Perspectives on an integrated computer learning environment

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Chapter 1

Introduction

This thesis is about my research and development work in the last decade that aimed at improving the contribution of information and communication technology (ICT) to inquiry-oriented mathematics and science education at secondary school level.

I focussed in my development work on the design and implementation of an integrated computer environment for learning mathematics and science in an inquiry-oriented approach. Much of this was realized in the environment named COACH (Heck, Kędzierska, & Ellermeijer, 2009), which has been under continuous development in the past twenty-five years at the University of Amsterdam. This hardware and software environment can be described in one sentence as a single, activity-based, open computer working environment that is designed for the educational setting and that offers its users a versatile set of integrated tools for the study of natural phenomena, mathematics, science, and technology. The versatility of the tools offered to students and teachers is illustrated by the following application areas: data collection (through measurement with sensors or collection of data on video clips and digital images); control of processes and devices; processing and analysis of data; construction, simulation, and validation of computer models; design, implementation and use of model-based animations; authoring of activities; and reporting of results. In this thesis I report on my contributions to the video analysis tool, the data processing and analysis tools, and the modeling tool. Part of my development work also concerned the design of sample activities for the purpose of exploring the potential of new and improved tools.

My research activities were mainly exploratory case studies on the performance of secondary school students and the usability of developed tools in ICT-supported practical investigation tasks in the classroom and in out-of-school research projects. In most of these studies, pre-university (vwo) students carried out quantitative mathematical modeling activities using ICT, that is, they explored mathematical models with the support of ICT tools in order to come to grips with natural phenomena and to interpret real data. By real data I mean data collected by students in experiments and secondary data originating from professional empirical research. I speak of practical investigations instead of investigations to emphasize that students often did experiments or practical exercises and used tools in their investigative work. My exploratory case studies served many goals: (1) They were meant to gain insight in the needs of secondary school students for doing authentic inquiry work. (2) They helped me specify requirements for an integrated computer learning environment from a mathematical point of view. (3) They served to test the usability and scope of (prototypical) implementations of particular tools for collecting, processing, and analyzing data. (4) They gave an impression of the potential of ICT regarding the realization of challenging, cross-disciplinary practical work in which secondary school students were engaged in activities such as experimenting, data collection and data analysis in much the same way as scientists and practitioners.

In summary, my research and development work was set up to contribute to many perspectives on ICT-supported practical investigations and research projects at upper secondary level. Its scope was limited to educational and software design perspectives on ICT use in inquiry activities in which students learn to apply and deepen their knowledge of mathematics and science. In fact, its main focus was on ICT-supported practical investigations and research projects at pre-university level in which students' work resembled the ways in which scientists explore phenomena.

This introductory chapter is organized as follows. Regarding the motivation and scope of my research and development work, I describe the main components of the multiform context of my study. To this end, I present in the first section the educational context, and especially changes in the Dutch curricula for pre-university mathematics and science education in the last decade. In the second section I go briefly into previous research and development work at AMSTEL (Amsterdam Mathematics Science and Technology Education Laboratory) that laid the foundations for my study. In the third section I point at the multiformity of ICT tools for secondary mathematics and science education and at the differences between ICT usage in these disciplines, which called for an investigation into the possibilities of an integrated computer environment for learning and doing both mathematics and science. In the fourth section I describe the aims and set-up of my research and development work. Finally I outline the structure of this thesis.

1.1 Educational Context

In this section I give a general perspective on the changes in upper secondary mathematics and science education that were relevant for my research and development work and that took place from 1998 until 2011. In particular, the following two changes had a large impact on my research and development work: (1) the new organization of the upper secondary education system as 'Tweede Fase' (Second Stage), which emphasizes a broad general education preparing students for modern society and which aims at improvement of the coherence between subjects by clustering them in four profiles; and (2) the advocacy of pedagogical reforms, lumped together as the 'Studiehuis' (Study House) concept, in which self-regulated learning and competencies (including inquiry skills and ICT skills) are emphasized in order to better prepare students for higher education and for life-long learning. These innovations in secondary education coincided with large investments in infrastructure (computers and networks) and in schooling of teachers and managers, and with curriculum reforms for mathematics and science. These changes at organizational, pedagogical, and curricular level created new opportunities for realizing ICT-supported practical work by students in mathematics and science education. With this in mind I briefly discuss seven aspects of the educational context in which my R&D work took place.

1. The Introduction of Profiles

Until 1998, upper secondary students had been free to pick their own combination of examination subjects. This free choice was replaced by a selection of one of four fixed subject combinations. These so-called profiles are: (1) Nature and Health; (2) Nature and Technology; (3) Economics and Society; and (4) Culture and Society. The first two profiles form the category of Nature Profiles; the last two profiles are categorized as Society Profiles. All profiles consist of a common core of subjects plus a number of specialized subjects and an optional component. The common core of subjects provides transferable knowledge and skills of general value and is expected to prepare students for modern society. Mathematics is no part of the common core but a compulsory specialized subject in all profiles. The specialized subjects in the profile determine for which higher education studies a student can apply. The optional part allows individual accents: A student has some freedom in the selection of two more subjects, depending on the school policy and on the personal abilities and interests.

The main motives for the introduction of profiles were to ensure that students would follow a coherent study programme and would be better prepared for higher education, which would hopefully lead to an increased success rate in higher education. Practical investigations and the so-called profile project, which is a rather large research or design project that students conduct at the end of their school career, were introduced so that students could demonstrate competencies that they had acquired through education. More freedom was built into the profiles in order to accommodate individual differences of students and to offer school opportunities to stress distinctive features.

The introduction of the Nature Profiles in the Second Stage was relevant for my research and development work because a coherent study programme offers teachers and students opportunities to engage in activities that draw upon more than one discipline. For example, in comparison with the situation before the introduction of the Second Stage, one may expect that it is easier for students in the Nature and Technology profile to study a cross-disciplinary topic because they share a common core of basic knowledge of mathematics and science, due to the fact that they have all received instruction in mathematics, physics, and chemistry. If the ideal of a common core of transferable knowledge and skills is not yet realized in school because of different instructional approaches in the various disciplines, it seems at least possible (though not easy) through a team effort of teachers to gear the disciplines for one another. This goal was one of the motives for my R&D work toward an integrated computer environment for learning mathematics and science in an inquiry-oriented approach.

2. The Change of Content in Mathematics Education

The contents of many subjects in Dutch secondary education have changed substantially in the last decades, but this holds in particular for mathematics and science education. For example, the introduction of the Second Stage in 1998 implied the introduction of new national curricula for mathematics and science. More recently, the introduction of the Renewed Second Stage in 2007 coincided with the introduction of the concept-context approach by science curriculum innovation committees. In this subsection I only point to major changes in Dutch mathematics education, acknowledging that the changes in science disciplines were large as well, because I expect that this sufficiently helps the reader comprehend the context of students' practical investigations and profile projects falling in the category of quantitative mathematical modeling using ICT. In science subjects, practical work of students already existed before the introduction of the Second Stage in the form of descriptive investigations, with an emphasis on observing and reporting about it, and practical investigations, with an emphasis on performing a practical experiment in the school laboratory. In mathematics education, investigative student work was new.

In mathematics education, a problem-oriented approach focusing on application and modeling was introduced in the Netherlands in 1989, when the mathematics curriculum taught at secondary school was split into two types, namely, Mathematics A and B. The introduction of Mathematics A, which had been developed for students preparing for studies in economics, social sciences, and humanities, reflected the international trend to emphasize that everyone must have some minimal mathematical, scientific, and technological knowledge and skills, as well as insight in applications of mathematics, science, and technology in order to take fully part in the modern society (cf., Osborne & Hennessy, 2003). In practice, Mathematics A was application-oriented by means of context problems from daily life (See, for example, Doorman et al., 2007; Van den Heuvel-Panhuizen & Wijers, 2005). The content of Mathematics B initially remained more classical and essentially consisted of the mathematics that was considered necessary for technical studies and studies in mathematics and science at university level. Gradually, context problems also found their way into Mathematics B and many mathematical concepts (for example, differentiation and integration) were placed in a framework of application of mathematics. Thus, problem solving in the sense of solving 'real world' problems using mathematics was introduced in both mathematics curricula. I deliberately write 'real world' between quotes because the contexts were and still are often criticized as being rather stretched and artificial. More realistic applications of mathematics and non-trivial problem-solving activities for which students do not yet have a routine solution strategy seemed mainly realizable in practical investigations and student research projects, once these curriculum elements had been introduced in the Second Stage.

The mathematics curricula were drastically restructured in the Renewed Second Stage, which started in 2007. They were replaced by profile-specific curricula called Mathematics A (Nature and Health, Economics and Society), Mathematics B (Nature and Technology), Mathematics C (Culture and Society), and Mathematics D (optional mathematics for the Nature and Technology profile), which all have their own aims and content. What the intended curricula unites is the vision that

> "mathematics education needs a good balance between mathematics as an independent discipline—a way of thinking in which abstraction, generalization, and formal manipulation play an important role—on the one hand, and mathematics as an instrument for modeling problem situations, as a tool that can be applied in practical, technical, and scientific situations. The calibration of this balance will differ on school type and profile."

The above statement is Viewpoint 2 of the vision document 'Rijk aan betekenis' (cTWO, 2007) of the mathematics curriculum innovation committee cTWO, summarized and elucidated by Siersma and Drijvers (2007). In pre-university education, Mathematics A should prepare students for university studies with social, economic, business, or medical-biological characteristics. The intended curriculum has a content that focuses on applied analysis, statistics and probability, and uses concrete applications to build mathematical concepts. Mathematics B should prepare students for studies in exact or technical sciences. The intended curriculum has a content in which analysis and geometry are emphasized with sufficient attention to algebraic skills, formula manipulation, reasoning, proofs, and applications in authentic situations. It uses the coherence of mathematics to build mathematical concepts, and it aims at an improvement of the transfer of knowledge and skills to and from science subjects taught at school. Mathematics D is an optional subject that aims at deepening of understanding and extension of mathematical knowledge and skills. cTWO has identified in both Mathematics B and D activities like structuring and abstraction, logical reasoning and proving, analytical thinking, modeling, and problem solving to form the thread through the curriculum. These activities, which are referred to as the central mathematical thinking activities, are linked with the core concepts of number, formula, function, change, space, and chance. Despite the differences between the four mathematics curricula it is fair to say that in all of them application of mathematics and mathematical modeling are considered key elements.

All practical investigations in the classroom and all out-of-school profile projects reported about in this thesis were carried out by students with a Mathematics A or B background (both before and after the renewal of the Second Stage), or took place in the context of Mathematics D. All activities fell in the category of ICT-supported quantitative mathematical modeling. Naturally, the increased interest of curriculum developers, researchers, and teachers in applied mathematical modeling, in computer-based modeling using a system dynamics approach, and in having students actively engaged in the full modeling cycle was relevant for my R&D work. As a matter of fact, many of the practical investigations carried out in the classroom were designed in such way that students were expected to be able to come to grips with a problem situation by applying their mathematical knowledge and skills in non-routine ways.

3. The Increased Emphasis on Competencies

The mathematics curricula in the Second Stage originally had a common set of skills in which the balance was more on the side of task-oriented performances than on cognitive abilities, probably because such skills were considered as trainable and easier to assess. They were grouped into four categories: (1) information skills; (2) research skills; (3) technical-instrumental skills; and (4) orientation toward tertiary education and profession. The skills were described via rather detailed attainment targets. Looking at the attainment targets regarding research skills (Kok, 1996), I cannot escape the impression that they were based on the idea that doing research is a body of techniques that can all be learned by practice. In this perspective, a person who has mastered the relevant techniques can successfully do research. However, there is no empirical evidence for this process approach. In my view, strong mathematical knowledge and skills are necessary, but not sufficient conditions for being able to conduct a real mathematical investigation.

The same idea of the existence of a body of essential techniques for doing research underpinned the listings of attainment targets for biology, chemistry, and physics (Gravenbergh, 1996). All lists contained detailed attainment targets that reflected the following steps in the so-called scientific method:

- Formulate a research question.
- Set up a hypothesis.

- Design and carry out an experiment to test the hypothesis.
- Make relevant observations and collect data.
- Analyze data and draw conclusions.
- Report results.

There is in fact not much evidence for the existence of a general scientific method applicable to a broad range of science fields (cf., Hodson, 1998). Actually the steps listed above constitute a rather simple descriptive model of actions that one can identify when experienced researchers are at work and that they do in an iterative or otherwise non-linear process. But even without the existence of a standard procedure with determined outcomes, it may give adequate guidance and scaffolds to students in learning to do investigative work and it may be more effective than a discovery approach in which students have to find out autonomously what doing scientific research means (cf., Kirschner, Sweller, & Clark, 2006; Mayer, 2004). It may provide students and teachers a practical scheme to organize work in a profile research project. For example, it may help students split their work into parts with short-term goals and intermediate products such as a work plan, literature review, a research question, a hypothesis, or a formulation of expectations about results, a research design, an overview of collected data, and so forth. These intermediate products are all concrete results of work that can be discussed with the teacher, who can point out strengths and weaknesses, make suggestions for improvements, guide students into new directions, and may use the intermediate results as a basis for the assessment of the students' process of doing research. The empirical fact that many schools and teachers apparently organize the profile projects of their students in this way is reflected in the common structure of many profile reports.

The original listings of detailed attainment targets for skills that students are expected to acquire or improve through education did not promote coherence in the mathematics and science education and they gave students a limited, fragmented view of the various disciplines (cf., Hodson, 1998). This was recognized by the Dutch curriculum innovation committees and they jointly reformulated the entire skills domain for the new curricula in similar, less detailed terms. Regarding research abilities it was brought more in line with a holistic view on processes in science education and on investigations by students, and with the currently more popular opinion that "students learn to do scientific investigations by actually doing scientific investigations, simple ones at first but complete investigations none the less, becoming more sophisticated as confidence and experience increase" (Woolnough, 1989, p. 121). This perspective on practical work by students emphasizes a shift toward realistic investigative tasks and higher-order learning goals, such as acquisition of scientific literacy, inquiry abilities, and a hands-on + minds-on mentality. From this viewpoint, students are encouraged to explore mathematics and science in authentic problem situations and to acquire and practice in this way several competencies, with the main role of the teacher to help students learn to do scientific inquiry of good quality.

The new broad formulation of research abilities, did not release curriculum developers and educational researchers from being specific about their interpretation of terms like scientific inquiry, scientific investigations by students, and quality of research. In practice, they often returned to statements that refer to the way scientists and practitioners do research, presented in an idealized form as an inquiry cycle (similar to the scientific method), and to statements that advocate inquiry-based or problem-based teaching and learning of mathematics and science (See, for example, Lederman, 2004). Various pedagogical models for inquiry were developed in the past, for example, discovery learning, guided inquiry learning, and the learning cycle. When a learning cycle was used to structure inquiry-based lessons it reflected more or less the selected definition of the inquiry cycle. As Lunetta, Hoffstein, and Clough (2007) found in an extensive review of the literature about inquiry learning and teaching at secondary school, this quite often still led to listings of essential features of classroom inquiry, listings of fundamental abilities required to do scientific inquiry, and to listings of fundamental understandings about scientific inquiry (See, for example, Bybee, 2002; Bybee, Taylor, Gardner, et al., 2006; Llewellyn, 2002; National Research Council, 2000; Wenning, 2005). For judgment of the quality of scientific research, educators and educational researchers made use of listings of features such as the list of concepts of evidence created and maintained by Gott, Duggan, and Roberts (2003).

I did the same for positioning the work presented in this thesis. I framed my research and development work, which aimed at improving the contribution of ICT to inquiry-oriented mathematics and science education at secondary school level, by adopting the following definition of inquiry (Linn, Davis, & Bell, 2004, p. 4):

> "We define inquiry as the intentional process of diagnosing problems, critiquing experiments, and distinguishing alternatives, planning investigations, researching conjectures, searching for information, constructing models, debating with peers, and forming coherent arguments."

Note that this definition of inquiry applies for both mathematics and science. Popular pedagogical approaches that give space to inquiry activities are inquiry-based science education and problem-based learning. In essence they are all problem-based approaches, that is, approaches in which learning begins with a problem to be solved and problems are posed in such way that students need to gain knowledge before they can solve the problem. But inquiry-based science education goes beyond it with the importance given to the experimental approach. In the student inquiry activities that I designed in my research study I did not emphasize the inductive approach in teaching, but focussed more on guiding students to conduct a cyclic and iterative inquiry process and making them aware of the link between modeling and experimenting. Types of investigative classroom activities ranged from structured inquiry, in which students investigated a given problem or question through a prescribed procedure, to guided inquiry, in which students designed or selected procedures to investigate a given problem. Therefore I prefer to speak of inquiry-oriented mathematics and science education. I often used the learning cycle to design practical investigation for students: I structured and analyzed many of the mathematical modeling activities in my case studies on the basis of the modeling cycle of Blum and Leiß (2005, p. 1626).

A third aspect of the increased emphasis on competencies in secondary mathematics and science education was the general acceptance of the role of ICT to support the learning process of the students while doing research activities. All competencies-related aspects put together can be looked upon as ingredients of the third stage in the gradual change in educational research and practice from attention on knowledge transfer, through education based on information-processing learning theories, toward a focus on knowledge construction as the underpinning cognitive theory on learning and instruction. This change did not only take place in the Netherlands, but actually on an international scale in various forms (cf., Steffe & Gale, 1995, and references herein), although the road to educational practice is still long and not always clearly visible. In this thesis I describe the steps I made on the road toward what could be labeled as ICT-supported, inquiry-oriented mathematics and science education. In particular, I describe my contribution to the design, implementation and evaluation in school practice of an integrated computer learning environment that is meant to:

- facilitate the students' construction of in-depth and integrated understanding of mathematics and science concepts and processes through inquiry;
- change the computer into an instrument to explore real-world phenomena;
- involve students in activities similar to what scientists and practitioners engage in and thus lead to authentic mathematics, science, and technology learning. To this end, students are offered tools for collecting, visualizing, processing, and analyzing data, and for creating computational models and animations;
- be universal and applicable at many levels of education, in several curricula, and in various types of instruction, and be adjustable by teachers to their students' abilities.

The last point is important because it allows teachers to organize instruction such that students can first master basic skills and then gradually progress to more complex abilities. Authenticity of student activities is discussed in the next paragraph.

4. The Call for Authentic Student Activities

The original listings of detailed attainment targets for skills that students are expected to acquire or improve through education did not promote coherence in the mathematics and science education and they gave students a limited, fragmented view of the various disciplines. This was recognized by the Dutch curriculum innovation committees and they jointly reformulated the entire skills domain for the new curricula in similar, less detailed terms. For example, all examination programmes for science disciplines used the following statement regarding research: "The candidate can prepare and carry out scientific research, handle the collected research results, and draw conclusions from them." This new formulation of research abilities was more in line with a holistic view on processes in science education and on investigations by students, and with the currently more popular opinion that students learn to do scientific investigations by actually doing scientific investigations. From this viewpoint, students should be encouraged to explore mathematics and science in authentic problem situations, with the teacher merely helping students to learn to do scientific inquiry of good quality.

The new formulation of abilities that students are expected to acquire or improve through education also reflects the current goal of mathematics and science education to increase students' mathematical and scientific literacy. I concur with Hodson (2009) and other educational researchers (e.g., Roth et al., 2008) that there are at least three major goals of mathematics, science and technology (MST) education:

1. Learning MST, by which is meant the familiarity and understanding of ideas and concepts inherent in these fields.

2. Learning about MST, which adopts a much broader view of MST, focusing on the philosophy, history, and methodology of these fields.

3. Learning to do MST, by which is meant that the learner gains the ability to engage in and develop expertise in mathematical and scientific inquiry and in problem solving.

The cited authors distinguished a fourth purpose of MST education, namely, engagement in sociopolitical action, but this hardly played a role in my work. My focus was on providing students with opportunities to experience how mathematics and science is enacted, that is, with authentic mathematics and science, and in particular on providing students with ICT tools that allow them to act as scientists and practitioners (without requiring that they behave exactly as professionals do).

Here, one of the underpinning views is that learning becomes more meaningful when it is done in a context. Authentic learning, interpreted in this thesis narrowly as working on real-world, complex problems, with the goal to come to grips with phenomena through scientific methods, is generally considered to motivate students and to lead to better understanding (Palmer, 2009). From this perspective, the task of the teacher or a developer of instructional materials is to give students ample opportunity to engage inside and outside school in authentic learning activities. The main instructional purposes of the practical investigations in the classroom that I designed and field-tested in my R&D work were to give students opportunities to

- build up general competencies such as research abilities, ICT skills, communication skills, and so on;

- deepen or enlarge existing mathematical and scientific knowledge; and

- become more proficient in applying knowledge and skills in practical situations.

Some of these practical investigations were starting points of profile research projects of students. Notwithstanding that in these cases the student researchers had prepared themselves through a practical investigation, and notwithstanding that their project was part of the examination programme for which a sufficient mark was needed for obtaining a secondary school diploma, I considered these student research projects to have still many characteristics of authentic activities. For example, the students had indeed to demonstrate the achieved level of knowledge, skills, and attitude in the form of a research report or a presentation of original work on a topic of their own choice. They had to demonstrate their research abilities, ranging from choosing a manageable problem, formulating a good research question, and structuring their work to drawing conclusions and presenting the results. Like many curriculum developers and teachers would do, I saw the projects still as a chance to expose students to the real world of research and design, and as an opportunity to let students enjoy doing research and development on a subject they personally relate to.

At this point it is good to realize that researchers on mathematics and science education use the adjective authentic in various ways. They use terms like authentic science, authentic practice, authentic learning, authentic inquiry, authentic modeling, and so on (See, for example, Edelson & Reiser, 2006; Palm, 2002; Roth, 1995; Roth et al., 2008; Schwartz & Crawford, 2004; Vos, 2011; Weiss, Herbst, & Chen, 2009; Woolnough, 2000). The meaning of the adjective 'authentic' is so diverse, even when connected with a single noun, that it is wise to first explicate the meaning of cross-disciplinary authentic inquiry by students that I use in the context of practical investigations and profile projects reported about in this thesis. I refer to an authentic student inquiry activity as a investigation that is carried out by students and has many of the following characteristics:

- Students work on a (preferably self-chosen) rather challenging, ill-defined or ill-structured, open-ended problem that is rooted in a real life situation instead of a more abstract or ideal situation.
- Students do not follow some standard recipes, but they examine their problem from different perspectives, using a variety of resources and high-order skills. Think, for example, of research abilities such as choosing a manageable problem, formulating a good research question, structuring work, and so forth.
- A broad range of competencies is required to make the project a success. Think of making good use of ICT for information gathering, data acquisition, data processing and analysis, problem-solving, and reporting.
- The students' work is open-ended in the sense that there exist multiple methods or approaches to obtain many possible or even competing results. The student researchers actually decide if the investigation is finished for whatever reason.
- It offers students the opportunity to be in contact with contemporary, cross-disciplinary research and to learn about the nature of mathematics and science.
- Students disclose their own understanding through a portfolio or a polished product like a report, paper, or presentation.

These characteristics are rather similar to the design characteristics of authentic tasks distinguished by Reeves, Herrington, and Oliver (2002). I call an inquiry activity 'cross-disciplinary' when more than one discipline contributes in an essential way to the process of coming to an understanding of the problem situation. The practical investigations and the student research projects presented in this thesis were almost all rooted in applied mathematics and physics. I use the term 'cross-disciplinary' and not a term like 'inter-disciplinary' to emphasize that all disciplines are required to get satisfactory results: The whole is more than the sum of the parts. Mathematical modeling and scientific experimentation went together in many of the inquiry activities reported about in this thesis.

5. The Introduction of the Study House Concept

At the same time when the Second Stage started, pedagogical changes and an alternative organization of the learning processes in upper secondary education were advocated and firmly promoted as the so-called 'Studiehuis' (Study House) concept. It stands for an educational approach with more emphasis on self-regulated learning by students and on active engagement of students in the learning processes. Traditional teaching is consider exceptional in the Study House concept. Instead, the teacher's role comprises to provision of support, selection of resources, and coaching of students (See, for example, Kok, 1996). ICT was expected to support the new vision on teaching and learning. Taking the Study House perspective, it is logical that students get open, multifaceted tasks that involve searching for and making use of information resources, generating questions and problems to be solved, generating and researching conjectures, constructing examples, proposing explanations, debating with peers, making predictions, communicating results, and so on. These types of actions can be found in similar listings of facets of scientific inquiry (e.g., National Research Council, 1996). They are considered fundamental in an inquiry-oriented approach to mathematics and science education, in which students have ample opportunity to design and carry out practical investigations, learn about research, and do research projects. This is the approach that I explored to some extent in my classroom studies and to a considerable extent in the associated profile projects.

6. The Proliferation of ICT Tools in Education

The current general consensus amongst many people working in education and educational research is that the main focus of ICT in education should be the improvement of the quality of teaching and learning. The attention has shifted from learning-from-technology to learning-with-technology, in which technologies are used as cognitive tools and mindtools (Jonassen, 2006), and to learning-through-technology, that is, learning to think through new media. But all this is easier said and written down than done, regardless of the manifest role of ICT in daily life. Also, a degree of 'interpretative flexibility' surrounds all learning technologies (cf., Hennessy, 2006; John & Wheeler, 2008; Keengwe, Onchwari, & Wachira, 2008; Osborne & Hennessy, 2003; Ruthven, Hennessy, & Deaney, 2008), that is, each learning technology has different meanings and interpretations for various stakeholders.

Therefore, it comes as no surprise that the design, implementation, and use of the integrated computer environment for learning mathematics and science in an inquiry-oriented approach discussed in this thesis took input from many perspectives. For example, this versatile hardware and software system should support the three modes of using a computer in education distinguished by Kaput (1992) as an educational medium, as a set of tools, and as a toolmaker/mediumbuilder, respectively, depending on the goals that its user (teacher or student) has. The mediative and representational perspective on educational technology brought up by Kaput and colleagues in various papers (e.g., Goldin & Kaput, 1996; Kaput, 1998; Kaput & Schorr, 2008; Shaffer & Kaput, 1998) also influenced my research and development work. In this perspective one views the effects of technologies as operating to a large extent through the ways that they alter the environments for learning, thinking, representing, communicating, and acting in the world. In this view, technology aids to representational translations and transformations during problem-solving and inquiry activities. Kaput and Shaffer (2002) referred to the processing power of new cognitive technologies as the new representational infrastructure of computational media, which co-acts with students and teachers, that is, which guides or is guided by its users.

The design of a computer-mediated representational infrastructure for learning takes years of design and implementation, not only at technological level, but also at pedagogical and curriculum level, and mostly in combination with content development and applied research on mathematics and science education. Successful embedding of technology in educational practice has many facets and depends on many factors; it is a combination of technology, pedagogy, curriculum, professionalization of teachers, school culture, and many more things that matter. See, for example, Roschelle et al. (2008a,b) and Ellermeijer (2004) for discussion of these facets in the context of the SimCalc project and the Coach project, respectively.

Not only changes and advances in computer technology continuously ask for revisions of perspectives on the use of ICT in education. The same holds for changes in pedagogical visions, such as the contemporary perspective on practical work in mathematics and science education that promotes practical work and research projects in which students are engaged in activities that resemble those of scientists and practitioners (cf., Gott & Duggan, 1995; Wellington, 1998; Woolnough, 2000). The point of view taken in my work was that educational technology should provide students a suitable computer-mediated, representational infrastructure for conducting such investigations. The envisioned role of ICT was to support meaningful learning through interactive multimedia simulations, modeling activities, and working with real data. It matched the following potential of ICT in inquiry-based science education (Novak & Krajcik, 2004, p. 99):

> "Various learning technologies embedded within the curriculum can promote in-depth learning. They allow students to engage in aspects of inquiry that they would not otherwise be able to do. Learning technologies allow students to explore their "What if..?" questions. They allow students to use similar tools and engage in similar activities of scientists. Because less time is needed for gathering and recording data, more time is available for interpreting and evaluating data."

7. Changes in Examination

In Dutch secondary education, the majority of the examination programmes are nowadays assessed in a nationwide written exam and in a school examination that consists of an examination file on the achievements of a student during the Second Stage. This examination file contains assessment results of the following formats: results of written tests with open and closed questions; reports or presentation sheets of practical investigations; proofs of mastered competencies, including results of empirical work; and the profile project, which is a masterpiece in which a student shows that (s)he has mastered the profile-specific competencies and can apply them autonomously in a substantially large project with a study load of eighty hours (or more when the work is done in teams). Important in the context of my study was that with the advent of school examinations in the Second Stage, non-traditional formats for assessing students' knowledge, understanding and skills became possible that are more appropriate for assessing students' practical work. The students' reports on practical investigations were valuable resources in my classroom research. The reports of profile projects offered me the opportunity to review these projects in much the same way as a referee of a submitted paper in a scientific journal would do, without being in close contact with the student researchers in all phases of their projects and in this way possibly influencing the authenticity of their work.

1.2 R&D at AMSTEL

The foundations for my study were laid by previous research and development work at AMSTEL (Amsterdam Mathematics Science and Technology Education Laboratory), a former institute in the Faculty of Science at the University of Amsterdam, that was aimed at improvement of primary and secondary mathematics, science, and technology education through the use of ICT in inquiry-oriented teaching and learning (cf., Ellermeijer, 2004). Especially the state of development of the Coach environment at the start of my R&D work in 1998 played a role. Below I describe this starting point.

Hardware and software are needed for data logging and for computer-based modeling in inquiry-oriented science education. Coach was developed for this purpose and with the vision of improving the quality of teaching and learning in science education through ICT. An interface for connecting sensors and actuators to a computer and the MS-DOS based software package IP-Coach 4 were released in 1993 for carrying out computer-based data logging and modeling. The name of the software environment reflected its purpose: IP stood for Interface Program', which refers to interfacing of sensors and actuators to the computer, and Coach referred to coaching and support of learning (De Beurs & Ellermeijer, 1996; Ellermeijer, 2004).

The STOLE Concept

IP-Coach 4 was one of the first implementations of the STOLE concept, which was an acronym for Scientific and Technical Open Learning Environment (Ellermeijer, 1988). In this concept, a hard- and software environment was envisioned in which tools for measuring, data processing, and modeling are integrated in a single system that supports students' learning in an inquiry-oriented approach of science education. STOLE focused on essential elements of doing investigative work, which included the following activities:

- Setting up and controlling experiments.
- Collecting data from experiments.
- Displaying measurement data graphically and analyzing data.
- Retrieving information and making hypotheses.
- Proposing and constructing computer models.
- Testing models, including comparison of model results with those from experiments.

Other central ideas in the STOLE concept were the following:

- Students are expected to be actively engaged in realistic investigations using the environment, while the teacher facilitates the learning process.
- The environment should reflect innovation in science itself and be suitable for a wide range of science experiments, serving many science topics and many teaching and learning approaches, but it should be all by itself content-free (i.e., the user should be able to add contents).

- The system is an integrated collection of tools that can be frequently used during science lessons and practical investigations. This goal is also based on the idea that the learning curve of becoming accustomed to and proficient with the hard- and software environment should be as smooth as possible and should follow the 'learn once and use frequently' philosophy.

Software tools selected for STOLE were grouped into functional modules that combined instruments needed by a student at a certain stage of a scientific investigation. The student was central in this concept and it should be possible to adapt the environment to the student's level and to the science curriculum in which the student and his or her teacher participate.

The Renewed STOLE Concept

In the nineties, a new vision on practical work in science education arose that promoted practical work and research projects in which students would be engaged in activities that resemble those of scientists and practitioners (cf., Gott & Duggan, 1995; Wellington, 1998; Woolnough, 2000). The changed technological and pedagogical circumstances asked for a revision and extension of the STOLE concept, especially for the design phase of student-directed practical work and research projects. In this phase, a student researcher needs information: (s)he must analyze the scientific problem, simulate a model, or look up information about work of others. Thus, the computer is considered more than only a tool to collect, process, and analyze data. It must also give access to information resources and allow the display of information in various formats. The resources may be supplied on a CD-ROM or through Internet and they can be in various formats (sound, picture, video, digital image, hyperlinked text, and so on). The display of information and the inquiry nature of students' activities ask for multiple linked representations in multimedia-based activities.

The application area of the computer environment was envisioned to become larger than science investigations: The field of technology also seemed appropriate for students undertaking design projects in which control of models is realized through computer models and programmable microworlds. Thus, the role of data logging with sensors connected to the computer became less prominent than before. The focus turned more on learning science and technology by practical work and by doing authentic investigations or design activities.

It was also envisioned that it should be possible to fine-tune the whole cycle of doing investigations and design work. This meant that a teacher should be able to design a sequence of activities for a particular investigation or design, and to organize these activities in a project to structure the instructional materials (experiments) for his or her students. This steering of the learning process by adapting or authoring student activities and bringing them together in a project is more important in lower secondary education than in upper secondary education. At lower secondary level, a teacher may not want to put the burden of selecting appropriate displays of information to his or her students and (s)he may want to provide information in an informal, qualitative, more visual or playful way. This is the reason that authoring of multimedia-based activities becomes important too. At higher secondary level, students are even expected to author activities themselves: from scratch or by selecting tools independently from prior choices made in an activity.

This renewed and extended STOLE concept of an integrated, tool-based environment suitable for an inquiry-oriented approach to science and technology learning, in which students and teachers work with multimedia-based activities and create such activities themselves by using a variety of resources, can be looked upon as a predecessor of the idea of working in a virtual learning environment. It was first implemented in Coach Junior, released in 1998. This marked the start of my study. The immediate goal was to implement the renewed and extended STOLE concept in the MS-Windows version of IP-Coach 4. It led to the release of Coach 5 in 2001. I used pre-releases to explore possibilities of the existing tools for mathematics education (Heck, 2000a-c). Since then, the quality of data processing and data analysis has been improved, more tools for video capture and measurement on digital images and video clips have been incorporated (also due to rapid advancement of ubiquitous technology at consumer level), authoring of activities and the structural organization of activities have been upgraded, and new modeling tools like graphical modeling and computer animations have been developed, amongst many other things. I report in this thesis about computer-based quantitative modeling in practical investigations rooted in mathematics in combination with other disciplines and about the tools needed for this purpose. Regarding development work, I report on my contributions to the functional design of the video analysis tool, the data processing and analysis tools, and the modeling tool. These tools have all been incorporated in the current version 6 of Coach. For a quick impression of Coach 6, the reader is referred to Section 3.1.

1.3 Multiformity of ICT Tools

Physics was the first subject in Dutch secondary education in which computer-based data logging and modeling were embedded in practical work because the concepts and skills of these activities had in fact already been included in the physics syllabus since 1988, schools had received extra budget to acquire the necessary equipment, and a national project for in-service training of physics teachers had taken place. From that time on, data logging and modeling became popular in the schools and much instructional material was developed: first for physics, later for chemistry and biology. Technology education used the context of measurement and control systems in the daily life for practical work in ICT. The tools for data acquisition, data analysis, control of devices and processes, and computer modeling implemented in Coach gradually became the standard for practical work in Dutch science education.

The developed instructional material was aimed at laboratory work in each science discipline separately and less at immediate use in the regular classroom when studying problem situations of variable origin. But technological advancement does not stop: At the time when I started my R&D work, one of the new technologies with high educational potential was video analysis. Digital cameras and webcams became more and more consumer products and thus affordable for schools to use in the classroom. Video analysis was welcomed by educators and educational researchers because of the possibility to bring in numerous problem situations on which students could work in science classes. In comparison with traditional laboratories, it also seemed easier to engage students in the research process by having them involved in the creation of the digital videos. Another anticipated advantage of video analysis and digital image analysis was that this was a common technology in all science disciplines and could be expected to be useful in all science disciplines taught at school, and even for mathematics education. Besides the enhancement of the teaching and learning of mathematics and science, video analysis was considered a cost-effective way for doing investigations: One does not need expensive measurement equipment to collect data and re-use of digital videos is easy and gives students a better view of the experimental setting in which the video was captured, when compared with use of experimental data obtained by measuring with technical equipment (See, for example, Bryan, 2010).

The use of ICT in Dutch mathematics education developed in a completely different manner. Pocket calculators, without graphing facilities, had replaced mathematical tables and the slide rule at school. Special purpose computer programs, often created by teachers or educational researchers interested in computers and software, were sporadically used. Despite many governmental stimulation projects in the late eighties and early nineties, technology use in mathematics education did not catch on in that period. It remained sporadic and experiments with computer work were mostly restricted to special subject areas like statistical data analysis, simulation of dynamical models, graphical analysis of functions, and geometry.

The situation changed with the introduction of the Second Stage in 1998, when new curriculum content had to be developed and the status of ICT in education was redefined to play an important role in the learning process of students. Functional use of the graphing calculator and some computer programs was included in the attainment targets of specific mathematical domains (cf., Drijvers & Doorman, 1996; Profi-team, 1996-1998). The graphing calculator started to dominate Dutch upper-level mathematics education, mainly due to its advantage of being an affordable, portable, private, easy-to-use, and ready-to-hand device that could be used for the core of mathematics taught at upper secondary school. Publishers also started to supplement their textbooks with dedicated computer programs. These programs had a more open character than the earlier educational software environments. They were created for drawing and manipulating graphs, dealing with matrix computations, working with statistical data, studying 2D and 3D geometry, doing numerical computations, and so on. For each domain there seemed to exist at that time separate, dedicated tools: CABRI GEOMETRY and other dynamic geometry systems for geometry; VU-LOSOP for solving equations; VU-GRAFIEK and the graphing calculator for investigating graphs; VU-DYNAMO and DYNASYS for simulation of dynamical systems; ORSTAT for operations research and linear programming; VU-STAT for statistics education; DERIVE for formula manipulation; JAVA APPLETS for learning various mathematic concepts; and so on. How well-thought, highly interactive, user-friendly and goal-oriented these software packages were, they formed a grab-bag of mathematical software packages, which in many cases did not work well together or with office software like text editors, spreadsheet programs, and presentation tools. By the way, office software had not been designed for educational purposes, but nevertheless penetrated education and started to play an important role herein. In summary, the Dutch mathematics education community had not yet adopted the STOLE concept of tool integration.

It was certainly considered a disadvantage that the use of ICT in Dutch mathematics education and in science education had each gone in different directions. Although everyone acknowledged that differences between the use of mathematics in the various disciplines cannot be ignored, at the same time all agreed that this should not lead to the situation that a student does not recognize similarities anymore. Many noticed that the transfer problem was reinforced by the difference in the use of ICT tools. For example, in mathematics lessons, a student was used to plot the graph of a function on a graphing calculator by entering a formula, while in science lessons the same student could obtain a graph of a relationship between two measured quantities or a graph computed via a simulation program. Kok (1996, p. 13) already brought up to the attention of teachers that gearing of ICT could help to bridge the gap between mathematics and science. Mathematics teachers were invited to ask themselves the following questions:

> "What position does the graphing calculator get in the science subjects? What other ICT applications get a lot of attention in these subjects? At many schools the package IP-COACH is for example used in physics and chemistry. It is interesting to look into possibilities that such a package has for mathematics. And in the other way around, VU-GRAFIEK might be useful in these subjects."

Although this quote shows great optimism to break down the walls between mathematics and science subjects, in reality the road to better connections between the fields regarding ICT usage turned out to be long and winding. At least it supports the motivation at the start of my study to explore the possibilities of an integrated computer learning environment for mathematics and science education, and to work on the design and implementation of such an environment. In particular, I investigated how an integrated computer learning environment could contribute to the realization of better connections between the disciplines in case of practical investigations and profile projects. I deliberately developed mathematics-intensive cross-disciplinary practical investigations that had in common with science that an empirical verification of the usability of a mathematical model was possible and that shared with mathematics the focus on consistency and generality of the methods used. In the choice of the content of the developed practical investigations, which are discussed in subsequent chapters of this thesis, the following unordered, non-exhaustive list of guiding principles was used. A subject must preferably

- make students curious and challenge them;
- invite students to explore on their own and do experiments;
- originate from real practice and have a contemporary and recognizable character;
- be rich in mathematical and scientific methods, as well as rich in the use of ICT;
- be scalable to the ability level and number of participating students and to the scope of the students' work;
- bring to the forefront highlights of a discipline; and
- lead to an assessable deliverable.

For this kind of activities I explored how a single, versatile computer learning environment could be a supportive means in the teaching and learning processes and in inquiry activities of students, and how it could improve the quality of the students' work.

1.4 Aims and Set-Up of the Study

The general purpose of my research and development work in the last decade was to improve the contribution of ICT to inquiry-oriented mathematics and science education at secondary school level. In particular, I aimed to contribute to

- the development of an open activity-based computer working environment that offers its users a versatile set of integrated tools for the study of natural phenomena, mathematics, science and technology; and
- perspectives on the role of ICT in quantitative mathematical modeling by secondary students.

More specifically, I aimed at contributing to the development of an integrated computer learning environment by making recommendations about the functional design on the basis of classroom experiments and sample activities, and by exploration and analysis of educational needs and possibilities, especially regarding inquiry activities. The second purpose of the classroom experiments was to explore how ICT can contribute to the realization of students' practical work that resembles applied mathematics and science practice. This is how I mainly interpreted the authentic nature of students' practical work: activities in which they do research in much the same way scientists and practitioners do and in which they use high-quality tools that are similar to professional tools, but that have been designed for educational purposes.

Instead of an iterative in-depth classroom study into one particular subject or domain, or into a particular type of educational technology, I decided to carry out exploratory case studies in a variety of subjects—human growth, gait analysis, shapes of bridges and hanging chains, survival analysis, weather data, bouncing balls, and quantitative pharmacology—and in a variety of technological tools—data logging, video analysis, computer modeling—so that I could contribute to many perspectives on ICT-supported practical investigations and research projects at secondary level. It is noted that the focus of my research was not on the construction of a framework for teaching and learning practical work, scientific inquiry or modeling. I also did not design and research a learning trajectory for studying a particular subject or domain, with the aim of generating empirically grounded domain-specific theories. The interested reader is referred for this type of research to recent studies in the context of Dutch secondary mathematics and science education such as, for example (the list is not exhaustive), the doctoral theses of Hubers (2003), Smits (2003), Van Rens (2005), Schalk (2006), Hendrikse (2008), Westra (2008), and Ormel (2010).

The scope of my study was limited to pedagogical and software design perspectives on ICT use in inquiry activities in which students develop mathematical and scientific literacy. Driving questions were:

- How can the use of ICT and in particular of an integrated computer learning environment contribute to the realization of challenging, cross-disciplinary practical work of good quality, in which pre-university students can work with real data, apply mathematical methods and techniques in concrete problem situations, improve their mathematical and scientific knowledge and skills, and increase their mathematical and scientific literacy?

- What integrated tools should the computer learning environment provide for inquiry-oriented mathematics and science education? What are the requirements for the computer learning environment from a mathematical point of view and do they link up with requirements coming from science fields?

In other words, the two main results at which I aimed in my study were: (1) better understanding of how, why, and to what extent ICT tools can support students in their learning and practice of scientific inquiry; and (2) more insight in what it takes to develop an integrated computer environment for learning mathematics and science in the context of inquiry-oriented approach, the usability of which is explored within educational practice. In both explored perspectives, I used a specific computer learning environment, namely, COACH (Heck, Kędzierska, & Ellermeijer, 2009), to learn lessons from developing ICT tools that are integrated in an open, activity-based, multimedia authoring environment for mathematics and science education, and to learn lessons from exploring their usability in specific practical investigations for upper secondary students, in sample activities, and in usability studies. Here I take from the field of human-computer interaction the following definition of usability of ICT (ISO 9241 standard, Part 11, 1998; a revised and renamed standard on *Ergonomics of Human System Interaction* was published in 2008), also referred to as a characteristic of 'quality in use' (Bevan, 1999): "The extent to which a product [service or environment] can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use." My users were mainly pre-university students learning and doing scientific inquiry work in the context of practical investigations and profile projects as part of their education in mathematics and science and teachers of mathematics and science at secondary schools. Because of the wide range of my users with different backgrounds and different levels of knowledge and experience regarding scientific inquiry and ICT, it seems better to speak of the aim of achieving 'quality in use for all' (Bevan, 2001). One of the biggest barriers in user-centered design for all is that the provision of appropriate functionality and support for computer-mediated activities for all is impossible, if taken literally. The heterogeneity of the intended group of users was also in my development work a constant point of attention in the design of ICT tools. Other usability principles, although not components of the ISO definition, that I took into account, like many other practitioners (e.g., Sharp, Rogers, & Preece, 2007), regarding use of ICT in education were: (1) the principle of learnability, that is, the ease with which new learners learn to use the ICT tools and experienced students use the ICT tools to do more; (2) the principle of memorability, that is, the ease with which students remember how to use the ICT tools; and (3) the principle of flexibility, that is, the multiplicity of ways to interact with the integrated ICT tools.

In my study, research and development were intertwined. Focus was on students' working with real data and on the design of supportive tools. The intention was to bridge the gap between mathematics and science education at school on the one side and modern research carried out by professionals on the other side, through provision of a suitable computer learning environment for inquiry-oriented mathematics and science education. A single ready-to-use framework for this work was not available (or at least was not found). The approach in my study was therefore to select elements from several frameworks for research and development in ICT-rich mathematics and science education that seemed promising for application and adaptation. Design research, case-based design of educational software, frameworks on using multiple representations, frameworks on evaluating inquiry activities of students, and models of modeling were the main sources of inspiration.

Design research has become a popular research methodology in mathematics and science education (cf., Kelly, Lesh, & Baek, 2008; Van den Akker et al., 2006), but it is subject to many interpretations and this is reflected in the use of various synonyms such as design-based research (Kelly, 2003), development or developmental research (Richey & Nelson, 1996; Van den Akker, 1999), design experiments (Brown, 1992; Cobb et al., 2003; Collins, 1992), user design research (Carr-Chellman & Savoy, 2004), and didactic engineering (Artigue, 1994). Whatever definition is used, the main common characteristic is that design and research processes are integrated. For the purpose of my study, the following definition from Wang and Hannafin (2004, p. 2) can be used: "Design-based research is a research methodology aimed to improve educational practices through systematic, flexible, and iterative review, analysis, design, development, and implementation, based upon collaboration among researchers and practitioners in real-world settings, and leading to design principles or theories." Below, I go through the key ideas of design-based research that I adopted for my work.

Looking at design research aspects of my study, it can be characterized as type I design research in the typology of Richey and Nelson (1996; see also, Richey, Klein, & Nelson, 2004, p. 1102): "The product development process used in a particular situation is described and analyzed, and the final product is evaluated." Within the distinction made by Van den Akker (1996, p. 6) between formative and reconstructive studies, my research work belonged to the first category and, like in many formative design research studies, the roles of designer and researcher coincided within the development context. In Van den Akker's labeling (1999, p. 6), my work would be considered an explorative design study: I did not aim at statements of general nature, at developing theories, and at generating empirically grounded understanding of students' inquiry processes. Instead I aimed at clarifying the design problem-in-context and at generating tentative design ideas, thus obtaining results that were context and product specific and that directed the development work.

From design research I took the perspective that it involves design of an intervention or experiment in the real word, that the output of my research must have practical value to real world users, and that teachers are involved in the research. This is why I also paid attention to implementation issues at school and to questions like "How can teachers set up and guide students' inquiry activities?" Throughout the period when I did the research and development work reported in this thesis, I cooperated with mathematics and physics teachers in all classroom experiments, partly thanks to the NWO-project 'Teacher in Research'. I did three types of case studies:

1. Classroom research studies, in which students did practical investigations on the basis of specially designed instructional materials.

2. Field experiments, in which ICT innovations were tried out on a small scale and not necessarily in the classroom.

3. Usability studies, in which I evaluated the potential of a specific ICT tool or a set of integrated tools in a particular subject or domain, leading to a set of sample activities.

My exploratory case studies served many goals:

- They were meant to gain insight in the needs of secondary school students for doing authentic inquiry work.
- They helped me specify requirements for an integrated computer learning environment from a mathematical point of view.
- They served to test the usability and scope of (prototypical) implementations of particular tools for collecting, processing, and analyzing data.
- They gave an impression of the potential of ICT regarding the realization of challenging, cross-disciplinary practical work in which secondary school students were engaged in activities such as experimenting, data collection, and data analysis in much the same way as scientists and practitioners.

In the classroom experiments, leading questions were: "How did the designed instructional materials and the ICT tools function in school practice?", "Were learning goals achieved?", "Did the students use the ICT tools in the envisioned way?", and "How could the instructional materials and the ICT tools be improved?" In other words, the exploratory case studies did not focus on a single or central research question, did not include a control group for effect comparison, and did not have the characteristics of a (quasi-)experimental design in which evidence of instructional effects is collected. Nonetheless, they were a source of considerable qualitative and quantitative data about ICT-supported student inquiry in practice and about the validity of the learning environment design and prototype functionality in diverse real-world contexts, with the goal of removing bugs and fixing technical flaws in otherwise functional designs.

I also took the cyclic and iterative process of design, which includes cycles of innovation and revision, and applied it to the development of tools in the computer learning environment for inquiry-oriented mathematics and science education. I hardly applied it to the development of the instructional materials for use in the classroom experiments. Otherwise stated, the case studies themselves were the cycles in my design research aiming at the development of an integrated set of tools for inquiry-oriented mathematics and science education. The cyclic research and development phase, occurring after an explorative phase in which a theoretical and practical orientation took place, is illustrated in Figure 1.1. In this thesis I mainly report on this phase.

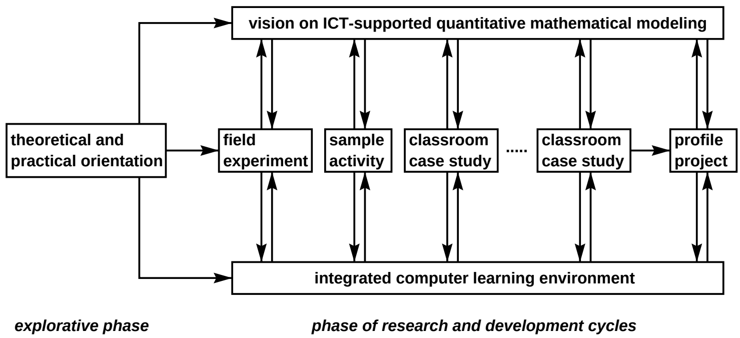

Figure 1.1: The set-up of the study from a design research point of view.

Decisions about the tool design were often made during implementation in response to context demands, which were found during classroom experiments and during the design of learning activities, and based on prototypes of the software tools. A cyclic structure in the tool development was therefore one of the characteristics, which typically went through the following phase of planning, development, testing, and release. The design of a new tool or improvement of an existing tool often started with a project definition in which the technological and educational goals were specified, design criteria were formulated, and similar tools in other educational software were inspected. Hereafter brainstorm sessions aiming at a functional specification took place, followed by a prototypical implementation. The prototype was tested within a small community of researchers and experienced teachers: Some sample activities were developed to explore the functionality and ease of use of the tool for educational purposes and to generate new and better ideas. Adaptations were made on the basis of these experiences. This spiral model of prototype development and enhancement led to a new version of the tool that could be field tested (again in collaboration with experienced teachers), and finally be tested in classroom experiments. Depending on the experiences in the field tests and classroom experiments, a new development cycle started or the final tool was included in the release of the computer learning environment. The released version of the tool was then ready for broad evaluation, including the adoption by a broader group of users. But this broad evaluation was hardly part of my research and development work. In other words, my R&D work was mostly restricted to the first three phases of the Integrated Learning Design (ILD) framework for design-based research (Bannan-Ritland, 2003), namely: (1) informed exploration, which means exploring theory, users and their needs; (2) enactment, that is, the design, implementation and formative testing of a prototype in as many cycles as necessary; and (3) local evaluation, which means evaluating the local impact of the prototype on its users and going back to the enactment phase if necessary.

The above phases in a product development cycle resemble the following user-centered design activities taken from the ISO 9421-210 (2010) standard: (1) understand and specify the context of use; (2) specify the user and organizational requirements; (3) produce design solutions to meet user requirements (typically in the form of prototypes); and (4) evaluate the designs against requirements. When these human-centered design activities are applied to software design for education and when emphasis is put on the understanding and specification of the users, the activities and the context of use, and on the evaluation of the design by case studies in the envisioned context of use, then one speaks of a case-based design of educational software (Khan, 2008). The case-based design process can be split into three parts that resemble the three phases of design research identified by Cobb et al. (2003), namely, preparing, conducting, and retrospectively analyzing a design experiment. Kahn (2008) identified them as the planning, development, and testing part of the case-based design process, and she linked the following five sequential phases of the design process into these parts: (1) studying pedagogical theory in preparation for the next phase; (2) making a conceptual design of the educational software; (3) constructing the program architecture; (4) developing a prototype; and (5) testing of the prototype. As shown in Figure 1.2, taken from Kahn (2008, p. 427), case studies inform phase 2 and 4, and teachers' feedback informs phase 2, 4 and 5.

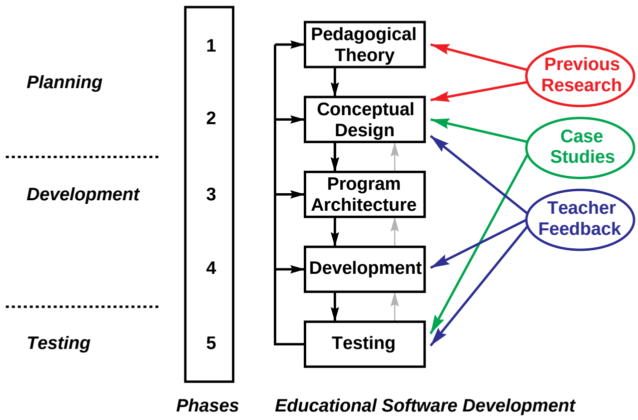

Figure 1.2: Phases of a case-based design process of educational software.

My personal experience, shared by others in the development team, is that this way of educational hard- and software development is quite effective when combined with other concerted actions for implementation in educational practice. I combined this type of usability evaluation of educational applications of ICT with expert evaluations of developed prototypes. I applied standard methods in the case studies and expert studies for usability evaluation, categorized by Tselios, Avouris, and Komis (2008) in the following four groups of methods: (1) usability inspection methods; (2) user testing methods; (3) exploratory methods; and (4) analytical evaluation methods.

The theoretical rationale of tool integration was that the use of multiple external representations is crucial for deep understanding of real phenomena and that this process of understanding is promoted when learners are not distracted by technical burdens that could have been avoided by the provision of tools that work well together. This view was underpinned by theoretical frameworks such as the Kaput-Goldin representational framework for mathematical cognition and learning (cf., Goldin, 2008; Goldin & Kaput, 1996; Kaput, 1992, 1994) and the Rule of Five framework on multiple representations (cf., Dick & Edwards, 2008). How strong my motivation for using multiple representations in mathematics and science education was, it did not mean that I closed my eyes for difficulties associated with using multiple representations. The cognitive load is definitely enlarged when multiple representations come into play and it has been reported in many research studies (cf., Ainsworth, 2006, 2008) that learners find retrieving information from representations, moving between and within representations, and coming up with appropriate representations difficult. But I believe that teachers can guide and support their students in learning to read and use information from representations and to work effectively with multiple representations.

I also concur with Kaput (1992, pp. 533-543) that computer technology, through the dynamic linking of representations and immediate feedback, can assist students in their learning process from concrete experiences to ever more abstract objects and relationships of more advanced mathematics and science, and can support visualization and experimentation with aspects of investigated phenomena. Ainsworth (2008) summarized a number of heuristics that could be used to guide design of effective multi-representational systems and that are obviously connected with principle(s) of multimedia learning listed by Mayer (2005, 2009) and with principles of cognitive load theory (cf., Kalyuga, 2009; Oviatt, 2006; Plass, Moreno & Brünken, 2010; Sweller, 2005; Sweller, Van Merriënboer, & Paas, 1998).

Most student activities for classroom experiments were developed with the instruction theory of authentic education in mind. I interpreted the authentic nature of the activities as the opportunity for students to work with real data, which they collect themselves or get from real and recent research work, and to apply mathematical methods and techniques in much the same way as practicing professionals. This was also a leading design principle for the development of the integrated learning environment: It must enable students to do investigations such that their work has a strong resemblance with the work of professionals. Authentic tasks can often be characterized as challenging, complex, open-ended, cross-disciplinary, and requiring a strong commitment and broad range of skills. I structured and analyzed many of my quantitative mathematical modeling activities in the case studies on the basis of the modeling cycle of Blum and Leiß (2005, p. 1626). In this thesis I discuss the potential role of ICT in these investigative activities with reference to this modeling cycle.

1.5 Structure of the Thesis

This thesis is divided into four chapters. In Chapter 1 I summarize the context, rationale, aim, and set-up of my research and development work. In Chapter 2 I report on results of classroom studies on ICT-supported practical investigations. In Chapter 3 I describe sample activities for students and usability studies in which the full potential of new tools was explored. In Chapter 4 I recap and discuss the results and conclusions of the reported research and development work, I reflect on my work as a whole, and I go into possible implications for future research and development.