The Role of Qualitative Models in Learning System Behavior

Literature Review,
Master's in Mathematics & Science Education

Miriam Brielmann

AMSTEL Institute
Faculty of Science
University of Amsterdam
Student Number: 0642924

Supervisor: Bert Bredeweg

Human Computer Studies
Informatics Institute
Faculty of Science
University of Amsterdam

July 20, 2009

Contents

[page intentionally left blank]

1 Introduction

It is hard to imagine science education without models. Typical examples of models encountered in a school career are busts with removable organs in biology, drawings of molecules in chemistry, or toy cars running down tracks in physics.

The use of modeling in education is tightly connected to theories as constructivism and discovery learning (e.g. Bruner, 1966); in the context of cognitive science, work on mental models and analogies stands in close relation (e.g. Collins & Gentner, 1987; Schumacher & Gentner, 1988). Moreover, arguments for cognitive tools including models are made (e.g. Jonassen, 2003; Van Joolingen et al., 2007).

The development of computer modeling tools makes the activity of modeling accessible to a broader group of people with a bigger diversity of possible uses. At the same time, there is a need for learning about increasingly complex systems and their behavior. Modeling is seen as a promising approach to facilitate people to understand and work with those systems (Forbus, 1996; Spector, 2008).

For practical reasons, learning with qualitative models is of special interest for building intelligent tutoring systems about systems behavior; the application of qualitative models and qualitative reasoning provide the means to select and sequence subject matter, to diagnose missing knowledge and misconceptions of the learner, and to generate explanations about the models (Bredeweg & Winkels, 1998).

In this literature review we investigate the role of qualitative models in learning system behavior. We look at how modeling is established in instructional theories, examine studies about the benefits of modeling for learning in general, and check studies that have researched the role of qualitative representations specifically. Finally, we draw our conclusions from the review about the role of qualitative models for the given subject as presented in literature.

1.1 Using Models in Education

The focus of our review is the influence of models on learning about a specific type of knowledge. In this section we give an overview of the use of modeling for education in general, including expectations for using models in education, and relevant terms describing the ways models are used.

1.1.1 Expectations for Using Models for Education

Using models instead of real systems for learning has some intuitive advantages. An enthusiastic essay about why computer models specifically should be used by everybody is given by Forbus (1996):

1. Computer models are more accessible than real systems and physical models. For example, it is much cheaper and less dangerous to practice the behavior in different situations in a flight simulator than in a real plane.

2. Computer models can simulate many different behaviors, show a system from many different perspectives, represent impossible situations and behaviors (including the manipulation of time) and show otherwise possibly invisible aspects.

3. Computer models can be used for generating an explanation of the model and its behavior.

In literature about science education many (more or less) concrete reasons why (computer) modeling should be applied can be found. However, the plausibility of these statements often is not as self-evident as the previously stated motivations for using computer models. Löhner (2005) summarizes the *expectations* given in literature in three categories as follows:

1. Learning about modeling:

   - Scientists also build models, building their own models lets student understand the nature of science better;
   - People have always tried to make sense of and learn about the world by creating models of it,
   - Decision making can improve, because computer modeling allows us to explore ideas, investigate consequences and make decisions,
   - Students should be introduced to the limitations of computer models;

2. Improving scientific reasoning skills:

   - Models are external representations that serve as a *concrete object on which reasoning can be based*,

- By constructing representations, students will develop an artifact that represents their own ideas and can be communicated to others, be encouraged for learning by doing, *take ownership of the knowledge* and *develop accurate and appropriate mental models*,
- Computer models can be simulated, i.e. the *reasoning capacity is extended* by numerical simulation,
- Using computer models is *engaging and motivating* students;

3. Learning domain content by modeling:

   - Computer modeling will help students *understand the behavior of complex dynamic systems*, focus attention on important aspects, help connect phenomena with causal processes, and lets students experiment without having to fear the consequences,
   - Computer modeling will help students *better understand the (science) content* by emphasizing the process of science and the structure and coherence of scientific knowledge.

1.1.2 Ways of Using Models

In general, there are different types of models and different ways of using them. An important distinction for this review is the one between *qualitative* and *quantitative* models. Intuitively, a qualitative model describes a system in terms of qualitative values and relations, while a quantitative model includes numbers and formula.

Moreover, there are two modes of modeling. One mode is building a model; the other is running a simulation of the behavior of a system based on a model of a system. Depending on the publication, the term "modeling" is used referring to either one or both of the modes.

"Computer modeling" is a self-explaining term that describes modeling with computers as a tool for creating or running models. A way of classifying tools for computer modeling into different categories is given by Löhner (2005), shown in table 1. The category "systems modeling tools" contains the tools in the scope of our review, i.e. learning system behavior.

In accordance with the definitions given above, in quantitative tools exact formula and numerical values have to be entered to describe the behavior of a system. "Semi-

quantitative" tools, or qualitative tools, allow the user to describe system in terms of qualitative values (e.g. a value is high, medium or low)[1].

Computer modeling tools					
Systems modeling tools				**Emergence based modeling tools**	
Equation oriented tools		**Diagram/structure oriented tools**			
Programming environments	**Equation based modeling tools**	**Quantitative diagram based modeling tools**	**Semi-quantitative modeling tools**	**Object based modeling tools**	**Cellular automata**
A certain amount of programming is required	No programming required	Precise (quantitative)	Imprecise / Intuitive (semi-quantitative / qualitative)	Describe the interaction of small grained units	Describe the interaction of cells on a grid

Tab. 1: Classification of modeling tools according to Löhner (2005)

1.2 Learning about System Behavior

For giving an overview of "learning about system behavior", the subject of this review, we use the ideas given by Bredeweg & Winkels (1998) and de Kleer (1990).

1.2.1 Examples of Systems

There are many systems humans interact with. In everyday life we make coffee, drive bikes (or cars), use elevators, computers, TV sets etc. We benefit from and contribute to a social system, and cause climate change by influencing an ecological system etc. The list of systems we make use or are part of can be continued almost infinitely with natural systems and human-made artifacts.

1.2.2 Ways of Interacting

How we interact with or use systems can be classified into categories, depending on whether structure and/or behavior change in the interaction. One categorization would be as given in Bredeweg & Winkels (1998) and de Kleer (1990): For controlling and operating, the

[1] Bliss et al. (1992) distinguishes between qualitative and semi-quantitative reasoning. However, this separation has not been found anywhere else during the review.

system is manipulated to reach a certain kind of behavior without changing its structure. When designing and constructing, the system structure is set up in a way that it can perform a certain behavior. In diagnosing and repairing, the behavior of a system that is not working in the way it should is analyzed and its structure changed. Furthermore, for instruction, a system needs to be explained, with the explanation activity itself not requiring a change of structure or behavior of the system.

1.2.3 Reasoning about System Behavior

For learning about systems and how to interact with them, we can either use real systems or models; we can learn by pure discovery or make use of explanations. Either way, understanding a system's behavior involves reasoning about its physical structure and the connected behavior evolving over time. The learner should be enabled to predict relevant behavior, i.e. how the behavior will change when the system is controlled, or postdict it, i.e. explain why changes happened. When we learn to drive, for example, we need to learn how the car reacts when turning the steering wheel, and we would also like to understand why the car stops (at least in simple cases, as when it is out of gas). On another scale, we would like to postdict (understand) what caused climate change and predict how our behavior will influence the further behavior of the atmosphere.

Qualitative reasoning, a field of research in Artificial Intelligence, provides a vocabulary for reasoning about the systems and their behavior. In this terminology, the behavior of a system is characterized by the changing values of the quantities involved. The quantities can take a set of qualitatively distinct values (e.g. solid, liquid, gas), called the "quantity space". The structure of the system causes a certain behavior. This causality is captured in causal models describing the influences of the systems' components on each other, relating the behavior in one point of time to the state in the next point of time. Typically, reasoning about systems also involves assumptions about the conditions the reasoning is valid for, e.g. when the behavior of a population is examined without considering immigration. Finally, reasoning about behavior is done with a certain perspective, e.g. the electrician has a different way of reasoning about a traffic light than the driver of a car.

1.3 Scope of the Literature Review

The goal of this literature review is to answer the main research question "What is the role of qualitative models in learning systems behavior?"

For answering this broad question, we explore literature about the following sub questions:

1. How is modeling established in curricula?
2. What are the benefits of using modeling in education as shown in studies?
3. What has been studied about the role of qualitative models in learning?

Considering the listing from Löhner (2005) in 1.1.1, we are interested in categories 2 and 3: how modeling helps students in reasoning about a topic and the resulting content knowledge. Improvement in modeling knowledge is considered relevant for our research if it shows effect on the reasoning or content knowledge.

Finally, we analyze our findings by looking for the role of qualitative models in the publications.

1.4 Literature Search

The literature list discussed in this paper was mainly compiled from recommendations given in discussions and correspondence with experts in the field of modeling in education, coming from the fields of Artificial Intelligence in Education, Mathematics and Science Education, and Social Science. This list of work in the field was condensed to central papers that address the research questions. Where considered necessary, the given collection was supplemented with references given by the initial list of publications, and additional literature research was done using the University's Digital Library and Google Scholar.

Aim of the review is to cover a broad spectrum of topics; at the same time each of the reviews has to be deep enough to point out the role of the qualitative models. We choose to consider one publication per topic as sufficient for our purposes, and rely on the experts' input that we cover the most important ideas.

2 Model-Based Curricula

How is modeling established in curricula? In the first part of the review, we want to get insight into how modeling in education is expressed as theories and guidelines for curriculum design. In particular, we want to find out what types of models are put forward in those guidelines. In addition, we are looking for the main motivations and expectations for applying models.

2.1 Model-Centered Instruction

"Model-Centered Instruction" (Gibbons, 2001; Kearsley, 2009) is a "theory of instruction" and a rather general, abstract approach to implementing modeling in instruction. The theory gives guidelines for the design of instruction that uses modeling in general, not necessarily in a classroom setting.

The models can be of different types (environments, cause-effect systems or human performance). A level of denaturing (i.e. simplification of reality) and a certain set of problems is chosen to present a certain view on the model to the learner. For solving the given problems, the learner is equipped with additional resources (information, materials, tools). The teaching/learning is goal oriented and it is considered important that the learner has the possibility to interact with the models.

Gibbons's central argument for promoting model-centered instruction is that, according to him, learning happens by experience. Learning companions like e.g. peers, teachers, experts, books, computer programs etc. assist the learner by augmenting the experience. In the past the roles of the experience and the instructor have often been distorted, focusing on a strong instructor and replacing direct experience. Model-centered instruction is intended to be a guide for designing instruction that designates appropriate relevance to the experience or as Gibbons calls it, "broadens and places in perspective the roles of the agents involved in instruction".

As mentioned before, the models can be of different types. For the different types, no further specification of what the models should look like is given. Therefore we cannot draw any conclusions about the qualitative-/quantitativeness of the models.

2.2 The Modeling Cycle

"The Modeling Cycle" is an approach for physics education, developed by Wells (Wells et al., 1995), based on the previous work on the "Modeling Method" by Halloun and Hestenes (Halloun & Hestenes, 1987; Hestenes, 1987). The modeling cycle can be regarded as a refinement of the learning cycle[2] and serves to structure the activities in teaching into coherent units with similar structure. A student-centered approach is emphasized: The students invent and evaluate models for themselves in an experimental context where they are meaningful. They work in small teams who develop models and present these models to the fellow students in plenary discussions using sketches on whiteboards. Physics instruction using the modeling cycle is built around basic models that reappear in physical phenomena and more complex models which are constructed by modifying the basic models. A model that has been developed by the students is always applied to a number of situations.

The authors' main motivations (which are not explicitly addressed in the evaluation of the teaching) for adopting a modeling approach for physics instruction are:

- It brings instruction closer to *emulating scientific practice* which is considered to be an important part of teaching physics.
- It addresses serious weaknesses in traditional instruction, by helping students to develop a more *coherent, flexible and systematic understanding* of physics. The knowledge that students acquire from traditional instruction tends to be fragmented and diffuse.
- It helps the students to develop problem-solving skills, including a qualitative analysis of the problem rather than plug-and-chuck methods. According to the authors, the *complete solution* to every physics problem is actually a model, and not (only) a number. They argue that expert physicists always presume some model in their answer to a physics problem.
- In the context of modeling the students have a framework for *testing and correcting their own ideas* in discourse, especially in regard to relevance and coherence with other ideas. As students are led to articulate their reasoning in the course of solving

[2] for the learning cycle see Karplus & Butts (1977)

a problem or analyzing an experiment, their naive beliefs about the physical world surface naturally.

"Models in physics are conceptual representations of physical systems and processes", according to the authors. A complete model is specified by "descriptors" (i.e. dependent and independent variables, the importance of the identification of them is pointed out), a description of the "system schema", (i.e. the organization of the system), laws of structure and laws of change. Eventually the goal is a "mathematical model" which "is not fully specified until it has been supplied with an interpretation" of how it relates to the object or system it represents.

The results of the research done on the teaching using the modeling cycle are discussed in section 3.1.1.

2.3 The Model-Enhanced ThinkerTools (METT) Curriculum

"The Model-Enhanced ThinkerTools (METT) Curriculum" presented in Schwarz & White (2005) is an approach for developing inquiry-based physics lessons. An emphasis is put on meta-modeling knowledge by including explicit discussion of and reflection about the modeling process which represents an important character of science. The students build their own models based on observations in experiments and by that are actively involved in the modeling process.

The authors' motivations to apply a model-based approach are:

1. Because *model creation and model-based reasoning are essential elements of both human cognition and scientific inquiry*, students should be involved in the process of creating, testing, revising, and using externalized scientific models that can represent their own internalized mental models;

2. Modeling can help the learners to *express, externalize, visualize and test* their ideas.

3. Modeling makes some *scientific content more accessible and interesting*;

4. Modeling is an increasingly important *skill in society* in general, and learners might have to use it later in their life.

In addition, the use of metacognitive knowledge is expected to:

1. Let the students develop an *appropriate view of science* as process of model building and of scientific knowledge as human construct;
2. Support the students in *reasoning about scientific evidence*;
3. Help the students in *integrating conceptual knowledge*.

For the implementation of the approach, the model-enhanced version of the Thinker-Tools software was used. In this modeling software, students build qualitative force-motion models by selecting rules out of sets of given rules. E.g. a student can select that a "motion with no force like friction" is most appropriately described by the option "constant speed" rather than that the motion of the object slows down or speeds up. The students then can run a simulation of the behavior caused by their laws.

The results of the research done about the teaching using the modeling cycle are discussed in section 3.2.4.

3 Effects of Using Models in Education

What are the advantages of using modeling in education? How is this supported by studies? In this section, we give an overview of studies that investigated the effects of models/the modeling activity on the learning of students.

3.1 Improving Scientific Reasoning Skills

3.1.1 Representation as Medium of Discussion

Wells et al. (1995) describe how the combination of using modeling and an increased focus on discussion improve the learning of the students. The researcher changed his own teaching strategy by centering the learning cycle around models and putting high emphasis on the discussion of the student groups' ideas as a form of scientific discourse. The models were developed and presented on simple whiteboards; moreover, the models served as complement to the numerical solutions of physics problems.

Comparing the results students scored in tests which measure knowledge in the mechanics domain, students who learned using the modeling method performed better than the ones that learned with Wells's previously used cooperative inquiry method. The models served as *representation* of the students' ideas and were the essential *medium of discussion* for testing the ideas, which helped them in uncovering and correcting their misconceptions.

3.1.2 Representation for Testing Ideas

Hartley (1998) researched whether beliefs are revised, i.e. misconceptions are corrected and conceptual change happens, during activities using a qualitative modeling software. A group of students first explored motion by running and controlling simulations of the motion of objects. Then they worked with a modeling software in which they built their own models by describing the system structure and cause-effect relationships. This description of the system then could be run, producing some output as e.g. a graph that could be compared to the initial expectations.

The results showed that in both steps of the experiment there were students who revised their initial misconceptions. The students who did not change their opinion in the first step, running the simulation, needed the second step, building the model themselves, for making their ideas explicit and testing them, in order to change their beliefs.

3.1.3 Motivation

Although motivation is often stated as a reason why to use models in education, the effects of modeling on motivation are often only mentioned as a side-effect of the modeling activities, or not discussed specifically for the modeling activity but for the curriculum as a whole.

In Stewart et al. (1992), students use the "Genetics Construction Kit", a simulation software, in a model-based reasoning course. They students learn about genetics from simulations and by revising given models. Although no statistical evidence about the attitudes of the students was collected, the authors claim to have anecdotal evidence about the high motivation of students who requested extra computer time, and "the pride of ownership and enthusiasm that the students had for their work and for the genetics class".

More observations of students' motivation about model-based curricula can be found in White & Frederiksen (1998) and White (1993), for example. In White & Frederiksen (1998), a study about a model-based curriculum is described in which previously low-achieving students performed remarkably well. One reason given for this good performance is their higher motivation which showed in a higher report hand-in rate. However, this is attributed to the "reflective assessment" which encourages students to reflect on the inquiry process, rather than to the use of modeling. Similarly, in White (1993), the authors report about the activities in a model-based curriculum that "if done well, students are highly motivated". The role of the models is difficult to discern, though, as this statement is made about scaffolding for inquiry learning as a whole.

In their comparison of students who are doing well and less well in quantitative modeling, Hogan & Thomas (2001) describe how the students' view of themselves, their interests and their capabilities ("self-efficacy" and "self-schema") influence their modeling behavior. The less successful students showed low "volition", i.e. perseverance and concentration, and believed that they are not "science types" and "visual and not mathematical", and likewise had doubts about their abilities to figure out the maths. The authors suggest that for encouraging the students to model, it would be helpful to let students work with more familiar, non-science related models, as "everyday or social systems that interest them".

3.2 Learning Domain Content

3.2.1 Understanding the Behavior of Complex Dynamic Systems

In van Borkulo (2009) two studies that show the benefit of modeling on learning complex system behavior are described. Both of the studies were conducted using "Co-Lab", a modeling tool that supports qualitative and quantitative reasoning, for the training sessions and concept maps for evaluation.

In one study van Borkulo (2009) compared the learning of two groups of students working in different conditions: The group in the "expository mode" was presented information in textual form with additional guidance in the form of assignments but no further tools; the group in the "modeling mode" worked in a guided inquiry approach, supported by modeling and simulation tools. Afterwards, the students were tested on domain-specific knowledge. Overall, the results showed no significant difference between the performance of both groups with a trend to a better performance of the modeling students. However, for the complex test items, the modeling students performed significantly better overall and for the "reproduce" and "evaluate" criteria. A possible explanation that is given is that complex conceptual knowledge depends more on reasoning skills than on simple reproduction. This might have worked in favor of the modeling students who are more trained in that respect. We can attribute the observed improvement of reasoning on the representation and the interaction with the simulation tool.

In a similar study, van Borkulo (2009) compared the performance of a group of students working with simulations and a group building their own models. Overall, the modeling group was better in the assessment of complex problems, specifically in applying complex knowledge and in creating simple models. The students in the simulation group performed better in reproducing simple conceptual knowledge. The results were as predicted, and were explained by the modeling students learning to reason step-by-step, while the simulation students only focused on the end points of the simulation which they tried to remember.

3.2.2 Causality

The focus of the research of Frederiksen & White (2002) was the use of multiple subject representations and the links between them for learning about the behavior of electrical circuits.

The authors' goal was to bridge the gap between the students' understanding of the behavior of an electrical circuit as it is happening physically and the numerical equations used to describe the behavior. For that, a curriculum running through a chain of increasingly abstract models was used, connecting microscopic circuit behavior (e.g. electrons repelling each other) with macroscopic circuit behavior (e.g. voltage distribution). The researchers investigated the importance of the links between these models varying the students view on one of the models. This model, the "Local Flow Model" connects the less abstract model ("particle interaction model") with the more abstract models (functional and rule-based models) by letting students reason about parallel local events in the circuit and their cumulative effects. One group of students (the transient group) watched a simulation of the local flow model that showed the transitions from the starting to the ending state of the circuit, i.e. how the iterative application of the flow equation leads to a final state of the circuit in which voltages and currents follow those laws. The other group (the steady-state group) were only shown the starting and the end states.

The students of the transient group showed a better understanding of the local flow model and significantly outperformed the students of the steady-state group in the assessment of the qualitative and quantitative reasoning about the circuit behavior. In other words, the better the understanding of the models involved was and the better connected the different problem representations were, the better the reasoning about the circuit behavior showed to be. The model representations that were used at the different levels of abstraction served as causal models for physical mechanisms in the electrical circuit.

3.2.3 Knowledge Transfer

More work on causality was done in Schumacher & Gentner (1988) in the context of the authors' work on analogies. They studied the relevance of "systematicity" in learning how to operate a device (the base) and in transferring this knowledge to the use of another device (the target). In the experiment, the students in the systematic condition were provided an explicit causal model while the students in the nonsystematic condition did not. The results showed that the students in the systematic condition learned the base model faster and hence, "giving a coherent causal model of a device helps initial learning of the device". Moreover, systematicity had a strong effect on transferring the knowledge to the target device.

Schumacher & Gentner conclude that "possessing a well-structured model for a device aids in transferring knowledge from one device to another", i.e. that understanding causal relationships helps in transferring knowledge to new problems.

3.2.4 Scientific Process

Schwarz & White (2005) did an experiment with a model-based curriculum which emphasized knowledge about the modeling process. The curriculum was a modification of a previously used model-based curriculum with the addition of the focus on metamodeling knowledge; another innovation was that the students built their own models by expressing their ideas in qualitative rules which assembled to the students' own runnable models and could be compared to "another" model which was actually the Newtonian model. In the old version of the curriculum, students used given simulations and constructed rules that were discussed in class, but not realized in a computer model.

The new approach of teaching with modeling was successful, as an increase of the students' knowledge about modeling, inquiry and physics content between the pre- and post-test was found. The overall increase of performance in the assessment of inquiry skills was insignificantly higher from what had been observed with the old version of the curriculum. However the students from the study with the new curriculum did better when it came to drawing conclusions from the findings from their investigation, and performed better in a far transfer problem. This improvement is attributed to a better understanding of the modeling process caused by the emphasis on it in the teaching.[3]

3.2.5 Integrating Knowledge

An indication that modeling encourages the integration of new knowledge into previous knowledge can be found in Sins et al. (2005). In this study, the behavior of successful novice modeling students working with quantitative models was compared to the work of less successful students. One result is that the most successful group is the only one that makes use of prior knowledge for their argumentation. The quantitative analysis of a bigger student population shows that in general groups hardly refer to prior knowledge. Still, we

[3] In the discussion of the results the major focus is on the metamodeling knowledge. It would certainly have been interesting to consider that the students in the given study built their own models while in the old curriculum they did not.

think we can still see it as an example of how students can be stimulated to integrate old and new knowledge by the use of modeling; we expect that this is possible with appropriate scaffolding.

4 Using Qualitative Representations for Learning

What has been studied about the role of qualitative representations in learning? There have been several studies in which the role of qualitative representations have been given special attention.

4.1 Coordinating Qualitative and Quantitative Representations

Ploetzner & Spada (1998) investigated to what extent qualitative and quantitative representations are complementary and in particular how quantitative representations can be rooted in qualitative problem representations. They used a cognitive simulation (Sepia) to predict quantitative problem solutions based on qualitative representations, including common misconceptions in the qualitative knowledge. The simulation predicted that students with misconceptions in the qualitative representations would either reach an impasse, i.e. not find a solution, or show inefficient problem solving behavior and possibly an incorrect solution.

In a study the authors compared students' problem solving behavior to the behavior predicted by the simulator and, as predicted, the students who showed a misconception in the qualitative knowledge either reached an incorrect or no solution. The low number of students that did reach a correct solution in spite of a misconception bent their qualitative knowledge to find a quantitative solution. Another observation was that misconceptions in the qualitative knowledge surfaced for most of the students although the problem required a precise quantitative solution and not explicitly a qualitative one.

Beyond the discussion about how the cognitive simulator Sepia can be used as part of a learning environment, the authors found that students have to learn how to coordinate (partial) qualitative and (partial) quantitative representations of problems in order to solve problems successfully. While in the beginning of the learning process students try to apply purely quantitative representations, which only works for very simple problems, their performance first goes down when qualitative representations are needed for solving the problems, and misconceptions surface. The performance increases as the students learn how to coordinate the two representations.

4.2 The Effect of Representations on the Students' Reasoning

Löhner et al. (2005) present an experiment in which they investigated how the reasoning behavior of students in an inquiry-learning activity differs depending on the representation in the modeling tool they are using. One group of students worked with a textual quantitative modeling tool requiring the input of exact algebraic formula for describing the system and its behavior. This group was compared to another group of students working with a graphical semi-quantitative modeling tool which allowed them to describe the system more freely.

The results show that actually the students in general did not follow the standard inquiry process, and most of them did not formulate hypothesis for their experiments. Students working with the graphical tool "designed more experiments with their own model; formulated more qualitative hypotheses; spent more time evaluating their own model, and supported their hypotheses more often by reasoning with a mechanism." Students working with the formula based tool "formulated more quantitative hypotheses than students in the graphical condition and formulated hardly any qualitative hypotheses". About the modeling activity itself it is said that "students in the graphical condition ran more models, tried more different relations and ran more system simulations. Moreover, in the graphical condition, the resulting students' models were on average closer to the target model". Lastly, students in the graphical conditions attained a better score in the quality of their models and a non-significant trend of hypothesizing generating better models was found. Finally, we want to mention that for our conclusions about qualitative models it might be a problematic point that in this study not only a qualitative representation was compared to a quantitative one, but that these representations were connected to the graphical and textual presentation of the model.

4.3 Problems in Quantitative Modeling

A study which only indirectly belongs to this section about qualitative models is described in Hogan & Thomas (2001) as it is looking at the behavior of novices while building quantitative models. The quantification of the models was a problem for the weaker groups. For example, when it came to putting in numbers for quantities, the successful students selected numbers that made sense relative to another. In contrast, the other students tried to find numbers from the real world rather than relative ones which resulted in difficulties in

exploring the system. Moreover, groups "showed a lack of sensitivity" about the influence of the equations on the system. The authors conclude that when working with modeling in education, support for model quantification should be provided.

A similar result was obtained by Sins et al. (2005) who looked at the problems of novice modeling students working with a quantitative model. One observation was that the less successful students tried to fit their model to the experimental data rather than trying to understand the behavior of the system as a whole.

5 Summary and Discussion

5.1 Summary of Findings

5.1.1 Curricula

How is modeling established in curricula?

The review of guidelines for implementing model-based curricula showed that a very important motivation for using modeling is the goal of teaching modeling as part of scientific inquiry in order to give the students insight into the nature of science (Wells et al., 1995; Schwarz & White, 2005). In addition to that, modeling is expected to give a representation of the students' ideas and to help them to structure and revise knowledge (Wells et al., 1995). Moreover, models are seen as an essential part of the solution to problems (Wells et al., 1995). Finally, models are expected to facilitate interactivity and by that emphasize the students' own experience (Gibbons, 2001).

While the model-based design does not specify any type of model to be used, in both of the other approaches the qualitative properties of the models are emphasized. In the modeling circle, it is pointed out that a qualitative understanding of the problem is important; from the students, a model is required as part of the answer to a problem, even when the final solution is a numerical one. In the model-enhanced ThinkerTools curriculum, a qualitative modeling is developed by the students.

5.1.2 Studies

What are the benefits of using modeling in education as shown in studies?

The studies about the general effects of models on learning, showed that models support improving scientific reasoning skills by serving as representations which the discussion and revision of students' ideas can be based on (Wells et al., 1995). Model-based activities seem to have a positive effect on students' motivation, even though studies suggest that this effect might result from the curriculum design as a whole rather than the models only (Stewart et al., 1992; White & Frederiksen, 1998; White, 1993); another positive influence on the attitude of the students toward the modeling activities might be the selection of the subject of modeling (Hogan & Thomas, 2001).

Learning domain content is supported by modeling because students' reasoning skills improve and students can rely on these skills rather than on reproduced of knowledge when

it comes to understanding the behavior of complex dynamic systems (van Borkulo, 2009). Another important factor for understanding system behavior is causality which connects different representations of a system and the behavior that is caused by a given structure; understanding causality is supported by the use of models (Frederiksen & White, 2002). Causality has also been shown to be beneficial for transferring knowledge to new problems (Schumacher & Gentner, 1988). Moreover, learning about the modeling process improved students inquiry skills (Schwarz & White, 2005). Finally, we found some indication that models might be useful to encourage the integration of old and new knowledge (Sins et al., 2005).

In these general studies, the differentiation between qualitative and quantitative models is not the main issue. The main point made is that it is important to have some, and if possible more than one, representation which is most effective when it is built by the students themselves and can be run. Indicators for the relevance of qualitative models again can be found in Wells et al. (1995) where it is emphasized that a numerical solution of a problem is not sufficient, and the students should have a qualitative understanding of their results. Moreover, we understand that the typical causal models that connect representations and explain the behavior of a system are of qualitative nature.

5.1.3 Qualitative vs. Quantitative Representations

What has been studied about the role of qualitative models in learning?

When looking at studies about qualitative representations as compared to quantitative representations, we found that students need to develop a correct qualitative representation in order to solve complex quantitative problems correctly (Hartley, 1998). Students showed a different way of reasoning when working with a semi-quantitative, graphical modeling tool than when working with a text-based, quantitative modeling tool; they formulated more and better supported hypotheses, and spent more time evaluating their models (Löhner et al., 2005). Lastly, a study about quantitative modeling showed that exactly the quantification of the models causes problems to novice modeling students, and requires extra scaffolding (Hogan & Thomas, 2001); quantitative modeling also entails the danger of encouraging students to fit their models to the given data rather than making sense of the system behavior as a whole (Sins et al., 2005).

These findings suggest that qualitative models are a necessary basis for quantitative problem-solving. Moreover, qualitative modeling gives students more freedom in creat-

ing and playing with different hypotheses and simulations, and gives focus to the overall behavior of the system.

5.2 Discussion

What is the role of qualitative models in learning system behavior?

With only one exception (Hogan & Thomas, 2001), the publications we reviewed about the three sub questions contain some agreement that supporting students in developing a qualitative understanding of systems is important.

The role that the qualitative models play differs from paper to paper. We found the following points of consensus:

1. A qualitative model of a system is required for understanding the behavior of a system, even if it is "only" for explaining quantitative representations with it (Wells et al., 1995; Ploetzner & Spada, 1998);

2. Quantitative modeling entails problems with the quantification of models for modeling novices (Löhner et al., 2005; Hogan & Thomas, 2001; Sins et al., 2005). Qualitative representations foster the experimental reasoning of students (Löhner et al., 2005).

Furthermore, we found that in general the use different representations of systems and relations, in particular causality, are beneficial for learning and transferring knowledge to new situations (Wells et al., 1995; Hartley, 1998; Frederiksen & White, 2002; Schumacher & Gentner, 1988). In the literature we reviewed causality was represented in causal models, however, in this context we did not encounter evidence about the role of the qualitativeness itself.

We conclude that the role of qualitative models is to provide a fundamental basis for the understanding of system behavior, and to serve as representation of the subject and the students' understanding. Moreover, the activity of qualitative modeling takes the burden of quantification from novice modeling students and supports a holistic view of the behavior of the system.

5.3 Further Work

For gaining further insight into the topic, we recommend to separate the research into two strands: First, we would investigate the role of developing qualitative models as part of the modeling process; relevant to this topic should be the work about mental models, (e.g. Collins & Gentner, 1987; Wenger, 1987; Darabi et al., 2009), for example. Second, we would look at the use of qualitative and quantitative modeling tools in educational settings and the benefits and problems that arise with it.

Another interesting topic which was only a side issue for our literature review, is modeling for the sake of modeling, and the role of different representations for it.

6 Reflections

What have I learned from the literature review process? The main impression I am finishing my work on this paper with, is that the planning should have been better. 6 ECTs stand for 168 hours which are 21 working days which are about 4 weeks of work. Doing the planning for such a short time should be possible. However, the work took me longer than expected, and at a certain point my planning turned out to be futile.

The following points are a collection of what I think I should have done better and should be of advice for others:

1. Choose a precise research question. If there are doubts about the feasibility of the research, refine the question; use sub questions if necessary.

2. Decide on a structure of the paper and the way the review will be presented: review article after article or fit the findings from the articles into an own line of reasoning.

3. Set goals and a method for the literature search: How to know that enough literature is covered? How to make sure the literature used is relevant? Dare to stop searching.

4. Plan time for searching, reading and writing. Leave some buffer, e.g. for including very important literature later. Make the planning concrete and set realistic, testable goals. Keep track of the planning.

5. Do not waste time on tools.

6. Learn speed-reading.

Beyond the practical issue of planning, I have learned that computer modeling is a field of research that is being investigated from different perspectives; modeling is already applied in classrooms, tools for modeling are developed, and research about how modeling influences cognitive processes is done. The groups also contribute to improvements of science education from different perspectives, and they can do it most effectively if they work and move forward together.

References

Bliss, J., Ogborn, J., Boohan, R., Briggs, J., Brosnan, T., Brough, D., Mellar, H., Miller, R., Nash, C., Rodgers, C., & Sakonidis, B. (1992). Reasoning supported by computational tools. *Computers & Education*, *18*(1-3), 1 – 9.
URL `http://www.sciencedirect.com/science/article/B6VCJ-468CM4M-19/2/6c046cd0709e8fc3f898456aebb88246`

Bredeweg, B., & Winkels, R. (1998). Qualitative models in interactive learning environments: an introduction. *Interactive Learning Environments*, *5*(1), 1–18.

Bruner, J. (1966). *Toward a theory of instruction*. Belknap Pr.

Collins, A., & Gentner, D. (1987). How people construct mental models. In *Cultural models in language and thought*, (p. 243). Cambridge University Press.

Darabi, A. A., Nelson, D. W., & Seel, N. M. (2009). Progression of mental models throughout the phases of a computer-based instructional simulation: Supportive information, practice, and performance. *Computers in Human Behavior*, *25*(3), 723 – 730. Including the Special Issue: Enabling elderly users to create and share self authored multimedia content.
URL `http://www.sciencedirect.com/science/article/B6VDC-4VRNNKS-2/2/c9a01a8015d9b87a4ad9bb58f25998b5`

de Kleer, J. (1990). Qualitative physics: A personal view. In D. S. Weld, & J. de Kleer (Eds.) *Qualitative Reasoning about Physical Systems*, chap. introduction, (pp. 1–8). Morgan Kaufmann Publishers.

Forbus, K. (1996). Why computer modeling should become a popular hobby. *D-Lib magazine*.
URL `http://www.dlib.org/dlib/october96/10forbus.html`

Frederiksen, J., & White, B. (2002). Conceptualizing and constructing linked models: creating coherence in complex knowledge systems. In P. Brna, M. Baker, K. Steuning, & A. Tiberghien (Eds.) *The role of communication in learning to model*, (pp. 69–96). Lawrence Erlbaum Associates.

Gibbons, A. S. (2001). Model-centered instruction. *Journal of Structural Learning and Intelligent Systems*, *14*, 511–540.

Halloun, I., & Hestenes, D. (1987). Modeling instruction in mechanics. *American Journal of Physics*, *55*, 455.

Hartley, J. (1998). Qualitative reasoning and conceptual change: computer based support in understanding science. *Interactive Learning Environments*, *5*(1), 53–64.

Hestenes, D. (1987). Toward a modeling theory of physics instruction. *American journal of physics*, *55*(5), 440–454.

Hogan, K., & Thomas, D. (2001). Cognitive comparisons of students' systems modeling in ecology. *Journal of Science Education and Technology*, *10*(4), 319–345.

Jonassen, D. (2003). Using cognitive tools to represent problems. *Journal of Research on Technology in Education*, *35*(3), 362–381.

Karplus, R., & Butts, D. P. (1977). Science teaching and the development of reasoning. *Journal of Research in Science Teaching*, *14*, 169–175.

Kearsley, G. (2009). The theory into practice database: Model-centered instruction and design layering (andrew s. gibbons). Accessed 24/05/2009.
URL `http://tip.psychology.org/gibbons.html`

Löhner, S. (2005). *Computer-based modeling tasks: The role of external representation*. Ph.D. thesis, University of Amsterdam.

Löhner, S., van Joolingen, W. R., Savelsbergh, E. R., & van Hout-Wolters, B. (2005). Students' reasoning during modeling in an inquiry learning environment. *Computers in Human Behavior*, *21*(3), 441 – 461.
URL `http://www.sciencedirect.com/science/article/B6VDC-4DVVYK1-3/2/802761aec4b847cb7709df34dbf970af`

Ploetzner, R., & Spada, H. (1998). Constructing quantitative problem representations on the basis of qualitative reasoning. *Interactive Learning Environments*, *5*(1), 95–107.

Schumacher, R., & Gentner, D. (1988). Transfer of training as analogical mapping. *IEEE Transactions on Systems, Man and Cybernetics*, *18*(4), 592–600.

Schwarz, C., & White, B. (2005). Metamodeling knowledge: Developing students' understanding of scientific modeling. *Cognition and Instruction*, *23*(2), 165–205.

Sins, P., Savelsbergh, E., & van Joolingen, W. (2005). The difficult process of scientific modelling: An analysis of novices' reasoning during computer-based modelling. *International Journal of Science Education*, *27*(14), 1695–1721.

Spector, J. (2008). Cognition and learning in the digital age: Promising research and practice. *Computers in Human Behavior*, *24*(2), 249–262.

Stewart, J., Hafner, R., Johnson, S., & Finkel, E. (1992). Science as model building: Computers and high-school genetics. *Educational Psychologist*, *27*(3), 317–336.

van Borkulo, S. P. (2009). *The assessment of learning outcomes of computer modeling in secondary science education*. Ph.D. thesis, University of Twente.

Van Joolingen, W., de Jong, T., & Dimitrakopoulou, A. (2007). Issues in computer supported inquiry learning in science. *Journal of Computer Assisted Learning*, *23*(2), 111–119.

Wells, M., Hestenes, D., & Swackhamer, G. (1995). A modeling method for high school physics instruction. *American Journal of Physics*, *63*(7), 606–619.
URL `http://link.aip.org/link/?AJP/63/606/1`

Wenger, E. (1987). *Artificial intelligence and tutoring systems*. Morgan Kaufmann Publishers.

White, B. (1993). ThinkerTools: Causal models, conceptual change, and science education. *Cognition and instruction*, *10*(1), 1–100.

White, B. Y., & Frederiksen, J. R. (1998). Inquiry, modeling, and metacognition: Making science accessible to all students. *Cognition and Instruction*, *16*(1), 3–118.
URL `http://www.jstor.org/stable/3233668`