SIMULATION AS SCIENCE DISCOVERY: WAYS OF INTERACTIVE MEANING-MAKING

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This article addresses how computer-based simulations may support conceptual learning in science education. The study investigates how these interactions unfold, and explores how it may inform design. The article reports on project-based learning in schools where four pairs of students from upper secondary school use a future climate simulator integrated in a web-based learning environment. Our analytical focus is on how the students make use of the simulator to make meaning through the process. The analysis shows a considerable variety in how the students interact with the simulator, and in how they engage in a conceptual level of understanding. The findings indicate that the design was engaging, and three main modes of surprisingly stable uses were identified: utilizing the simulator as a way to get facts, enjoying the aesthetics of interaction as playability, and finally, making use of the simulator as a tool for discovery through cumulative micro-experiments.

Keywords: Computer-based simulations; inquiry learning; studies of use.

1. Introduction

Computer-based simulations are important parts of many inquiry-learning environments. Simulations can encourage students to actively explore and discover information and conceptual relations, allowing scientific discovery by means of a simulated realistic setting (de Jong, 2006). Discoveries can be stimulated, scaffolded, and encouraged, but the learner should experience the discovery as "theirs" and discover through their own inquiry (Rieber *et al.*, 2004). One characteristic feature of most computer-based simulations is their openness and lack of structure.

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As opposed to structured approaches such as filling in forms or answering prompts, i.e. interfaces where a sequence is implicit, these learning environments can be operated and navigated by the users' choice. A non-sequential object such as a simulator does not inherently direct the user: students have the possibility of discovering for themselves the novel relationships that exist between elements and in this way gain new insight, but they may also enter into meaningless dead-ends and thereby miss the opportunity to construct an appropriate understanding of the problem at hand.

This exploratory article is about how such interactions unfold. To investigate this process, we study students' interactions with a computer-based simulator in a classroom setting. Our focus is on how interactions develop into meaning for the students in open learning environments, with the use of technology in context. The empirical material in this paper derives from a study of four pairs of students (dyads) interacting with a simulator integrated into a web-based learning environment. The topic is future climate change and how developments in energy consumption, energy efficiency, wealth, and population growth may affect this process. Using a simulator, the students can modify a set of parameters and study the outcomes in terms of future CO_2 emissions, changes in global sea level, and rise in average global temperature. This study investigates the relationship between material interaction with the simulator and conceptual learning in simulation-based open learning environments.

In Section 2, the theoretical grounding for the study is presented with regard to how simulation can be used in inquiries regarding structure and student activity. Two approaches to learning research are outlined and the research question concludes this section. Section 3 contains the trial description and method. The detailed use studies are in Section 4. The last two sections contain a discussion of interactive meaning-making and conclusions.

2. Simulation-Based Learning Environments and Inquiry

The active character of simulations makes them suitable for the pedagogical frame of learning through science discovery. Employing a mode of investigation, the students can discover relationships and explore them. This model of learning through science discovery is based on a student having a certain degree of freedom to explore; hence simulations are suitable environments for experiments (Veermans *et al.*, 2006; de Jong, 2006). It is about bringing the scientific process of inquiry into learning (van Joolingen *et al.*, 2007). This process should not be like walking down an existing path, rather, it should be an investigation of the environment in an attempt to discover and build knowledge from these discoveries (de Jong & van Joolingen, 1998).

The process of discovery learning is, however, not straightforward. Based on a literature review, de Jong and van Joolingen (1998) identify a number of characteristic problems that students encounter in discovery learning, classifying them according to what they call the main discovery learning processes: hypothesis generation, design of experiments, interpretation of data, and regulation of learning.

They argue for the need to support students during the discovery process, asserting that the main focus for research in the area should be on how this can be done in an efficient manner: "Studies should aim to find out when and how to provide learners with means to overcome their deficiencies in discovery learning — in other words, when and how to provide scaffolding for the discovery learning process" (de Jong & van Joolingen, 1998, p. 195). There is a challenge to overcome the inherent contradiction in discovery learning — guiding students to the "right" path, but at the same time letting them discover and make the discovery their own. This is a process that is difficult to orchestrate. Whereas asking students to read a text and recite or answer questions about its content is a straightforward course of action, discovery is a process that needs to be stimulated rather than commanded (Hodgkin, 1985).

In line with the appeal from de Jong and van Joolingen (1998) many studies have addressed particular aspects of the discovery learning process and have investigated how digital learning environments may scaffold these processes in efficient and relevant ways. Based on an analysis of previous studies, Chang *et al.* (2008) recognize five types of learning support that are used in simulation-based learning: provide background knowledge, help learners make hypotheses, help learners conduct experiments, help learners interpret data, and finally, help learners regulate the learning process. Studies addressing these issues have contributed to knowledge of how various configurations of the technological environment impact upon students' skills and understanding in a range of knowledge domains.

2.1. *Inquiry and structure*

The open-ended character of computer-based simulations invites the user to experiment with a variety of elements, potentially providing an exploratory learning environment appropriate for learning through scientific discovery. There are, however, several challenges involved in developing such learning environments, and many of these difficulties are due to the complexity involved in the process of experimentation. The undertaking of an experiment involves a complex orchestration of activities (Glaser *et al.*, 1992). Although there are some patterns of strategies and heuristics performed more often by successful discoverers than those who are unsuccessful or inefficient, there appears to be no pattern of strategies that guarantees success (Schauble *et al.*, 1991).

One approach is to support students' development of relevant hypotheses in order to make use of the simulator in an efficient manner. The process of forming an appropriate hypothesis when facing a problem, or modifying the existing hypothesis based on the gathered information, are difficult obstacles for students to overcome (Chinn & Brewer, 1993). Studies have demonstrated that insufficient background knowledge may result in reduced ability to make appropriate hypotheses and accurately interpret relevant data (Glaser *et al.*, 1992). In order to provide background knowledge and help learners acquire better knowledge of definitions and key concepts, Shute (1993) makes use of online dictionaries as a supplement to

simulation-based learning. In a similar way, Manlove *et al.* (2007) offer a set of help files containing domain information that some found to be too difficult to infer from interactions with the simulator. Another approach taken by van Joolingen and de Jong (1991) makes use of a menu to form hypotheses by choosing a set of variables, correlations and conditions.

One issue in open-ended environments is to make students understand how to carry out their inquiry. Studies have shown that students often conduct these inquiries in inefficient or inappropriate ways. For example, van Joolingen and de Jong (1991) find that students often manipulate variables that are irrelevant to the hypothesis, and that, consequently, the percentages of successful experiments in their study turned out low. One way to mitigate these problems, which has proved to increase the efficiency in terms of learning outcome, is to provide learners with general information about inquiry design (Reid *et al.*, 2003). Njoo and de Jong (1993) offer students six information sheets and a set of fill-in forms, each categorised according to learning processes reminiscent of the phases in scientific investigation. A more visually oriented method is applied by Manlove *et al.* (2007), who provide a tool that includes a visualization of the main activities involved in scientific experimentation.

An important part of learning through scientific discovery is the interpretation of data resulting from interaction with the simulator. Successful learners are better at finding regularities in the data than are unsuccessful learners (Schauble *et al.*, 1991). Prior knowledge helps students interpret patterns of evidence, but if prior knowledge is incorrect or incomplete, students may ignore, distort or selectively interpret the data (Glaser *et al.*, 1992). To support the process of interpretation, Zhang *et al.* (2004) provide a table showing the comparison of variables. This feature is intended to help the process of interpreting data in order to draw appropriate conclusions.

Knowledge gains in learning through scientific discovery are not only a product of processes such as hypothesis generation, experimentation, and interpretation of data, but must also be seen in relation to metacognitive factors such as the students' knowledge and regulation of their learning processes (Chin & Brown, 2000; Kuhn *et al.*, 2000). Studies have shown that successful learners systematically plan and monitor their activities, while unsuccessful learners work in unsystematic ways (Simmons & Lunetta, 1993). Azevedo (2005) argues that during the scientific discovery process, students should monitor their own activities and be in control of the learning progress.

One approach to this issue is to stimulate these processes by technical scaffolds as additional features. Students' monitoring strategies may be enhanced by the use of techniques such as explicit prompting and strategic feedback. Manlove *et al.* (2007) make use of hints, cues, and prompts to promote monitoring through note-taking. Students often report their work in the science classroom by writing lab reports. Manlove *et al.* (2006) include a report template and provide issues and suggestions against which students' learning processes and physical outcomes are

evaluated. Zhang *et al.* (2004) direct students to fill in a form that guides them to reflect on an experiment they conducted by use of a simulator.

Furberg (2009) offers an alternative perspective on scaffolds and shows how prompts formed as questions may turn the inquiry into a test-like situation for the students. The questions stimulate the students to move the focus away from the substance of the inquiry and over to what they believe is expected of them (Chinn & Malhotra, 2002). Furberg (2009) makes a distinction between content-oriented questions that trigger the test-like situation and other prompts or scaffolds for the procedural aspects of inquiry. The procedural support for the inquiry seems to more effectively trigger the reflection aimed for in inquiry learning, particularly since the inquiry in itself is challenging to handle as a process for the students. The content-oriented prompts are more disposed to trigger fact-finding behavior.

2.2. *To do and to understand*

Simulations are invitations to act and carry an implicit assumption of learning as a result of the activity. Several authors have studied the relationship between acting and learning in a context of using a digital inquiry environment. Krange and Ludvigsen (2008) show how students, through use of artifacts, can engage in activities that stay limited to procedural problem solving. This activity does transcend to link the concepts to the larger system of a domain (conceptual learning), but rests in the mechanical solving of a problem according to a recipe. van Joolingen *et al.* (2007) use the terms first-order and second-order learning in relation to the effects of scaffolds on the inquiry-based learning of science. The first-order is about performance of the operations; the second-order is about actual knowledge gain. Rieber *et al.* (2004) use the term implicit knowledge when the learners are able to use a simulator to produce results within the frame of the technology, and explicit learning as knowledge gain in the domain measured by use of traditional tests. Common for all studies is that they link procedural and conceptual problem-solving activities and have the first one as a source for the other. Deeper conceptual knowledge building derives from procedural activities. Indeed, the digital environment designed in the studies above is concerned with facilitating the procedural activity in order to support the leap to conceptual knowledge.

Schön (1983) provides an alternative to the dichotomies presented above, yet has elements of the same reasoning of moving from action to understanding in his notions of reflection-in-action and reflection-on-action. Working from a broader structural level of education in society, Donald Schön also studies the micro-processes of design and learning (Schön, 1992). From studies of professional design work, he observes how designers act, study the consequences, and act again based on conversation with the materials of the design situation. Expected outcomes of actions, together with unexpected ones, become a basis for new reflections and activities. As the literature above can be said to make a distinction between action and reflection (procedural vs. conceptual, type 1 vs. type 2, implicit vs. explicit), Schön

tries to see how reflection is integrated in action. Detailed studies of the cycles of see-move-see reveal how the development of human knowledge is entangled in the material qualities of the objects on which we operate.

2.3. *Systemic vs. dialogic*

A majority of the studies presented above can be characterized as what Arnseth and Ludvigsen (2006) call a systemic approach to learning research. A fundamental tenet in these studies is to generate models of how features of the technological system affect reasoning, collaboration and structures of discourse, and the main task for the analyst is to describe and account for how configurations of the system contribute to the process of learning. The result of this practice is the formulation of models, or the readjustment of previous models, and the specification of correlations between parameters in such models.

Arnseth and Ludvigsen argue that not enough attention has been given to the emergent characteristics of activities that unfold when tools are introduced into the classroom, and that this is particularly the case in studies following a systemic approach. In a context of computer-supported collaborative learning (CSCL), they contend that there is a need to "examine more closely how the meaning and functions of CSCL applications are actually constituted in practice" (Arnseth & Ludvigsen, 2006).

This is the approach taken by studies that Arnseth and Ludvigsen call dialogic. Dialogic studies do not have their analytical focus on the impact of the learning environment on learning outcome; rather, their main focus is on understanding the process of learning in the setting where the activities take place. Another important element in these studies is an emphasis on the cultural, institutional, and historical contexts of action (Wertsch, 1998), implying that the ways in which students make meaning with technology in the classroom must be seen as part of a particular tradition of teaching and learning.

Our study is in line with this latter approach. We study how a computer-based simulator is used in order to better understand how the interactions unfold in the context of the classroom. Hence, our focus is on the process of use as learning rather than on the outcome as product. Yet, the process is studied in order to find out what kind of knowledge the students build and how they build it. In line with dialogic thinking, this study does not look for how close the students come to an ideal model for inquiry learning, but rather, studies the interaction and dialogue as they unfold. Our analytical focus is on the students' interactions with the technology and the discussions that emerge as they work together in pairs. We investigate the students' processes of meaning-making through use in the context of the classroom.

2.4. *Research questions*

The computer-supported inquiry learning (as noted above) is presented according structure, to learning activities and as a way to move from doing to understanding.

The study presented here enters into a detailed investigation on the ways in which the students interact with the digital environment and how they discuss their findings during their interaction. In an environment blending structure and open exploration, this study looks for learning where it emerges during the process of use. The video and audio data enable us to scrutinize the operations the students execute together with the discoveries revealed verbally by the students. The study targets interactive meaning-making and asks:

- How do the pupils use the technology in context to make meaning and engage in conceptual learning?

This question enables the study to capture what emerges as the most salient elements in the use of technology and the context of that usage when it moves into conceptual learning. This includes how elements in the design of technology enables, restricts, and engages the students. Interactivity is studied to determine the extent of the activity as a driving force in the transformation from procedural to conceptual learning. Here, we investigate how interaction may bridge the gap between performing a procedure and reaching a conceptual level of understanding by use of the technology. In a study of simulations used for science learning, Rieber *et al.* explicitly call for qualitative studies to understand relations between implicit and explicit learning, due to their "explanative power" (Rieber *et al.*, 2004, p. 321). An aim with this study is to dive into the processes in which the students engage when using a digital environment for discovery learning, specifically analysing the activities and discussions that are generated.

3. The Trial

This article is based on project-based learning in two classes in two different upper secondary schools. The students were 16 and 17 years old, working together in small groups of two and three persons. The topic for the project was climate change. The work was distributed over three weeks, filling a total of 15 school hours. The basic "story" frame was that the students should prepare themselves to act as youth representatives at a simulated conference as part of the United Nations Intergovernmental Panel on Climate Change (IPCC).

The student project contained two main phases. In the first phase, the students used a curriculum on the Viten website. Viten is a collection of different curriculums for learning science in upper secondary schools and high schools in Norway (www.viten.no). For this project, a modified version of the Viten curriculum, "On Thin Ice", was used. The modification consisted of the climate simulator and an extension of the workbook with issues relevant for the simulator. The workbook is a sequence of questions in a pop-up window where the students enter answers in a field below the questions as they proceed through the content of "Viten".

There were nine questions with which the students needed to use the simulator in particular. The workbook for the simulator begins with four fact-based questions,

mainly to make the students familiar with the simulator and the interaction. Then the five last questions gradually move into a more explorative form, inviting the students to investigate relationships. Examples of questions are:

Q2: Which scenario gives the largest CO_2 emission, largest increase in temperature, and rise in sea level? Use the climate simulator.
Q4: How much may the average global temperature increase in the year 2100 if the world develops as the scenario "a divided world"?
Q6: [explanation of how to interact]. What effect has a steady development of fossil fuel use on CO_2 emissions, temperature increase and rise in sea level?
Q8: What are the dependencies between emission of CO_2, temperature increase and rise in sea level (the three graphs in the right coordinate system)?

In the last question, students were invited to experiment freely, develop their own scenario, list the reasons for the foreseen development, and investigate the consequences in terms of CO_2 emissions, temperature increase and rise in sea level.

In the next phase of the project, the students got the assignment to focus on the "conference" and worked to collect relevant and good-quality information to supplement the material from Viten. They prepared their presentations and wrote short reports. The project ended with a conference lasting two to three hours, during which each group presented their material. This phase is not included in the present study.

3.1. *The future climate simulator and context of use*

The focus in this paper is the students' use of the simulator as they worked on the questions. The question structure gave them, on the one hand, a sequence of questions to answer and, on the other hand, a "spatial" and non-sequential simulator as an object on which to operate. The simulator is designed according to the IPCC scenarios for the years between 2000 and 2100 (see Figure 1).

The general learning goals for using the simulator and answering the questions were that the students should be able to discover the relationships between the four driving forces and their impact on climate (temperature) and sea level. The students could interact with the simulator by choosing between the four tabs representing the four main scenarios developed by IPCC. They could also alter the graphs by direct manipulation. The four driving forces for every 10th year between 2010 and 2100 was represented by a bullet; The bullet could be altered by dragging it up or down, resulting in the graphs changing. When manipulating the left curves, the curves in the right system responded directly and changed. The pedagogical idea was that the students should commence by familiarising themselves with the simulator, to get the information they needed to answer the first questions and, from there, begin more exploration activities by answering the forthcoming open questions.

In the design of the simulator, efforts were put into making it inviting for interaction. Activity as a motivating factor was an important design principle. The curves
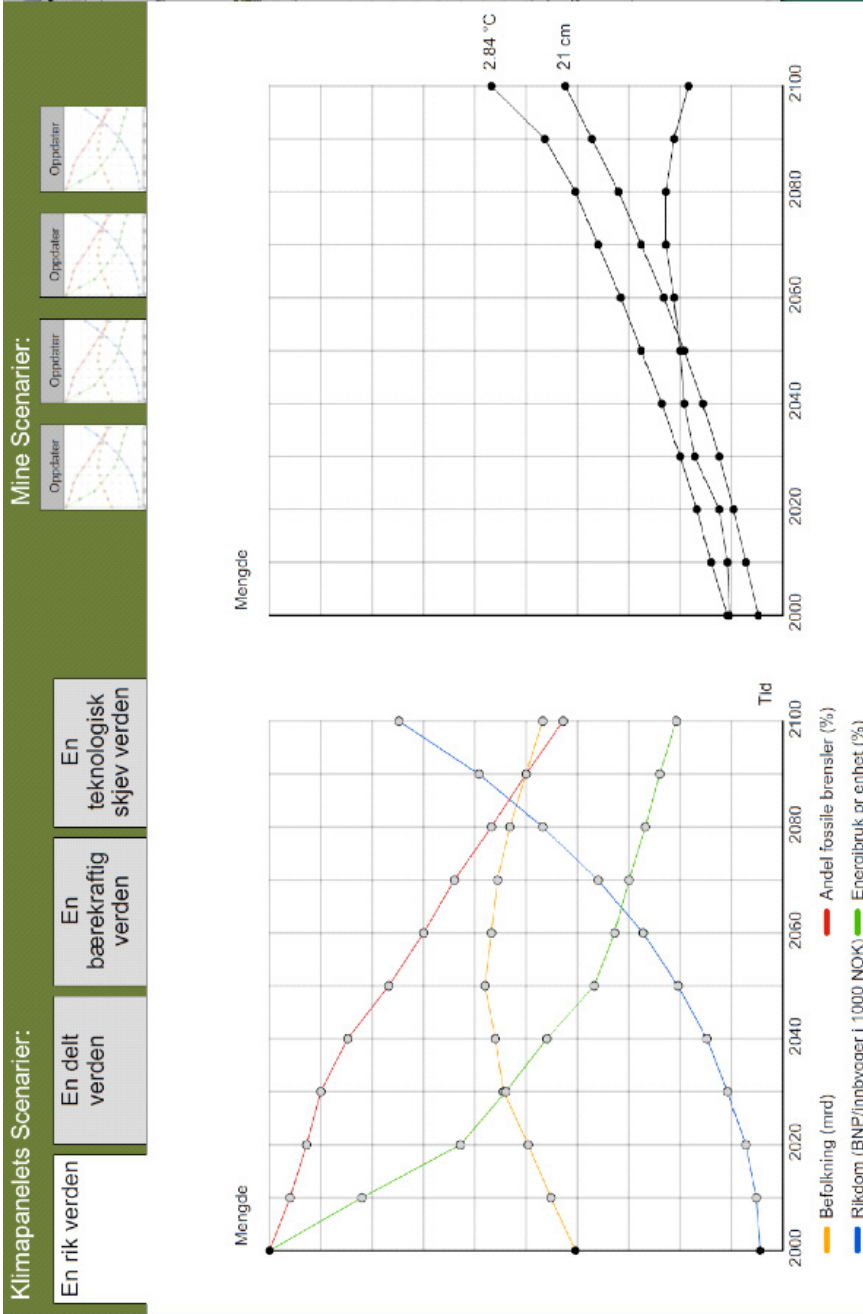
Figure 1. The future climate simulator: The left graph gives the driving forces for the three curves in the right graphs. The curves in the left graph represent (1) world population in billions, (2-below) world wealth in GNP/inhabitant, (3) fossil fuel use as a percentage of total fuel use, and (4-below) energy efficiency as a percentage of the efficiency in the year 2000. The curves in the right graph represent CO_2 emissions (without number in endpoint), rise in temperature (here: 2.84°C) and increase in the sea level (here: 21 cm).

that could be manipulated were coloured, and the right set of curves were in black to indicate that they were not possible to manipulate directly, but were rather a result of the other curves. One goal of the design was that the users should be able to enjoy the feeling of being in control, as the consequences of their actions immediately appeared as changes in the right graphs. They should be able to experience having the power of development of the global population, wealth, energy use and efficiency in their hands.

As the coordinate systems both had several graphs, the axis could not be used to show the values. This issue was solved using a mouse-over interaction technique. When the user would place the mouse pointer on a point un the graph, the corresponding denomination would become visible at the axis, and the value pair at the point would appear next to the mouse pointer (known as "tooltip" interaction technique). This was done in both coordinate systems. In addition, the two curves representing rise in temperature and increase in sea level had values of 2100 continually present in the right-hand end of the curves (see Figure 1). The rationale for this was that the values represented a kind of end result for the simulator, answering the question, "How much can climate, and its subsequent sea level, change in 100 years?"

3.2. *Method*

This is a qualitative and interpretative study (Walsham, 1995), carried out as a field trial with video observation analyses, combining interaction analyses and observation of use (Jordan & Henderson, 1995; Kluge, 2005; Derry *et al.*, 2010). Four dyads were selected for observation with video cameras. The video recordings of the students' discussions as well as how they operated the simulator are the main material for analyses in this paper. The students' workbooks, as they were written in Viten, their reports and presentations, as well as the general observations conducted throughout the project period, were used as background information.

The issue in this article is interactive meaning-making, and the research question concerns use and discovery in the classroom. The analysis is based on excerpts consisting of talk and computer interaction. The students were encouraged to talk within their group as they were working, as this gave access to the reasoning they were employing at a given point in time. The video-material shows their interaction with the digital environment. The extracts of data were studied in detail as transcriptions and video material, shared and discussed with other researchers outside the project. The excerpts presented in this article were selected as representative for the group with regard to interactive meaning-making (Derry *et al.*, 2010). To qualify for selection, the students had to engage in talk related to the concepts in the simulator and at the same time engage in interaction relevant for the talk and for conceptual relations. These instances of talk and interaction in the groups are the units on which the analysis is based (Fjuk & Ludvigsen, 2001). Two of the groups are represented with only one excerpt in the text as it, for the purpose of this article,

covers the pattern of activities well. The two other groups have a larger spectrum of activities relevant for this study, and are as a consequence represented with three shorter excerpts each. Based on video studies and examination of transcripts, 18 excerpts of the four groups were originally selected.

At the outset, six groups were selected for video observation. The selection was based on two criteria:

- we wanted a mix of high achievers and lower achievers
- they should all be talkative

The teachers selected the groups for us, partly also on a more indefinable notion of who could handle intense observation and research attention. Data from only four groups are used in this paper. The material from the two groups was discarded for different reasons; one three-person group was very difficult to observe properly because the computers were moved around and the students' heads made the screen invisible on the video. The other group was discarded, as they did not really engage in the project work and one of them was absent for more than half of the project.

The four dyads in the material consisted of two clearly high achievers (groups B and D), and the two others who were more middling achievers and a mix of both (groups A and C). Gender was not a specific issue for this study, but we wanted to have a reasonable mix. Groups A, B and C were formed by a girl and a boy, and group D consisted of two boys.

As an exploratory study, the two groups omitted do not imply a serious validity problem for the study. The four dyads represent a reasonable variation in order to explore issues on interactive meaning-making in relation to this specific technology.

4. Use of the Future Climate Simulator

The groups worked with the climate simulator for about two school hours to answer questions. The session with the climate simulator followed a session where they had already answered several questions about global warming based on the information in "Viten". The groups followed a standard "script" suitable for Viten; based on information they found on the Viten website, they answered questions (Furberg, 2009). As they began to engage with the simulator, use developed further, as reported below.

4.1. *Group A*

Even though group A finished first, they were not on target all the time. Within their very efficient answering of questions, they diverged to other non-curricular issues a number of times during the period of using the simulator.

Group A was active and seemingly in a constant hurry when answering the questions. When confronted with questions, they sought to find immediate solutions by

using the simulator. In the excerpt below, they have just seen question 6, including the description of how they could alter the curves. The question asks them to keep the portion of fossil fuel use stable, and study the effect of the resulting graphs (see question 6 page 8). The statements and the actions are organised in the excerpts according to time development, with simultaneous and activities aligned vertically.

Excerpt I

1. Kari: "Ohhh... you can do things here!" (positively surprised)
2. Kari: "Oh, oh, oh... they are connected, right." (enthusiastic)
3. Gerwan: "What is the question?"
4. Kari: "OK, what is this?
5. Kari: "CO_2."
6. Gerwan: "The effect is... what is this again?"
7. Kari: "CO_2."
8. Gerwan: "Increases ...!"
9. Kari: "...drastic."
10. Gerwan: "... drastic."
11. Gerwan: "But, the temperature and increase in sea level is stable."
12. Kari: "Is it?"
13. Gerwan: "Isn't it?"
14. Kari: "Yes, it is as it was ... like."
15. Gerwan: "Let me try to drag it down and see if anything happens. Well, yes, it's rather ... [stops]."
16. Kari: "OK. Write that."

a. Kari moves to the graph and immediately starts changing one of the curves.
b. She moves the different curves in the graph to the extreme top and bottom, studying the effect on the right-side curves.
c. They both read from the screen.
d. Kari marks the text on the screen as they read it.
e. Gerwan now has the keyboard and mouse. He moves the mouse over to get the mouse-over information.
f. They both laugh. Gerwan writes the answer.
g. He moves the graph, % fossil fuel up and down, but only for the year 2100 (the last year in the simulator). Studies it.

In the beginning of Excerpt I, Kari enjoys the possibility of operating the simulator. The students do not discover it themselves; only when reading the question do they realize the possibility. When they do, Kari immediately tries out the extreme positions of the curves and obviously enjoys what she is doing (action "f" in Excerpt I).

As they seek to give an answer about the relations between the curves, Gerwan puts up a small "experiment" in the last part of the excerpt (statement 15 and action "g") by trying to alter the curve showing the fraction of fossil fuel. But, he only does it for the last year, 2100, thereby making it impossible to study the long-term effect, as the simulator ends with the year 2100. The group seems, in this

situation, to be on the verge of discovery. Yet, they leave the issue without getting the relationship which the question asks them to explore, that is, between the two sets of curves (driving forces and resulting effects).

Excerpt I illustrates how Kari in particular presses on to get definitive answers, and she does not have the time for Gerwan's experiment. The dyad as a whole then works for quick and definitive answers as their workbook also reveals. They do not pick up the invitation to explore the questions. The group becomes by far the first group in the class to consider the answers completed in the workbook. They aim for a quick solution from the digital environment, and as they encounter situations in which more complicated interaction and reasoning are invited, they prioritize efficiency, even though it occasionally leads to tension within the group.

4.2. *Group B*

Group B was motivated, ambitious and hardworking throughout the project. Both members of the group considered to be high achievers by their teacher. They seldom diverged from the assignment they were working on. Similar to group A, they only discovered the direct interactive possibility with the curves when they were told so in the question.

In Excerpt II, as group A in Excerpt I, group B is working to answer question 6 (where directions for changes are given,) and they are invited to discuss the consequences with regard to CO_2 emissions, global temperature and rise in sea level:

<div align="center">Excerpt II</div>

1. Hilde: "Are we supposed to put this one up like that? ... Is this fossil fuel?"	a. Changes the curves according to suggestions in the question text.
2. Per: "Yes ... and it gets warm."	b. Writes the numbers by hand in a notebook, the results from hanging the level of fossil fuel use.
3. Hilde: "Should we just write down the numbers, then we have them."	
4. Hilde: "What is 24 cm?"	c. Uses mouse-over to get the information.
5. Per: "Rise in sea level."	d. Writes what he is saying.
6. Hilde: "It will be increased in both temperature, sea level, emissions ... or ... "	e. Writes what she is saying.
7. Per: "All the three factors ... curves ... temperature increases by 3.44 degrees."	
8. Hilde: "...and the sea level increases by 24 centimetres by the year 2100."	

It is representative for the group that they begin to answer a question by asking themselves what the expectations are of them — what they are "supposed to [do]" (1). Hilde operates the simulator and positions it according to the suggestions in the question (to keep the fossil fuel portion stable) and then leaves it there. They look for definitive answers in numbers and use the mouse-over function implemented to get them. They focus on numbers (statement 3), and then build on this to continue their reasoning with additional factual numerical information (statements 4, 7 and 8).

As the two alternated between using the simulator and answering the questions, they were generally cautious, staying close to the text in the question. When they came to the questions inviting the students to explore, they began to hesitate. They looked for definitive answers, and when confronted with a reply to open questions, Hilde said with obvious frustration, "It is difficult to write", and Per agrees: "Yes, it is difficult to write". Important dynamic relationships with which to explore the question can be expressed by use of the simulator, yet they discuss relationships in a more static way, giving them numbers rather than discovering general dependencies. They use the simulator to look up information such as facts and do not explore by changing the graph. The answer in the workbook consists mainly of the three numbers read from the simulator: the two in the excerpt and the number for the CO_2 emission. Group B spends time writing in the text boxes rather than interacting with the simulator, and have generally longer answers than the other groups.

4.3. *Group C*

Both members of group C were active both verbally and with the simulator throughout the project, but it is mainly Inger in the group who interacts with the simulator. They moved in and out of the curricular topic and switched between discussing personal issues and project-oriented work with ease. Group C was the only one of the four groups observed that discovered that they could change the curves in the left system of coordinates before they came to the text that directed them to do so. They started to make their own scenario as soon as they opened the simulator. The group did not relate it to any information about a probable development, but were fascinated by doing the interaction as such. As Inger said (jokingly) after having worked with the simulator for about 30 minutes, "I think I am going to play this when I get home". This playful and intensive interaction characterised their operations throughout the project as they used the simulator. Shifting between playful and serious use, they directed their activities towards the simulator, occasionally even interacting in a mode of distraction when discussing other issues. Figure 2 shows the resulting model of the group's interaction before they began to answer the questions. In Excerpt III, they are reopening and analyzing the
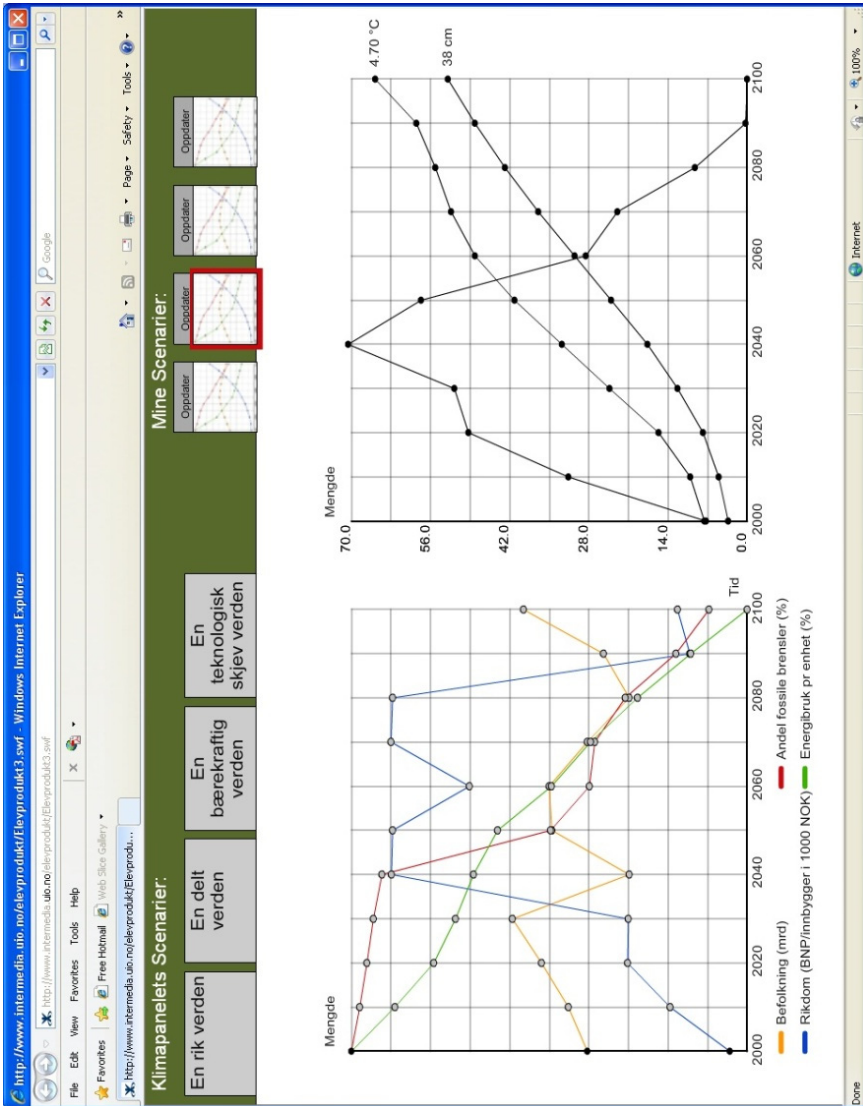
Figure 2. The playful model made by group C.

scenario they made when playing with the curves at an earlier stage (represented in Figure 2).

<div align="center">Excerpt III</div>

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1. Carl: "I will say that this is a sustainable world."(jokingly)
2. Carl: "Maybe a little unstable in the economy, and the death rate . . . "
3. Inger: "Oh, look at this, how much it [CO_2 emission] increases."
4. Carl: "Yes, it completely crazy. Uh . . . ohhh, how did we do that!!"
5. Inger: "CO_2 went all the way down; that is because we took these down."
6. Carl: "OK."
7. Inger: "But why did it increase so much there? OK, we should take it more down, it looks better."
8. Carl: "A little maybe; imagine how cheap it [oil] will be. OK, now everything changed. Don't touch it more now — it became such a nice curve."

a. Points at the curves they have made.
b. Inger laughs.
c. Points at the temperature and sea level with the mouse.
d. Points at population and wealth.
e. Points at CO_2 emission at the peak of the curve (in 2040, see Figure 2).
f. Pull down population and wealth for 2010–2030.
g. Changes the curves according to suggestions in the question text.

Here the unrestricted scenario they have played with previously becomes a vehicle for further exploration. Inger tries to turn the discussion towards some of the relevant relations between the driving forces and the consequences, but does not really succeed. They enjoy their previous efforts and do not seem to be very far from getting the discussion to turn to issues on the relationships between the elements, as statement 5 and 7 from Inger indicate. Yet, they both turn towards a more aesthetic view on the simulator ("it looks better" in 7 and "it became such a nice curve" in 8), and motivation for the "better look" overrules the investigation and therefore the opportunity for scientific discovery in the further interaction.

In Excerpt IV, they have come to a question about making specific changes in the scenario, "The Divided World", in order to understand the consequences of increased wealth in the less developed world. The students were asked to increase wealth globally and experiment with changes in the other three driving forces to make the whole picture in the right graph as stable as possible.

Excerpt IV

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1. Carl: "Hey, come on, drag the last one down, a little bit down... there — there — there."	a. Inger moves energy use down for the year 2100; following his instructions.
2. Inger: "No, it is 2.92."	b. Carl is leaning forward, engaged.
3. ...	c. Points to the resulting curves.
4. Inger: "OK, but this one must be higher. And, that one has to increase; it is right only it should be lower. How can we get it lower?"	

They operate with a high level of precision and they are both engaged in the work. Carl, who had been leaning backwards until this point, now leans forward and becomes considerably more engaged in the task. They handle the question literally to get exactly the "right" numbers, even though the question states that they should approximate levels as the resulting values.

Here the issues of relationships between the driving forces and the resulting emissions, temperature and sea level fade away. They do not refer to what the curve represents any more. Even in the playful exploration illustrated in Excerpt IV, they treat the curves according to what they represent ("economy", "death rate" III.2, "CO_2" III.5); however, in Excerpt IV, they have lost its denomination and refer to it as "the last one" (statement 1), "this one" and "that one" (statement 3). They point to the curves, refer to the number (statement 2) and decide whether the other curves should be dragged up or down, but they seem to discard what theyrepresent and the actual content of the question they work with.

In Excerpt V, they come back to a content-related discussion. When they are to sum up the discussion in writing, they need to describe, in writing, their pointing and moving. The relations seem to return from being understood as curves to being moved up and down to again represent CO_2 emissions, energy, population and wealth.

In this part of the project, Inger and Carl are starting a discussion about the actual substance of the simulator, the relations between the different driving forces for the emissions and how emissions affect temperature. They study the different scenarios and begin to ask core questions about the whole project, namely what caused an increase in temperature (energy? (5) wealth? (7)). However, then Carl thinks Inger by chance has the "right" temperature — the temperature they worked so intensively to get in the previous question in Excerpt IV (statement 8). This is not the case, as Inger explains, but Carl's outburst derails this highly relevant discussion. It was cut off at that point and observations indicate that the discussion did not resume at a later stage. In addition, the written answer did not reveal any development towards understanding the driving forces. In the workbook, the

Excerpt V

1. Inger: "Population has a lot to do with CO_2 emissions."
2. Carl: "Yes."
3. Inger: "What influenced the temperature so damn much? It was ..."
4. Carl: "It was ... all of them really. Look."
5. Inger: "Mostly energy ... ?"
6. Carl: "No."
7. Inger: "Oh, wealth?"
8. Carl: "But, there you are! Wait, stop. Do you see the number you have there now?!"
9. Inger: "That is just because I have taken that scenario."
10. Carl: [disappointed] "OK, I thought ... "

a. Inger writes it.
b. They study the different pre-made scenarios.
c. They are at the scenario "A Parted World", which has the "right" values for all the resulting variables.

question finally became short and superficial ("We have to get energy use and portion of fossil fuel use down").

4.4. *Group D*

Mark and Morten in group D are, as group B, considered to be high achievers by their teacher. They stayed firmly focused on the task throughout the project. If they sometimes digressed, it was related to the issue, e.g. discussing low-energy light bulbs, engine efficiency in cars, etc. It was not easy to capture their activities by observations *in situ*, as they were soft-spoken and often used internal language. However, and this was a surprise, in the video material, with a microphone in front of them, they came through very well with their exchange of viewpoints and use of the digital environment.

Group D begins to use the simulator by browsing through the four scenarios. They examine every scenario in some detail and study what the different curves represent and the relations between them. This is done prior to considering any questions. They have not even opened the workbook where the questions were posed at that stage. As they take one scenario at a time, in a systematic way, they comment on what kind of development that may lead to the scenario. They talk about how the right set of curves is a consequence of the four driving forces, characterizing it adequately as "the result", and also that the increase in temperature is a consequence of CO_2 emissions.

Group D (as A and B) do not discover that they can change the curves to the left before this was explained in the question (although the video reveals that they were quite close to moving the curves on a couple of occasions). Thus, the interaction was limited to shifting between the four existing scenarios by selecting the tabs (see Figure 1) and to using mouse-over to get more specific information, i.e. the numerical values. Still, they worked through all the scenarios and explored their differences verbally. By doing this, they discussed central relationships illustrated in the simulation, still without involving the questions in the workbook. This open exploration enabled them to answer the first and more factual questions very quickly, as they more or less answered them already in their discussions. For the most part, answering the questions consisted of double-checking a result they more or less knew from exploring the scenarios previously.

When the group realized in the fifth question that it was possible to change the curves on the left side of the simulator, both of them were quite surprised and engaged:

Excerpt VI

1. Morten: "\<excited\> did . . . could we do that??"	a. They both read in the task that it is possible to change the curves. Morten alters one of the curves (for the first time).
2. Mark: "Can we drag this one?"	
3. Morten: "oh, oh \<whistles\>."	
4. Mark: "I want to do this."	b. Mark tries to take over the keyboard, but Morten will not let him.

For the next few minutes, they are very active in changing all four driving forces represented by the curves, but they seem for the most part to have a purpose in what they are doing. The operations have the character of small "What if. . ." experiments, e.g. "If we drag everything down [to 0], shouldn't it get colder, then?" and they explore the issue. They explain between the two of them what kind of micro-experiment they are engaged in, and what kind of consequences they are looking for.

Below, they discuss results of one such experiment they have done. The question is about the consequences of keeping the level of the driving forces from the year 2000 and throughout this century to the year 2100.

In Excerpt VII Morten talks as he tries out ideas. He changes the curves and immediately concludes by saying that it is "pretty big" (statement 1). He reasons as he interacts, positioning the curves "all up there" (statement 1) to explore the consequences. Here group D is very different than, for instance, the preceding group (C). Morten and Mark discuss the relationships in general terms ("we get [. . .] an increased temperature and sea level") (statement 3), and when they use numbers, it

Excerpt VII

1. Morten: "It has to be all up there, because it was on the top before. The increase . . . pretty big . . . gets 1 cm more on the sea level . . . wasn't it. . . ?"	a. He changes the share of fossil fuel so it remains at the level for 2000.
2. Mark: "What was the difference?"	b. Mark writes.
3. Morten: "We get . . . I don't remember exactly, but we get an increased temperature and sea level."	

is contextualised into more of the total picture of the development, e.g. temperature or in this case, sea level (statement 1).

They keep focus on the relationships throughout, working to put results into context of what they already knew. They stay on target as they explore and discover relationships. They rarely interact without expressing a direction of the activity where relationships are to be explored.

There are no explicit indicators of more aesthetic approaches towards the simulator. Still, as Excerpt VI indicates, they both become engaged by the opportunity to interact directly and to control the development. When they both made use of this opportunity later, they show signs of enjoying the control over the environment and how it changed. During the presentation that took place after project work was completed, group D were the only ones who made use of the simulator to illustrate their points.

In Excerpt VIII, Morten is reasoning about the latency effect, that is, the fact that emissions stay in the atmosphere for several decades, so today's emissions will contribute to global warming in many decades to come. This is probably the most advanced relationship they could elicit from the simulator, and group D were the only ones who verbalized this consequence of emissions:

Excerpt VIII

1. Morten: "If I place it [the reduction] there, I end up with 1.10 [degree increase in temperature]". That is ten years before 2090, then it is up 1.96, right, so it is obvious that it takes more time [to get an effect].	a. Moves the percentage of fossil fuel in the year 2080 up and down.
	b. Drags down the level for the year 2100.
2. Morten: So, it you had put another ten years there, a change would have had a lot more effect in the last years, but it is only calculated to the year 2100, so we do not get the effect after that."	

Here Morten uses the simulator to explain relationships. The interaction contributes to illustrating his points. Morten also seeks confirmations of his reasoning here, in particular from his co-worker, keeping the analysis in a tentative tone, giving Mark a chance to follow his reasoning and to protest. In addition, his explorative use pattern towards the simulator as he is reasoning indicates that he is continually engaged in an experiment, testing whether the relationship he argues for are correct according to the logic in the application. In addition to being the only group that came to this advanced conclusion, group D was also the only group that discussed in some depth how the different driving forces had different "driving" power, and how the four powers could be seen to be interconnected.

Although the differences between the groups are more striking than the similarities, all the groups enjoyed being active. Below, the similarities and differences between the groups' activities will be discussed according to the goals of design, scientific discovery, and modes of use.

5. Discussion

In this study, the students' use and conceptual learning processes are considered in concert. The aim is to see how learning and collaborative use develop together to make meaning for the students.

5.1. *Discovery of technical possibilities*

One aim for design of the simulator was that it should provide intuitive guidance for interaction. Standard elements such as tabs for the different scenarios and the mouse-over function for specific information did not pose any problems for the students. They started to use it immediately and were able to read the rather complicated set-up — four graphs in one diagram and three in the other, implying seven different scales altogether — in some level of detail. The more experimental attempt to indicate that elements were accessible for interaction by colour, while the elements that were only showing information as black, was less of a success. The material does not give any indications of the pupils inferring that the coloured spots were for interaction. Rather, three of the four groups needed to be told that the curves could be altered. One reason for this may be that the unfamiliar form of interaction, both in form and substance: changing curves (often understood as "facts") at your own wish.

Yet, when they do discover the possibility of directly altering the four curves in the graph, they all express joy and engagement, verbally as well as through pleasurable interaction. The one group that did find out about the interactive possibility on their own even compared it to playing games. One puzzling choice they repeatedly made was to manipulate the last part of the diagram, namely the levels of the driving forces for 2100. One important consequence of doing this is that no illustration of the latency effect can be discovered in this way of interacting. The students do

not have the chance to see what the changes bring about when they only alter the year 2100. The CO_2 emissions for the year 2100 will increase, but the increase of temperature and rising sea level will then come in the years after 2100, which is not a part of the simulation. One possible explanation of the behaviour is that the resulting graph had values for temperature increase and sea level rise permanently shown in the corresponding results graph (see Figures 2 and 3), and that could have dragged the students' attention towards the same year in the other graph. They seem in this case to match the expression of the number with interaction in the corresponding graph.

The interaction opens up different access to the information. The students engage directly and immediately experience the effect. But what does this engagement lead them to in terms of scientific discovery? It is clear that the groups make use of the interactive possibility in different ways.

5.2. *Science discovery and its antagonists*

As shown previously, group D is the only group to discover the latency effect. The fact that CO_2 stays in the atmosphere for several decades is an important learning opportunity with the simulator. Why is it that the other groups did not get to that discovery? What seems to be leading up to discovery by use of technology and resources, and what was working against it?

Several discourses in the excerpts show that the groups are moving in directions that appear promising with regard to making discoveries. When Gerwan in group *A* says: "Let me drag this down and see if anything happens. Well, yes, it's rather ..." (Excerpt I.15) and at the same time moves one of the curves up and down and studies the effect (Excerpt I.g), he demonstrates exploring activity that opens up discoveries about the relationships between the elements. However, the push for efficiency, triggered by the questions, make Gerwan call off the exploring activity and go on to write the answer. Efficiency here becomes the antagonist for exploring and discovery.

Group B follows to some extent in the same track as group A when it comes to being hesitant to explore. As with group A, their work remains tied to the structure of questions. Yet, the institutional structure of what they are at school to do is even more obvious. In the beginning of the session with the simulator, they answer questions in a comprehensive way. Initially, the first four questions are factual and not inviting to exploration. As the question becomes more open, they start to ask themselves what they are "supposed to do" (Excerpt II.1), and are struggling to find the pattern from the facts to answering the question. They try to find a connection between the facts to exploring an object for potential discoveries, but they do not find a bridge to cross. They are reluctant to interact by changing the curves, mostly using mouse-over to get information without actually affecting the simulator. The invitation to explore is not acknowledged. They seem to look for a procedure up front, a known path that can lead them to the right answer, rather than trying

to discover the terrain. In exploratory activities, the blueprint of what they are used to in school, that is, finding the correct answer to the questions, does not help them.

As a clear contrast, group C did not look for procedures or paths. Before we could observe them, they have found the direct interactive possibility and made their own scenario (see Figure 2). As group B prepared and planned their interaction before they took action, group C acted first and then, if it caught interest, tried to find out what it meant later. Yet, as the members of group C move towards analyses, they are stopped on the way. Their lively interaction before the group were confronted with the questions, seems to have kept them on a non-science track. Tendencies to move to discuss concepts and relations are hindered by aesthetical considerations (Excerpts III.7 and III.8) and of the playful mode (Excerpt V). They are close to moving into discussions about central relations between the concepts in the project, but the aesthetical and playful elements overshadow the emerging conceptual discussions. The playful interaction they engage in is also as an esthetical one. When they are asked to make curves that are probable, (e.g. as world population for instance most likely will not change in big jumps up or down over the coming years, and the same goes for the other driving forces) the motivation to make "nice curves" becomes a integrated part of the playful goal-oriented activity to get the "right" values in the curves.

When group D discovers the latency effect, it is a result of a series of actions and discussions they have engaged in. Compared to the other groups, the members of group D are not too engaged in the interaction as such, being efficient, or expecting to get right answers, but are productive in making use of the resources available to them. As Morten discovers the latency effect, he uses both the simulator and his group companion to ensure that his discovery is good. He manipulates the curves as he speaks to justify his points, and explains in a tentative way giving Mark and the simulator a chance to prove him wrong. He makes his demonstration explicit in interaction and in words and thereby open contradicting results in the simulator and counterarguments from Mark.

The way the different groups choose to act can be framed according to Schön's conversation with materials (Schön, 1991). The students "reflect in action". The "see–move–see" structure is described as a series of design "experiments" by Schön (1992). The students' conversation with the simulator follows this iterative path, but with what can be described as a different "turnover rate". The two first groups use the simulator to look up facts, similar to the way one might look up facts in a table to get answers. Group C moves over to the other end of the spectrum and almost cuts short the "seeing" phase of reflection of what is been done. In this process, action and reflection converge, and Schön's cycle collapses into a game-like activity. The issue at hand fades away. Rather than reflection in action, action triggers another and virtually instinctive action in a frequency that hampers reflection and, as a consequence, the possibility of discovery and knowledge building. The playful

activity turns into gaming, and verges on being a gameplay[a] experience for the dyad. Rather than moving the dialectic in a cycle between doing and reflecting, the gameplay appears to contain its own cause and effect in continuous action, leaving the actual issue behind.

Group D balances the actual exploring activity with reflection. They are continuously active, alternating between the scenarios in the beginning and later manipulating the curves, while simultaneously reflecting, as the conversation between them signifies. They seem to be able to balance the two processes of exploring and reflection, making it into a genuine intertwined reflection-in-action process (see Figure 3). If we compare with the activity of group C where game-like action overrides reflection and whirls out into non-reflective and irrelevant activity with regard to knowledge building, the exploring and reflection in which group D engages balance each other. The exploring activity feeds reflection and reflection results in new ideas to explore. This balance between constructive processes contributes to keeping the group on track and moves their knowledge forward. Rather than being iterative in isolated events of action and reflection, the group interacts as they reflect and reflect as they interact. Still, they manage to let the responses from the environment influence them as they use the simulator as a device of discovery as well as a live illustrator that can confirm or reject their discoveries.

As illustrated in Figure 3, playing misses a balancing counterpart compared to the other two "Schönian variations". Look-up/scanning are inherently sequential, rather than iterative. It is a mechanistic and almost book-like operation that can be done effectively in this digital environment (as in other searchable information objects), but does not bring substantially new processes to the fore. The integrated exploration composed of a balanced "Schönian" activity of exploration and reflection makes use of the combination of control panel and information (Manovich, 2001) that is so characteristic for digital environments. Still, improperly balanced results in exploration never getting started. Too much weight on reflection gives
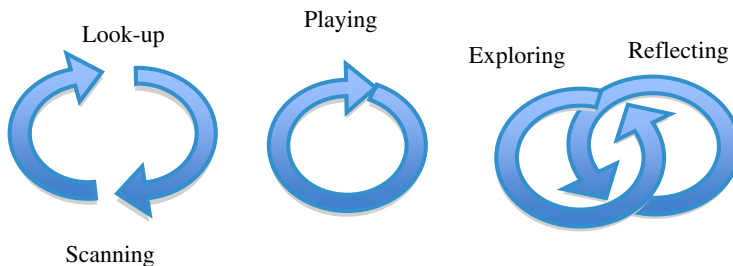

Figure 3. "Schönian" variations.

the exploration too little fuel to proceed, and too much exploration without reflection directs the activity towards playing and even gaming, rather that knowledge building.

The varied use illustrates how the simulator as an interactive object can fill many roles. The question then becomes how design may enhance or correct the processes that do not contribute to knowledge building. One approach can be to improve the expressiveness of the simulator. The students at occasions move into playful activity without considering what issues they should be engaged in. A design that did not let them so easily neglect the important issues may have increased the possibility of keeping them on target. The abstract presentation form of the simulator might let the issue fade more easily. Using, for instance, illustrations of rising sea level on a map, rather than abstract numbers, might have made it more difficult to disregard the issue at hand. In general, to encompass the practice of finding the necessary information with little effort and allowing for the activity of exploration and reflection seems to be a vital undertaking in order to make the simulation suitable for science inquiry. At the same time, this immediacy is instrumental to whirling the activity into a mode of gameplay that is empty of content.

The ways to use the environment illustrated in Figure 3 are surprisingly stable within the groups. Do we here see and indication of different modes of action developing as patterns of use?

5.3. *Modes of interaction*

There are several occasions where the groups are on the verge of discovery, but then cut short their activity. The modus operandi is stronger than the movement towards exploration. They are dragged back to their mode of interaction just as they seemed poised to cross the border toward new discoveries (see Excerpts I, III, and V).

Groups A and B engage with the simulator to look up information. They expect to find direct answers to the questions there, which was the case with the first questions. Both groups have selected the questions as the main the structure in which to work, rather than to put the simulator to the fore. As they became aware of the possibility of exploration by use of the simulator, they hesitate to follow this possibility. The mode in which they are working becomes a stronger force in forming their actions than the opportunity of discovery being offered. When Gerwan formulates an exploratory question, he shows that he has an idea of the potential of discovery by use of the simulator, but terminates the activity before it has started. He returns to the structure of questions and answers. In group B, the "look-up" approach is even more obvious as they focus on the numerical answers they can get, and do very little exploration with the simulator. When they are explicitly invited to explore, they are more or less pacified and find it difficult to write. In group C, on one occasion, they are beginning to move away from the playful mode of use and into productive discussions, but when they are given just a stimulation that

goes in the direction of playfulness, the discussion vaporises. In fact, the playful model (Figure 2) is a very good illustration of the latency effect. The driving forces are on high levels in the beginning of the century, resulting in a high level of CO_2 emissions. But as they have moved energy use to 0 (!), CO_2 emissions are also 0 in year 2100. But, the temperature still increases, and so does the sea level, due to the latency effect. Yet, the playful mode does stimulate group C to do these types of analyses of their model.

Here again, the members of group D seem to make a different choice than the others. They place the simulator in the foreground, both literally on the screen and with regard to what they direct their attention to. When they are invited to use the simulator to answer questions, they spend time and resources to explore the tool. This gives them enough background to answer the first questions in a very efficient manner, and gradually build knowledge that paves the way for discovery.

The data indicates that modes develop through intricate processes where the institutional ways of "doing school" (Furberg, 2009), the social structure within the pair and the rest of the class, former knowledge and technological competence enter into multifaceted relationships. One of the elements seems to dominate the others, but the dominating factor varies across groups. The clearest indication in this material seems to be how the groups select either the simulator or the questions as the departure point for their activity. Group A makes the choice rather explicit, as the group declines to follow the possibilities they see in the simulator and favour the questions. The questions equip the group with a structure that is familiar to them: Answer questions, finish up and engage in more interesting activities. Group A accepts the placement of the prompting question/answer structure of the school at the fore and downplays the exploring possibilities offered by the simulator.

Group C favours interaction with the simulator over answering questions as their prime activity, yet when the questions offer a narrow and one-dimensional focus to their interactions, they jump at this opportunity rather than explore other options. Group D, on the contrary, neglects the question/answer structure as the simulator is presented. They investigate the simulator for 11 minutes, detached from the questions, exploring the simulator's opportunities and what it may deliver as a resource for them, and then turn to answer the simple fact-oriented questions, seemingly as a compulsory exercise.

Yet, the data in this study does not give substantial empirical material on how modes develop. Rather, the empirical material is here used to describe and analyse how the modes work and how they affect exploration and the probability of making discoveries.

The students who do the work of advanced discovery tend to perform unstructured experiments with the simulator, generate hypotheses, choose variables they believe to be relevant and draw conclusions. In contrast to a structured approach to discovery learning (e.g. Manlove *et al.*, 2007; Reid *et al.*, 2003; Chang *et al.*, 2008), the successful students do not follow a series of steps, but rather engage in unsystematic exploration, and then, at a later stage, perform steps of inquiry that are both swift and tentative; generating hypotheses, experiments and conclusions, they move

back and forth between the steps. The immediacy of the simulator, based on direct interaction and immediate illustration of consequences, makes it possible to use it as an illustrative tool, through a quick process of inquiry. Here, the simulator in the capacity of illustrating relationships works to ensure the quality of the conclusions.

The successful students utilise the simulator as a resource by a variation in use, as they also are able to make use of each other to verify their conclusions. The creative element that is needed for discovery relies on such collaborative exploration and the varied use of available resources. Discovery cannot be limited to walking an existing path for the students, therefore not only should the discovery be "theirs", but also to some extent the path to that discovery should be theirs as well. How the successful students chose to use the simulator as an active object during their presentations is another illustration of how they were able to make use of the technology as a versatile resource.

6. Conclusion and Relevance for Design

In this article, we have investigated how students can make meaning by investigating and interacting with a simulator together with a sequence of questions, and we asked: How do the pupils use the technology in context to make meaning and engage in conceptual knowledge building?

The variations in use between the groups are striking. While they all made small discoveries about relations between the driving forces and the resulting emissions, one group was also able to leap to the more basic discovery of the latency effect that accompanies CO_2 emissions.

Variations in the ways in which the simulator was employed turned out to be the recipe for success. A part of the variation was an unsystematic, yet purposeful use. They played, explored and reflected in a productive cycle that led them to a discovery at a conceptual level of understanding. The purely playful mode, however, omitted reflection and led to an intensive whirl of action that, in effect, blocked productive learning processes. A third mode was fact-finding, where the invitation to explore was not taken up, as it was a step too far from what the students saw as their primary task at school. Neither the exploratory questions nor the inviting non-sequential simulator had the strength to change this practice.

The empirical data indicate that the modes of use are stable over time. None of the groups change their modes of use as they are described here in any major way during the observed period. They seem to establish a way to make meaning by use of the simulator quite early, and stick to that approach throughout. The modes of "look-up" (using the simulator to get numerical facts), play (enjoying interaction and aesthetics, without relating it to curricular issues) and exploration (cumulative micro-experiments) are stable during the whole session of use.

On occasion, all groups were on the verge of engaging in exploratory activities. They all enjoyed direct interaction with the simulator, especially the opportunity to see the consequences of their activity immediately. However, it seems that the visual impression of the simulator was too weak as an abstraction in curves and

numbers, rather than a simulation of a known object. A design that gives physical illustrations of changes in wealth, emissions, sea level and more, might display an expressive power that would be difficult to ignore.

Acknowledgments

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