DESIGN AND IMPLEMENTATION OF AN INTEGRATED COMPUTER WORKING ENVIRONMENT FOR DOING MATHEMATICS AND SCIENCE

André Heck, Ewa Kędzierska, Ton Ellermeijer

Universiteit van Amsterdam, The Netherlands

A.J.P.Heck@uva.nl, E.Kedzierska@uva.nl, A.L.Ellermeijer@uva.nl

In this paper we report on the sustained research and development work at the AMSTEL Institute of the University of Amsterdam to improve mathematics and science education at primary and secondary school level, which has lead amongst other things to the development of the integrated computer working environment Coach 6. This environment consists of integrated tools for data collection (through measurement with sensors or collection of data on video clips and digital images), for control of processes and devices, for processing and analyzing data, for construction, simulation, animation, and validation of computer models, and for authoring of activities by teachers and students. It is meant to facilitate the students' construction of in-depth and integrated understanding of mathematics and science concepts and processes through inquiry. This is realized by offering students the opportunity to work directly with high-quality, real-time data by means of tools that resemble technologies used by 'real' scientists. We review the R&D work at AMSTEL in the Dutch perspective on introducing learning technologies in school mathematics and science. We also present an illustrated review of the principled design and implementation of Coach 6.

WITH SEVEN-LEAGUE STRIDES THROUGH DUTCH HISTORY

The AMSTEL Institute (www.science.uva.nl/amstelinstituut) is an institute inside the Faculty of Science of the University of Amsterdam that has the mission to contribute through re-

search, education, teacher professionalization, curriculum development, and development of educational hardware and software to the improvement of teaching and learning of mathematics, science, and technology education at all levels, ranging from primary education up to university education. From the start of the introduction of the computer in secondary education in the early eighties in the Netherlands the possibilities of this medium in education have been seriously investigated at the University of Amsterdam, especially in physics education, and learning technologies have been developed. This ongoing work is driven by research, classroom experience, and information technology, and it is closely linked with the continuous efforts of integrating the use of information and communication technology (ICT) in mathematics, science and technology education in the Netherlands. De Beurs & Ellermeier (1996) and Ellermeijer (2004) have described the work that has led in the last twenty-five years to a rather successful integration of ICT in science and technology education in the Netherlands and to the development of the computer working environment Coach (www.cma.science.uva.nl). Here we only summarize the main factors that contributed in our opinion to this success and that we characterize as a consistent approach for many years and a concerted action that made innovation possible in conjunction with investment in infrastructure, teacher training, and change of curriculum and examination.

Initially the computer was introduced in science education in Dutch secondary schools as an aid for practical work, namely for computer-based data logging and modeling. This introduction acquired momentum by two actions. The government donated IBM-compatible computers to secondary schools and introduced computer science into lower secondary education as a minor subject to train basic computer skills. Since 1993 specific science-related ICT attainment targets were set, which required pupils to be skilled in using the computer for acquiring and processing (science related) data, and for understanding processes (simulations and modeling). In upper secondary education no new computer science subject was intro-

duced, but instead the use of ICT was promoted in all existing subjects (e.g., in mathematics, physics, and economics) and the syllabi of several subjects paid explicit attention to computer science related concepts and skills as part of a curriculum with a strong focus on students' competencies. This marked the change of view on ICT usage as a goal in itself towards a means to improve the quality of teaching and learning.

Physics was actually the first of the subjects for which this was realized in school because the concepts and skills of computer-based data logging and modeling 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 been carried out. From that time on, data logging and modeling became popular in the schools: first in physics, later in chemistry and biology. Technology education used the context of 'measurement and control systems in the daily life' for practical work in ICT. For these activities, the University of Amsterdam had developed an interface and the MS-DOS based integrated software package IP-Coach 4. It consisted of tools for data acquisition, data analysis, control of devices and processes, and modeling that became the de-facto standard.

With the advent of the MS-Windows operating system, the user interface of software changed dramatically, from text-based to non-linguistic (iconic, GUI) modes of interaction. As a consequence, the use of computers became easier and ubiquitous, and could be adopted much earlier in education. Coach Junior was introduced in 1994 for science education at lower levels of secondary school and Coach 5, which was designed as a multimedia computer learning and authoring environment, replaced IP-Coach 4 around the year 2000. Teachers and developers got authoring tools to prepare activities for their students in addition to the extended set of tools for science and technology education and the increased variety of hardware platforms supported. They could select and prepare texts, graphs, images, videos, and measurement settings and they could gear activities according to the needs and abilities of

their students. So, the computer working environment could be adapted to pupils from age 10 up to undergraduate students. Quickly, Coach 5 was used in almost all Dutch secondary schools and also in many European countries due to translations into several languages and localizations of sample materials.

At the end of the nineties, the widespread access of teachers and students to computers, the rapidly growing connectivity of school and homes to Internet, and the increased attention to individual learning gave a main breakthrough for new types of computer use in education. Nowadays, almost all textbooks include CD-ROMS and web sites for students and teachers with all kind of educational materials, such as videos, images, presentations, simulations, diagnostic tests, extra learning resources, and (self-)assessments. Almost all schools in the Netherlands have a large network of computers with broadband connections to the portal of the national support center for ICT in Education, called Kennisnet (Knowledge-Net, www.kennisnet.nl). Many organizations and projects deliver a variety of content to Kennisnet and create dedicated web sites. Alongside the large investments in infrastructure, the Dutch government provided considerable means for schooling of teachers and school managers. It also initiated in the year 2000 the first pilots of national examinations with computers. In mathematics, biology, and physics education, large-scale experiments have been conducted in the last 8 years with computer exams in parallel with traditional, nationwide, written exams (Boeijen & Uylings, 2004) using the video measurement and modeling tools of Coach 5.

Besides the computer use in school labs and computer rooms, most Dutch schools have made computers available in or around classrooms and they have created special working places at the 'Study House' and in media libraries, where students have access to sources on the digital learning environment of the school and on the Internet, and where they make their reports or presentations. The 'Study House' concept, which was introduced in 1998 in connection with the start of the 'Second Stage' in Dutch secondary education, is an alterna-

tive organization of the learning processes in upper secondary education that emphasizes learning and narrows teaching to guidance and coaching. This means that traditional teaching is considered exceptional in the study house. Students are expected to play an active and self-responsible role in their own learning and to collaborate with their peers. To this end, students get more open tasks, find and use information resources, carry out practical investigations, and do a substantial design or research project at the end of their school career. This shift in teaching and learning approaches arose from new didactic insights that advocated the use of real-life contexts to motivate and engage students. Active learning was promoted by starting from concrete situations, by giving the students' own constructions and skills an important role in the learning process, and by stimulating classroom discussions, practical work and students' investigations. Another need for changing the mathematics and science curricula was to let the study programs meet better the requirements of the knowledge-economy based society by including contemporary subject matter and by bringing students at their own level in contact with modern methods applied in research laboratories and workplaces. In other words, there has been a trend from content-driven classroom teaching towards application-oriented, inquiry-based, ICT-supported education inside and outside the classroom in which individual accents can be laid and attention is given to students' abilities.

This problem-oriented approach of mathematics and science education with a strong focus on application, inquiry, modeling, interdisciplinarity, and competencies (including research abilities, study skills, communicative skills, and so on) is further developed in the current curriculum reform in the Netherlands that will lead to new mathematics and science curricula in the 'New Second Stage' of secondary education. These curricula, which will become effective between the years 2011-2013, promote active learning of mathematics and science through contexts that are meaningful, motivating and challenging for students. The envisioned role of ICT is to support meaningful learning through interactive multimedia

simulations, modeling activities, and working with real data. It matches the following potential of ICT in inquiry-based science education (Novak & Kracjik, 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."

With this role of ICT in education in mind, the Coach learning environment has been extended and updated during the last years, leading to the current version 6. The quality of data processing and data analysis has been raised, more tools for video capture and measurement on digital images and video clips have been incorporated, 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. Also new instructional domains have been explored: application of Coach in mathematics education has been investigated (c.f., Heck & Holleman, 2002, 2003; Heck, 2007) as well as the use of Coach for science education at primary school (van den Berg & Ellermeijer, 2006).

DESIGN PRINCIPLES AND IMPEMENTATION OF COACH 6

The consistent approach for many years at the AMSTEL Institute regarding ICT in education is reflected in the main design principles that underpin the development of the computer working environment Coach and that have in essence not changed in the last two decades. A one-sentence description of the environment, which holds since its first release, is as follows:

> Coach is a single, activity-based, open computer working environment that is designed for the educational setting and that offers a versatile set of integrated tools for the study of natural phenomena, mathematics and technology.

A closer look at the elements of this description will reveal that it is meant to

- aid students in collecting, processing, and analyzing various types of data, to provide visualization and analysis tools, and to offer opportunities for creating computational models and animations;

- change the computer into an instrument that allows students to explore real-world phenomena in similar activities to what 'real' scientists engage in and thus lead to effective and meaningful learning, in which various higher order thinking skills like problem solving and connecting contexts with scientific concepts are highly valued;

- transform mathematics and science lessons into learning activities in which students are deeply engaged in building up knowledge, experience, and skills;

- be universal and applicable in several curricula, in various instruction models, and at many levels of education, and be adjustable by teachers to their students' abilities;

In this section we discuss some keywords in the one-sentence description of Coach

ACTIVITIES

Coach activities are mostly based on the selected tool for collecting, generating, or processing and analyzing data. Teachers can use ready-made activities or author new activities as parts of projects to structure the lesson materials (experiments). Activities may contain:

- texts with activity explanations or instructions;

- pictures illustrating experiments, equipment, and/or context situations;

- video clips or digital images to illustrate phenomena or to use for measurement;

- measured data presented as graphs, tables, meters, or digital values;

- models (textual, equations based, or graphical) to describe and simulate phenomena;

- programs to control devices and to make mathematical computations

- links to Internet sites and other external resources for students

A basic description of several types of activities and concrete examples are given below.

In a **measurement activity** (time-based or event-based measurement, with or without triggering) students gain insight into data acquisition with sensors and how to set up measurement experiments. This understanding helps students interpret graphical representations of the data, especially because dynamic links between data and different representations such as graphs, tables, and meters are maintained during and after the measurement. Experiments are easily set-up (drag-and-drop sensor icons and automatic sensor recognition) with a variety of interfaces supported and a large library of calibrated sensors (e.g., for temperature, light, sound level, pH, etc.) and actuators (e.g., lamp, motor, fan, heating element, etc.) available.

Figure 1 shows a screen shot of the measurement and signal analysis of the voice sound 'eeh' recorded with the €Sense interface, which is mostly used at primary school or by beginners. The diagrams show that the sound signal is well described by a sinusoidal signal that consists of four frequencies. A visual representation of the €Sense interface with the built-in microphone is also present in the activity screen to make the experimental set-up clear to students. A text window is used for explanation and description of tasks.
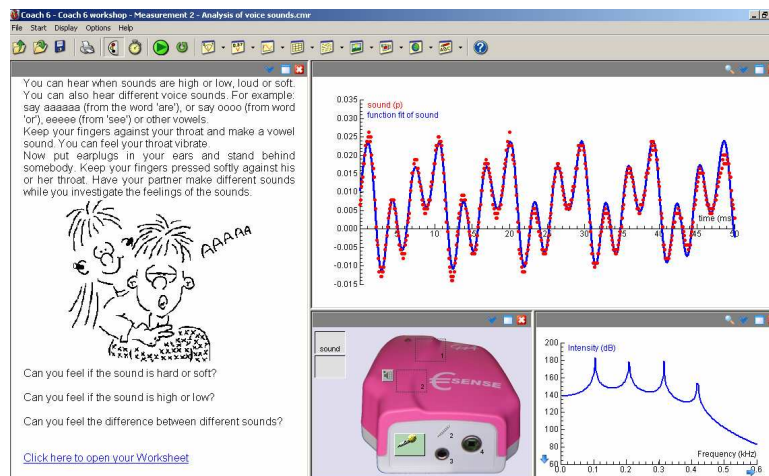

Figure 1. Measurement and signal analysis of voice sounds with the €Sense interface.

A **control activity** offers several modes of programming with varying difficulty. These modes are manual control mode, instruction mode, microworld programming mode, and free programming mode using the Coach language. They are used to create and execute

programs for automated measurements (for example, an automated pH titration system in which a titrator is controlled while measuring with a pH sensor), for manipulation of measurement data (for example, converting voltage signal from a sound sensor to decibels), for control of systems such as LEGO® models or models controlled by the Coachlab interface, and for programming any phenomenon (mathematical, scientific, natural, artificial, or whatsoever). Figure 2 is a screen shoot of part of a control activity in which the Coach language has been used to create a programming microworld for manipulating the robot arm. The student's task has been to build with common LEGO® bricks and the programmable LEGO® RCX a robot arm, and to construct a program with the supplied commands that makes the robot arm grab bricks, swivel around, and drop them into bins. A position sensor has been used to measure the position of the robot arm and two motors have been used to control the motion of the arm and grab. A follow-up task for a student may be to add a light sensor so that the arm can be programmed to sort the bricks by color or to extend the construction with a programmable conveyor-belt from which the bricks must be taken. These kinds of activities offer students the opportunity to create physical artifacts, such as vehicles, line-followers and robots, and program them with interesting behavior. In this way a design project becomes a fun project and at the same time students learn a lot about the difficulties that technicians and engineers have to overcome in similar work.

Figure 2. A computer microworld for manipulating a robot arm.

Figure 3 is a screen shot of a **data video activity** in which position and time data are collected from a video clip. The video clip of the motion of a self-made yoyo that is winding up and down has been captured within Coach 6 through a web cam. The data recording in

such a movie is often done by mouse clicking in selected frames on the location(s) of the item(s) of interest. In this case, the position of the point near the rim of the disk and marked by a sticker (P1) is measured in a slightly moving coordinate frame whose origin is at the hand of the person holding the end of the cord of the yoyo. But point-tracking makes the measurement at hand easier and less time-consuming: in the starting frame, the position of the hand and of the sticker are specified and the shapes of the search areas (white boxes) are set, and then the coordinates of these points are automatically recorded in subsequent frames. In the diagram to the right, the horizontal position and the vertical position of P1 are plotted against time. This is combined in the diagram with a sinusoidal fit of the horizontal displacement of the yoyo, due to an unintentional pendular motion of the yoyo, and a quadratic function fit of the vertical position during the first phase in which the yoyo unwinds. These trend curves can be used as coordinate functions of a computed point that is displayed in the video clip (P2): It turns out to be close to the position of the axle during the unwinding phase of the yoyo. For detailed modeling of the yoyo motion we refer to (Heck & Uylings, 2005). For details about the algorithm implemented in Coach for point-tracking and for other features of the tool (such as perspective correction) we refer to (Heck & Uylings, 2006), in which other inspiring examples of data video activities can be found too.
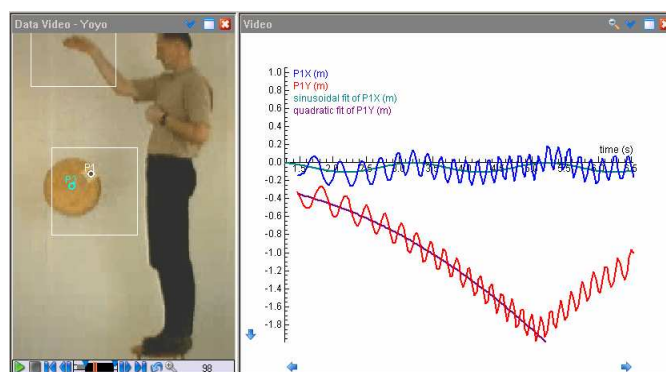

Figure 3. Screen shot of a video analysis activity about the motion of yoyo.

Data video and **image measurement** have potential for studying real world, everyday scenes of motion and for linking mathematics and science with the real world. An example of a

measurement on a digital image that is otherwise difficult to realize is shown in Figure 4, in which the shape of the Golden Gate Bridge is investigated. The digital image to the left is the original picture but it is perspectively distorted. Therefore data collection is done in a modified image in which a fronto-parallel view of the bridge has been realized. Technology can be used to raise questions: in the diagram to the right several regression curves that successfully match the recorded position data of suspension cable are shown, but which one is the best and on the basis of what criteria? In popular wording: tool use can turn brains on.
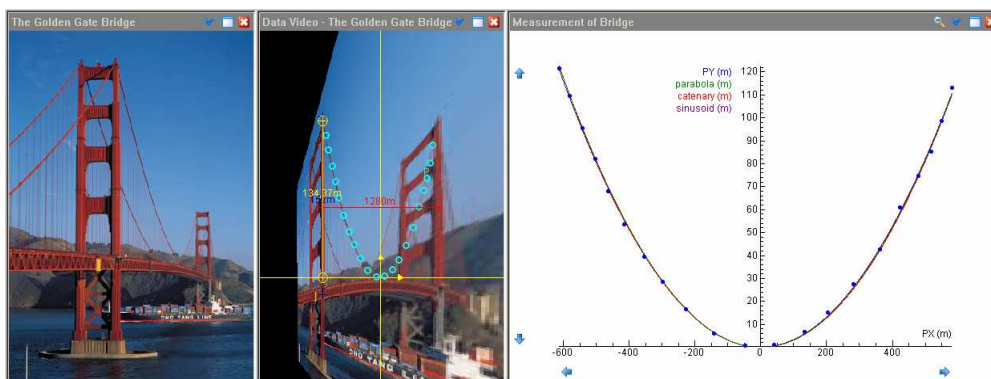

Figure 4. Screen shot of a photogrammetry activity with image rectification and regression.

Instead of regression, one can also use numerical models to investigative the shape of the above bridge. A **modeling activity** offers the environment to create and run numerical models and to compare theory (the model) with measurement (experimental data). To this end, three types of model editors are available: text-based, equations-based, and graphical. Figure 5 shows a graphical model of the main span of Golden Gate bridge that is based on the approximation of the suspension cable by k_{max} straight line segments with horizontally equidistant joint. It leads to a parabolic approximation (Heck & Holleman, 2002). The meanings of the icons in the graphical model are similar to those of system dynamics software like STELLA (www.iseesystems.com) or Powersim (www.powersim.no), which use a stock-flow metaphor for dynamic changing systems: there are icons for state variables (stock), rate of changes (flows), auxiliary variables, constants, and connectors. The graphical elements represent a computer model, which provides in many cases a numerical solution of a system of dif-

ferential equations. Research (Löhner, 2005) seems to indicate that graphical modeling offers students an easier-to-use and richer framework for understanding the structure of a dynamic system in comparison with text-based modeling and that it allows them to build more complex models of high quality because they can concentrate on qualitative specifications during initial stages of the modeling process and do quantitative, formula-based specifications at later stages.
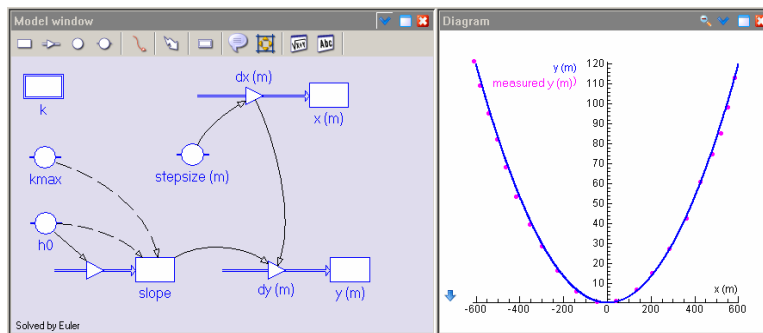

Figure 5. A graphical model of the shape of the Golden Gate Bridge.

Coach is in fact a hybrid system that combines a traditional system dynamics approach with event-based modeling. This extends the set of realistic problems that can be solved by students without the need of sophisticated mathematics beyond their school level. Examples are models of yoyos (Heck & Uylings, 2005), bouncing balls (Heck *et al*, 2008), alcohol metabolism (Heck, 2007), and sprinting (Heck, n.d.). Another example, which also illustrates the possibility to create a manipulable **animation** based on the computer model of a physical phenomenon, is shown in Figure 6.
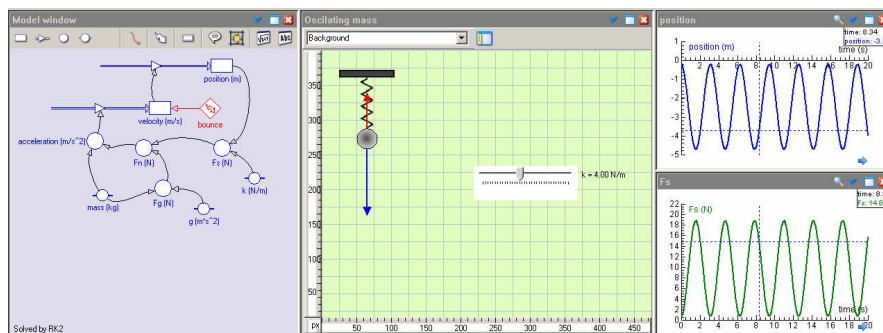

Figure 6. A graphical model of the harmonic motion of oscillating ball that can bounce against the ceiling and an animation of the motion.

The left window shows a graphical model of a ball hanging on a vertical spring attached to the ceiling and that can also bounce against the ceiling; a special event-icon (with the thunderbolt symbol) is used to specify what should happen when the ball bounces. The window in the middle is an animation window that displays the simulation results as animations where model variables are presented as animated graphics objects. A student can interact with the animation through a slider bar, that is, select the value of the spring coefficient before the start of the simulation or change it while the simulation runs. Animation allows students to first concentrate on understanding a phenomenon with the help of simulations before going into the details of how the simulations have been implemented by means of computer models.

TOOLS

As the sample activities have illustrated, Coach is tool-oriented software in which interconnected windows, with their own objects and operations, materialize the tools. The tools can be organized according to functionality:

set-up/definition: set-up for measurement (including data video), control, or modeling; program editor for control; editor for animation.

running, viewing, processing and analysis: run-controls; digital and analog meters; animations; diagrams; tables; data processing and data analysis (smoothing, filtering, numerical derivatives, curve fitting, and so on).

support, reporting, and access to resources: help; printing; file structure; multimedia texts; hyperlinks; students' notes.

Depending on the subject and the competency of the students, the teacher can make a choice of tools. For example, for an experiment in which quantities are measured, a natural choice would be the set-up measurement window (the interface panel), a text window with explanation and tasks, and the graph or table window (Figure 1). Optionally an experiment could be

synchronously captured in a video window and this video clip could be separately used for measurement. The selected tools in an activity are so that students can see the graphs being built up during a measurement or simulation. Later on they can replay the measurement or in scan mode have a close look at relationships between graphs, tables, events in the experiment (captured for instance in a video clip) or the computer model.

OPEN ENVIRONMENT

The main idea of a single open environment is that the toolkit can serve a manifold of distinct purposes and is in itself independent of the many choices that are part of the educational process. In particular it is open in the sense that it is

- a universal toolkit for teachers and students, each with their own perspective, and not for a particular purpose other than education;
- an environment for solving open problems, which need definition, set-up, exploration, modeling, and so on;
- not closely tightened to a particular didactical framework, but can support various instructional methods and strategies.

STUDY OF NATURAL PHENOMENA, MATHEMATICS, AND TECHNOLOGY

The computer working environment is directed towards mathematics, natural sciences, and technology. All these disciplines use texts, tables, graphs, and so on. One of the great challenges in educational software design of a versatile working environment lies in coping with the different conventions in the fields about notations, naming of variables, use of language, and so on (c.f., Ellermeijer & Heck, 2002) and with the different nature of the disciplines.

EDUCATIONAL SETTING

The fact that the computer working environment Coach is designed for the educational setting influences how it is perceived at distinct levels.

The student regards it as a set of tools for measurement, control, data analysis, modeling, simulation, manipulable animation, receipt of tasks, and for reporting results.

The teacher perceives Coach as an environment where the student can explore phenomena and do practical work and investigations. The teacher can gear activities to students' needs and abilities. An inexperienced student benefits from materials with a predefined layout of tools and screen casts that teach how to use the environment. For the more experienced student, the choice of tools is part of the learning activity.

The author is a third level. For instance, the author can be a teacher, a student who does a research project, a textbook author, or an educational publisher. Dutch mathematics and physics textbooks include chapters in which use of Coach is integrated. Klett-Verlag has recently published a physics textbook (Bredthauer, 2007) in which the video and modeling tool of Coach 6 have been fully integrated in the learning text. This is all achieved with the authoring environment that offers an easy-to-use extension of the functionality to create multimedia materials.

CONCLUSIONS

Looking back at twenty-five years of research on the use of ICT in education, curriculum development, and software, and hardware development it is fair to say that a lot has been achieved in the Netherlands. Hardware and software development, including the development of the working environment Coach, has been able up to now to meet more or less the requirements of trends in mathematics, science, and technology education such as the change towards context-rich education, emphasis on scientific approaches, better preparation for higher education through a stronger focus on competencies, and emphasis on individual learning and provision of students' autonomy over the process of knowledge and skills acquisition. This work will undoubtedly continue, due to the very nature of technology and education, and new demands from society. A sustained approach and concerted action of innova-

tion, investment in infrastructure, teacher professionalization, and change of curriculum and

examination lead to the best results.

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