaching have been evaluated in a number of field studies. Zuman and Weaver (1988) employed STELLA to teach the concepts of exponential growth and decay. They wanted the students (aged about 14 to 16) to understand the ideas of *level* and *flow*. Among the examples were population growth, cooling curves, and charging a capacitor. Getting acquainted with the user-interface of STELLA posed no problem. Qualitative analysis of pre- and posttests showed that the students developed an understanding of exponential increase that could be transferred to further problems.

Tinker (1990) reports about teaching experiments with pairs of students using SDM-tools for learning calculus as a mathematical means to describe processes of change. The students measured and predicted the outflow of water from different containers. According to Tinker the software systems did not help the students to understand the processes of differentiation and integration.

> Students, after several sessions in which they used STELLA to transform a function into its accumulated function, had little idea of what type of procedure the software was following in order to perform the transformations. (Tinker, 1990, 24)

Webb (1988) used STELLA with younger students (fourth year) in a sequence of lessons to model an AIDS epidemic in biology. The lessons were observed, audio taped, and evaluated under the aspects of interactions between teacher, pupils, and computer. Webb found that the systems diagram proved to be very helpful for clarifying the pupils ideas of the components involved. Defining the relationships, especially in a way in which they could be quantified, was much more difficult. The pupils needed a lot of prompting to build up the diagram but the ideas all came from them (Webb, 1988, 122).

Hassell (1987) did similar research with sixth formers in geography, who had some experience with system dynamics. The lessons dealt with immigration and emigration for a country and the hydrological cycle. His findings are positive. Hassell attributes this success partly to the fact that the students were rather old.

> The concepts and ideas involved in the systems approach were grasped well by most of the pupils and they proved to be able to relate reality to their models quite well. Their discussions ... showed that they had developed a good understanding of the subject matter and models. (Hassell, 1987, 109)

A pilot study on using the SDM-tool CoMet-MODUS was carried out in North-Rhine Westfalia in 1990 with 165 students aged 13 to 15 (Klieme and Maichle, 1991). Ten classes used the system dynamics approach in different subjects. The aim was to enable younger students to apply systems thinking to analyze complex phenomena using an SDM software tool. The trials were accompanied by questionnaires, pre- and posttests, teacher questionnaires and lesson protocols. More than half of the students saw themselves able to handle the software technically, but only 40% believed they could build a model from scratch. The final test showed that there were considerable problems understanding the SDM approach. Only one student was able to sketch a proper CoMet-MODUS model for the dynamics of a bank account (income, rent, interests) in the final test.

5.2 Own empirical research

The studies reviewed above give no clear picture. With respect to long-term effects of applying the SDM approach in physics teaching their findings are not very useful. The studies are based on rather short teaching experiments, not exceeding about 5 weeks. There was no clear didactic framework for the use of SDM-tools and no embedding of SDM into new teaching strategies aiming at open-ended and learner-directed learning. Using tools like STELLA that are meant for higher education with students under the age of 15 or 16 probably causes additional problems. For younger students even more qualitative tools are necessary. Development of tools completely omitting the (difference) equation level are under way (Miller, 1993).

Our own research results are based on four courses that used the SDM method repeatedly during three years of high school physics. The students were 16 to 19 years old.

A general finding is that system dynamics modeling in physics education affords global, not just local changes of content and methods. If you just want to build one or two models and then put the SDM-tool back on the shelf it is not worth the teacher's and the students' time and efforts. SDM will be an advancement of teaching and a helpful tool for the students if it is employed repeatedly over a longer period of time and over a large selection of topics. SDM methods have to become familiar problem solving tools for the students—just like micro-based laboratory materials or spreadsheets.

Handling the modeling system (STELLA, MODUS) proved to be largely unproblematic. It took only 2 or 3 introductory examples in kinematics until most of the students were able to either work with the software in groups or contribute to model building in a class forum. The use of computers did not distract the students from physics. Very soon the regarded the software as "just a tool". In an interview a student said:

> "In the beginning the question was: How does *Stella* work? But now it just works, because most of the people have got it. Together we think about the problem, and then—bang!—the inputs are made. That is no problem anymore. It just was in the beginning, when we had to learn it a bit."

During SDM units a larger proportion of lesson time than usual was devoted to student-student and student-teacher interaction. Formulating the model structure stimulated intense reflection of the physics involved with questions like "Have we included all the relevant influences?", "Can you explain why you drew that arrow?", "Don't we have to model that quantity as a stock?".

SDM definitely changed the content structure of the courses towards more complex and more open-ended investigations. Students appreciated this shift.: "I found those things most interesting, where we did *not* know the answer right from the beginning." Most of the students found that the SDM approach made physics lessons more interesting, because stimulating new phenomena were investigated that would otherwise not have been topics of school physics.

SDM was not appreciated by all students as helpful for physics learning. Some preferred to write down and solve equations. Some were even afraid that the reduction of formal, mathematics-oriented physics might lead to deficits compared to students in other physics courses. Although most of the students fruitfully learned to use SDM for physical problem solving, only few of them developed an idea of systems thinking as a general means to structure complex phenomena. Their ability to use the SDM-tool stayed *context-bound.*

We have preliminary results from interview studies that system dynamics modeling leads to a clearer understanding of the main conceptual features of physical domains. We found that students tend to employ qualitative domain-bound SDM-strategies even in situations where no explicit inducement is given and no computer is at hand. Describing a new experiment the students argued *as if* they were constructing an SDM model, e.g. arguing along the lines of an appropriate core model used for other cases before (Schecker 1993, pp. 198).

6 System dynamics modeling as a part of hypermedia

Stimulation of physical reflection is particularly successful when modeling and experimenting are brought together. Both ways of looking at a physical phenomenon—theoretically by modeling and predicting as well as experimentally by measuring the system's real behavior—profit from each other. A good example in several courses was the launch of a rocket driven by compressed air and water. Differences between measured height and values predicted by a first model led to new activities. Additional experiments were designed, e.g. to determine how long the burning phase of the water rocket lasted. Changes in the model were made to match its prediction as closely as possible with the experimental results. Another example from a university student project about oscillatory circuits is published in Schecker (in press).

The interplay of measuring and modeling affords a flexible exchange of data between SDM-tools and micro-based lab software. The best way is to integrate the two tools in a hypermedia package together with a spreadsheet for importing and processing data from both. The Bremer Interface System is a step in this direction (Schecker, in press).

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