Learning System Thinking : The role of semiotic and cognitive resources

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2009

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LEARNING SYSTEMS THINKING

THE ROLE OF SEMIOTIC AND COGNITIVE RESOURCES

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Lund University Cognitive Studies 145

Maria Larsson (2009).
Learning Systems Thinking. The role of semiotic and cognitive resources.
Lund university Cognitive Studies, 145

Cover picture created in Wordle, a free tool on the web for generating "word clouds" from a body of text. The clouds give greater prominence to words that appear more frequently in the source text (www.wordle.net).

ISBN 978-91-977380-6-4
ISSN 1101-8453
LUHFDA/HFKO -1025-SE
Printed at Media-Tryck, 2009

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Acknowledgements

"[…] 'tis the pathway, which is worth our while."
(Boye, 1927)

I have very much enjoyed the process of writing a thesis. The result is this book, but it is of course impossible to capture all my experiences of being a doctoral student on these pages. The past years have given me the opportunity to gain insight into the activities of doing research and to learn what it is like to be a scholar. I feel privileged to have been given the opportunity. The Ph.D. has been supported by Lund University and funding from E-learning Öresund.

Pursuing a long project such as writing a thesis has rendered me indebted to many people. First of all, many thanks to the students at LUMES. Without your open and generous attitude in letting me film you in the quite stressful situation that it is to complete an assignment in a limited time, there would be no thesis. I still see some of you in the streets of Lund, and my first instinct is to greet you as I greet a good friend. However, you only met me during a couple of weeks some years ago and have probably forgotten all about it, while I have the feeling of knowing you quite well after watching you on video from time to time over several years!

I would like to thank my supervisor, Peter Gärdenfors, for encouraging me to take on the project of writing a thesis, something that I never imagined I would do. Thank you for continuous support and guidance. Many thanks to Jorge de Sousa Pires, not only my second supervisor, but a good friend as well. With a genuinely curious mind and a never-ending flow of ideas, you are such an inspiration. Thank you, Mats Svensson, who I think of as my third supervisor, always enthusiastically answering my questions about System Dynamics and serving me yet another book on the subject! I am also grateful to the team of tutors at LUMES for welcoming me into their group and treating me as one of the team. You create a great atmosphere for the students.

I would like to thank all members of the seminars at Lund University Cognitive Science (LUCS), who have engaged in reading and constructive commenting on my text. In particular I wish to mention Petra Björne, Agneta Gulz, Jana Holsanova and Annika Wallin. I've truly enjoyed working with you and getting to know you. Thank you for good discussions and many helpful comments, not to mention the pep talks…

On the family side, I would like to extend a special gratitude to my parents Kjell and Gunnel, and my mother-in-law, Dagny who have encouraged my work and have been a great support with practicalities in day-to-day life. Finally, my husband Roland deserves a special appreciation for his support and encouragement. A big hug to you, and to Emma and Julia. You bring me so much joy.

Svedala, November 2009

Maria Larsson

1. Introduction

Throughout the history of mankind, teaching has relied on two major components: to show and to tell. Consequently, the most fundamental learning activities are imitating and listening (Gärdenfors, 2010). A skilled person can show a novice how to perform a task, and more abstract knowledge can be conveyed through the use of spoken language. Body and language are thus the first tools that we depended upon in our learning process, and they are still very prominent.

However, we have also developed other tools that support learning. When spoken language was supplemented with written language, the textbook became a central piece in the activities of teaching and learning. Increasingly, textbooks also include pictorial elements. Although visual representations such as symbols and drawings can be used without other reference, they are often used to further explain what is written in a body of text, or to structure information that is alternative to linear text. Modern technology such as computers offers still more tools that aim to support our learning processes. This provides us with opportunities to integrate text with other media in new ways, including various graphics and animations. Visual representations have become important tools in teaching and learning activities, as well as in other situations when we want to express our understanding.

Part of learning a subject matter is learning the language, that is, the terminology and the symbols connected to it. Technical terms and symbols are used to convey and structure information in a certain way. In the course of our educational life we are introduced to various subject areas, each with its specific way of representing knowledge. Some are easier to understand and use than others. In school we are introduced to xy-graphs, and learn how to represent an ecosystem with text and graphical symbols in a circular flow. Learning traffic conduct includes learning about yielding right of way and about the meaning of various road signs; learning to play an instrument involves learning musical notation and the meaning of andante. The challenge for the learner is to be able to think in ways that are supported by, and match, the representational format. A fundamental question for the science of learning concerns how this is achieved. In this thesis, it will be argued that by observing individuals collaboratively constructing their own graphic representations in a subject area that is new to them, it is possible to gain insight into this learning process.

The aim of the thesis is to investigate and analyze how meaning is made in the process of learning to think in terms of dynamic systems. Three empirical studies provide detailed analyses of video-recorded collaborative work in System Dynamics education, with a focus on how students draw on various cognitive and semiotic resources when learning to use tools specific to this subject domain. A number of research questions related to the overarching aim are addressed, with the focus on how interacting with System Dynamic artifacts influences students' ways of making meaning in the process of completing an assignment, and how the features of the tool are present, or not present, in the students' work process.

The objective of the research reported here is to study the interplay between features of individual cognition, socio-cultural activity and mediating artifacts in a formal learning situation. It aims at an integrative account of social and individual perspectives, long recognized among scholars, (Forman, Minick, & Stone, 1993; Hatano, 1994; Kirshner & Whitson, 1997; Lave, 1988), and also currently discussed (Alexander, 2007; Hodkinson, Biesta, & James, 2008; Mason, 2007; Vosniadou, 2007). The detailed examination of the empirical data in this thesis describes and analyzes aspects of the work process during which students develop an understanding of a problem through the collaborative construction of a specific external representation, a model based on causal relations. I discuss the role of cognition, dialogue and actions in order to provide an understanding of how learners make meaning when they are forced to use a specific representational tool, and the impact of terminology, rules and symbols of the tool on their work. In relation to much research reported in the area of learning and models where the *content* of the model is the object of learning, my studies concern the *process* of learning to model.

The central question addresses how students in an educational setting use a range of semiotic and cognitive resources when collaborating to construct visual representations of abstract models. More specifically, the thesis deals with the interaction between students in a university Master's level course working face-to-face in a collaborative learning task that aims at using specific tools, the Causal Loop Diagram and computer modeling software, to express dynamic causal structures. In order to understand such a complex activity, I believe that there is a need to bring together various research orientations. On a theoretical level there may be problems integrating perspectives, but on a practical level it is important to attenuate the tension between different paradigms when the aim is to understand an authentic learning situation with all its complexities.

The ability to model complex dynamic systems is of interest in many of the social, natural, and engineering sciences, and learning to use models has gained ground in higher education. A common view in the debate on complex problems, such as global warming and the international economy, is that the problems we experience today are due to a lack of systems thinking, a framework that rests on the notion that most phenomena in the world are based on dynamic feedback structures. Arguments are raised that education should include systems thinking in the school curriculum and in the educational administrative system in order to tackle the problems and understand the consequences of our actions (Richmond, 2005; Senge, 2000). There are various representational tools to support systems thinking so that we are able to express our understanding and share it with others. Learning systems thinking includes learning to use these tools, together with the formalism that the tool is built upon.

My aim is to provide a conceptual lens to address and discuss the complexity of learning to think and express ideas in terms of a System Dynamics framework, an example of a set of representational tools for expressing complex ideas. This work is intended to contribute to the burgeoning discussion concerning the concepts of mediation, external representations, and meaning making. Insight into how students work when introduced to a new representational tool to explore a problem may identify critical issues and events in the work process, inform teaching practice, and thereby promote learning. For the community of System Dynamics educators, I believe it could be worthwhile to think of the systems thinking/System Dynamics approach in terms of cultural, mediated tools and of what implications such an approach may have for how learning activities should be organized and what kind of support students need.

In order to address some of the issues that students have to deal with in their work process, it is important to examine the ongoing activities of students' meaning making. Figuratively speaking, I would like to open up the "black box" and investigate some aspects of the students' work process. Roschelle (1991) used the metaphor of "opening up the black box" to characterize an approach where detailed analyses of video recordings were used in order to investigate the "nature of qualitative understanding and associated learning processes" (p. 2), as opposed to using pre- and post-tests to assess students' learning and evaluate interventions. Roschelle's approach was applied in the context of using computer simulations, but could be used in any learning situation.

Empirically, the thesis relies on video recordings of eight pairs of university Master students interacting in a learning task. Their sketches on paper and their resulting report documents are used as supplementary information. The data is presented in the form of case study analyses of the group work in order to explore how a newly introduced representational tool, the Causal Loop Diagram, impacts the conceptualization and meaning making of the problem that the students were assigned to work with.

The core of the research reported here consists of the three case studies, presented in Chapters 5 through 7, of students in dyads interacting with their peer and with the evolving representation on paper. In addition to each case study having a specific focus, useful comparisons can be drawn between phenomena noted across the various groups. These comparisons should provide useful information for practitioners in the System Dynamics field, both for educational practice and for further research.

The position taken here is that meaning making is both an individual and a social process, as illustrated in Figure 1. In this process we rely on various resources that can either be part of our individual cognitive ability, such as memory capacity, prior knowledge, and various communicative abilities, or socially constructed, such as semiotic resources like language and visual representations.

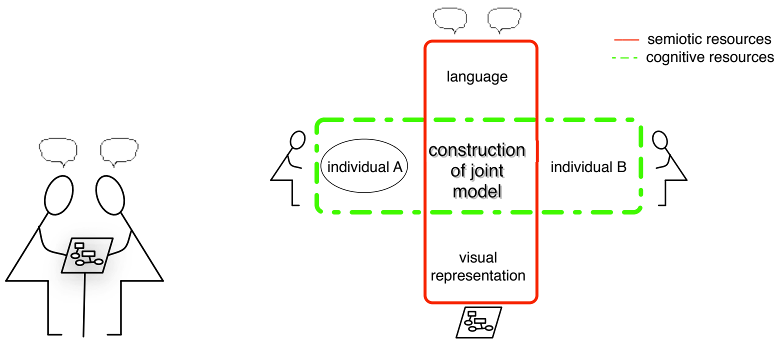

Figure 1: Integration of the components necessary to characterize the conceptual framework of the thesis. Students collaboratively constructing a model. Cognitive resources – both individual and social – and semiotic resources used in the collaborative process.

Overview of the thesis

The thesis comprises three case studies. Before these are presented, an overview of the domain of the empirical studies, systems thinking and System Dynamics, is introduced in Chapter 2. Chapter 3 outlines the perspectives and theories related to the area of interest: the socio-cultural perspective, and the perspectives of social semiotics and constructivism. After a description of the theoretical framework underlying the research, Chapter 4 gives an introduction to the empirical studies, including a presentation of the research questions and methods used in the research. The three case studies illustrating principal features of the students' work are presented and discussed in Chapters 5, 6, and 7. Chapter 8 addresses a second phase in the students' work, the computer modeling phase. Finally, Chapter 9 has a summary and a general discussion of the main results of the empirical studies, together with conclusions.

2. The domain of the thesis: systems thinking and System Dynamics

To imagine possible events, we use our knowledge of causal relationships. To look deep into the past and infer events that were not witnessed, we use causal relationships as well. […] Knowledge of causal relationships allows us to go beyond the immediate here and now. (Wolff, 2008)

We base much of our understanding of the world in terms of causal relations; you could even say that the main body of modern scientific community builds upon theories in which causality is the dominant explanatory principle. Our notion of causal relationships enables us to make predictions and inferences, see implications, and formulate explanations. Causality is a notion that underlies our intuitive understanding of the world, and we are prone to look for it when trying to make sense of situations we find ourselves in, or trying to anticipate the response of someone or something we interact with. But the causal relations we perceive are often conceptualized as simple one-way phenomena (Booth Sweeney & Sterman, 2007) with a short time perspective. We tend to simplify problems and focus on only one cause of them.

One example of a solution that falls short because of a too narrow and short-term view of a problem is the case of the involvement of aid organizations in the Sahel region in Africa. It is also a problem that can be explored using systems thinking for the purpose of analyzing complexity:

Sahel, the narrow area of land south of the Sahara desert, has been the home of nomads for centuries. It has never been an easy place to live in but the nomads have survived amazingly well. In recent years, people acting for organizations like the UN decided to improve the life for the nomads. These organizations did two major things. First, they introduced modern medicine. They vaccinated the nomads against smallpox and *measles, thereby bringing malaria and sleeping sickness under control. Modern medicine greatly increased the life span of the nomads. Animal diseases were also controlled. Secondly, more water was made available. There are great supplies of underground water in the Sahel, which nomad's hand-dug wells never reached. Deep wells were drilled using modern machinery. This large new supply increased the number of animals possible for the nomads to own. Although the animals had water, they soon ate or trampled the little grass available. A six-year drought further decimated the grass and the animals began to die of starvation. Because of the drought and the loss of animals, many nomads starved. The UN was faced with a more severe problem than the one it originally wanted to solve.* (Excerpt from LUMES student assignment, 2005.)

There are many examples as the case of Sahel, about interventions that were made with the good intention to solve an urgent problem, but overlooking the consequences in a wider perspective. To think in terms of causality in many steps and seeing a phenomenon as part of a system is cognitively demanding for the human mind (Dörner, 1980). To think in terms of dynamic behavior, where there are no static states, is even more demanding (Jensen & Brehmer, 2003; Senge, 1990; Sloman, 2005). Yet many of the phenomena in the world are causal and dynamic and we need to make sense of them to be able to make informed decisions. Empirical evidence suggests that individuals in general have rather limited intuitive systems thinking abilities (Booth Sweeney & Sterman, 2007), and individual decision making in dynamic tasks is quite poor relative to simple decision heuristics (Atkins, Wood, & Rutgers, 2002; Brehmer, Hagafors, & Johansson, 1980; Gary & Wood, 2005; Hogarth & Makridakis, 1981; Kleinmuntz, 1985; Paich & Sterman, 1993; Sterman, 1989). Feltovich et al. (1996) note that one of the difficulties involves the misunderstanding of situations in which there are multiple, co-occurring processes of interaction. In this kind of situations, individuals often narrow their attention to one or a few of the dimensions rather than the many that are relevant (see also Dörner, 1996). Studies of decision rationales reported by Atkins et al. (2002) showed that, although participants were aware of complexity factors in a problem, they were unable to cope with them. As a result, many people have difficulties understanding phenomena such as the emergence of traffic jams on a highway, the population variations within an ecosystem, or the fluctuations of the international economy. Visual representations that depict dynamic interactions can be of help in understanding phenomena like these. System Dynamics is one such methodology.

Areas of use for systems thinking and System Dynamics

There are many tools that claim to help people make informed decisions. Various traditions with the aim of supporting decision makers have developed, each with different starting points. Two common traditions are based on argumentation structure and problem structure.

The tradition of using argumentation structure can be traced back to the work of Toulmin (1958) on the construction of argument, which in turn has a long history within the area of logic. The main hypothesis behind research in this tradition is that by making the structure of arguments explicit, they can be more rigorously constructed and communicated (Brown, 1986; Smolensky, Fox, King, & Lewis, 1988). Such approaches aim at identifying the rationale of decisions, and point to contingent argumentation fallacies. The approach has been adapted in decision support methodologies such as IBIS, the Issue-Based Information System (Kunz & Rittel, 1970), and DRL, Decision Representation Language (Lee & Lai, 1991).

System Dynamics is an example of the second tradition, that of supporting the identification of the structure of a problem. It means seeing the problem as interlinked cause–effect relations and feedbacks that behave nonlinearly (Forrester, 1971; Senge, 1990). Applying this approach aims to give insight into the consequences of decisions. The method can be considered as a source for understanding the reasons that cause changes in a system's performance, resulting from counterintuitive effects of the system's structural behavior (Morecroft & Robinson, 2005). System Dynamics has been adapted in a variety of decision support methodologies such as group model building (Vennix, 1996), soft systems methodology (Checkland, 2000), and transition management (Rotmans, Kemp, & van Asselt, 2001).

The literature in general presents two major approaches to System Dynamics (SD). It can be perceived as either a methodology, or a theory/field of study. Vanderminden (2006) acknowledges both, but suggests a clear distinction between them: "SD as a methodology is a method by how one can model process structures and analyze their behavior through the investigation of how resources flow, accumulate and interact in the system, over time, in dynamic interdependent feedback loops. SD as a field of study is the science of viability, emergence and sustainable dynamic adaptation of self-organizing systems" (ibid., p. 23). The approach taken in this thesis is the methodological one, where the concept of systems thinking also can be applied.

This chapter presents some of the characteristics of System Dynamics and systems thinking, together with their applications. It is not an exhaustive description of the field, but is intended to present the history and the characteristics of systems thinking and System Dynamics, in order to put the empirical studies in a context.

Distinction between systems thinking and System Dynamics

Part of the System Dynamics community uses a definition of systems thinking which is somehow independent of the System Dynamics modeling approach. The relationship of systems thinking to System Dynamics, according to the System Dynamics Society, is that systems thinking addresses the same kind of problems from the same perspective as does System Dynamics, but that System Dynamics takes the work further. "The two techniques share the same causal loop mapping techniques. System Dynamics takes the additional step of constructing computer simulation models to confirm that the structure hypothesized can lead to the observed behavior and to test the effects of alternative policies on key variables over time." (System Dynamics Society). System Dynamics could thus be considered as one of the quantitative methods of systems thinking.

Jay Forrester, the originator of System Dynamics, wants to keep a clear distinction and writes rather critically: "'Systems thinking' has no clear definition or usage. […] Some use systems thinking to mean the same as system dynamics. […] 'Systems thinking' is coming to mean little more than thinking about systems, talking about systems, and acknowledging that systems are important. In other words, systems thinking implies a rather general and superficial awareness of systems." (Forrester, 1994b, pp. 10-11). He accepts systems thinking as a door opener for System Dynamic modeling but opposes the idea of equality of System Dynamics and systems thinking.

However, some scholars do not apply the distinction between systems thinking and System Dynamics. Ossimitz (2000) uses the two concepts side-by-side when referring to his own empirical studies. He presents the ability to think in interrelated, systemic structures and thinking in dynamic processes (for example delays and oscillations) as two of the essential dimensions of the compound subject System Dynamics/systems thinking.

The view taken in this thesis is in line with Ossimitz (ibid.) and also with Coyle (1996), who does not want to make the distinction either, but holds that System Dynamics as a method can be used in two related, but different, ways. One way is to use it qualitatively as an aid to thinking about and understanding how a system works. A Causal Loop Diagram is one way to represent this step, showing the influences at work in the system, that is, the causes of its dynamic behavior.

Another way to use the method is to make qualitative simulation models in order to test consequences of changes in the system. The creation and use of a computer model is the most common and practical way to work with this step.

Both a qualitative and a quantitative method

The core idea of System Dynamics was to bring the emerging power of computer simulation to the analysis of complex socio-economic issues (Forrester, 1961, 1975). Personal computers and the development of the programming language Dynamo (Fox & Pugh, 1959) made the complex calculations possible. Numbers and algebraic relations have traditionally played a major role in modeling, and the basis of the analysis was differential equations. In its original form, the subject of System Dynamics was purely a quantitative computer simulation method (Forrester, 1961).

Given that System Dynamics models were basically feedback models, an innovation was to introduce the idea of Causal Loop Diagrams (CLD), also called Influence Diagrams, to describe the feedback processes. When they first appeared, they were used towards the end of a study to summarize and explain the behavior of the completed simulation model (Forrester, 1968). Later on the practice changed, and this kind of diagrams began to be used at the start of studies as a qualitative tool, to help modelers frame the problem by generating and representing an initial dynamic hypothesis. Thus, this type of representation was a means of conceptualizing systems in terms of their feedback loop structure (Wolstenholme, 1982, 1999) and provided a preliminary diagram from which the simulation was written. It was later suggested that Causal Loop Diagrams could be used without formal computer simulation modeling, to emphasize the role of system description and problem identification.

Diagramming methods are seen as "an intermediate transition between a verbal description and a set of equations" (Forrester, 1961). Although there is a range of diagramming approaches used in System Dynamics, there are two methods for the qualitative modeling which predominate in the System Dynamics community (Scholl, 1995). Representations of the variables and feedback structure of a model are conveyed using Causal Loop Diagrams, see Figure 2. The other method, Stock & Flow Diagrams, Figure 3, is more detailed as these discriminate between two kinds of variables (state and flow). These two methods are rather standardized and can be described as the international diagramming conventions (Lane, 2000). (For a more extensive review of the diagramming methods employed in System Dynamics, see Lane, 2008).

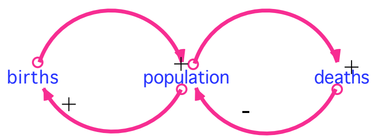

Figure 2: Causal Loop Diagram. In the figure, the arrows that link each variable indicate places where a cause-and-effect relationship exists; the plus or minus sign at the head of each arrow indicates whether the cause increases or decreases the magnitude of the effect variable when all the other variables (conceptually) remain constant (System Dynamics Society). Births cause a population to grow larger. A larger population results in even more births, causing the population to grow even larger, and so on. At the same time, deaths cause a population to decrease, and a smaller population results in fewer deaths. The arrows that depict this scenario are called feedback loops (description from Quaden, Ticotsky, & Lyneis, 2008).

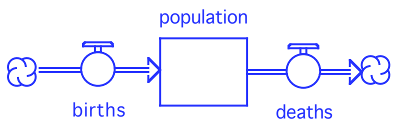

Figure 3: Stock & Flow Diagram. In terms of a metaphor, a stock can be thought of as a bathtub and a flow can be thought of as a faucet and pipe assembly that fills or drains the stock as shown in the figure. Births fill up the population, while deaths drain the population. The dynamic behavior of the system arises due to the flows into, and out of, the stock (description from Quaden et al., 2008).

A common language for representing dynamic systems

System Dynamics and systems thinking provide a framework to talk about and represent complexity and change. The framework is used to solve a problem or to reach a goal by constructing models that are governed by a methodological structure. While many scientific methods recommend studying the world by breaking it up into smaller and smaller pieces, System Dynamics emphasizes looking at things as a whole.

A system is seen as a complex whole of which the functioning depends on its parts and the interactions between those parts. There can be systems of different types (Jackson, 2003):

- Physical, such as a lake
- Biological, such as a living organism
- Designed, such as a car
- Abstract, such as a decision support system
- Social, such as a family

The central concept is to understand how parts in a system interact and to seek underlying systemic interrelationships that are responsible for the patterns of behavior, be it an ecosystem, a bank account, or a football team. The focus is on causal relationships and feedback within a system. The objects and people in a system interact through feedback, where a change in one variable affects other variables over time, which in turn affects the original variable, and so on (Richmond, 2000). The type of feedback at work within the system can be determined by observing the causes and effects that arise from the influences among endogenous variables.

Systems like those exemplified above often have characteristics that are not recognizable from the parts. The whole emerges from the interactions by which the parts affect each other through networks of relationships. Once the whole has emerged and is identified, it is the whole that gives meaning to the parts and the interactions. The interactions are represented by a feedback process that is looped back to control a system within itself. Feedback describes the situation when output from (or information about the result of) an event or phenomenon in the past will influence the same event or phenomenon in the present or future. The systems can become very complex, as illustrated in Figure 4.

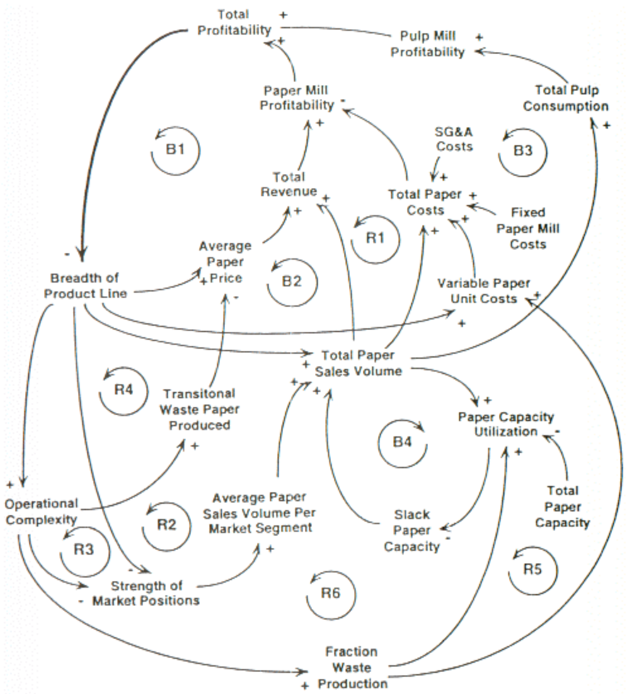

Figure 4: A causal loop diagram created to support the design of a corporate strategy in the pulp and paper industry (Risch, Troyano-Bermúdez, & Sterman, 1995).

Many System Dynamics models deal with interactions between people and the environment: in economics, sustainability studies and management of business and government. It is used to analyze why social, economic, ecological, and other managed systems do not always behave as anticipated.

A boundary must be defined in order to build a model, indicating what elements to include in the analysis and what elements to leave out (Sterman, 2000). The choice of a problem and a time horizon defines this boundary. As Forrester (1975, p. 112) explains: "The boundary encloses the system of interest. It states that the modes of behavior under study are created by the interaction of the system components within the boundary. The boundary implies that no influences from outside of the boundary are necessary for generating the particular behavior being generated." Following this notion, there is an emphasis in the literature that models should be developed to address a concrete problem, as opposed to modeling a general system (Richardson & Pugh, 1981; Roberts, Andersen, Deal, Garet, & Shaffer, 1983; Sterman, 2000).

Different academic, cultural and professional backgrounds create communicative challenges when a group of people come together to solve a problem. Making use of tools for constructing abstract representations presents opportunities for successfully talking about and finding solutions. The external, visual model may also help to capture inconsistencies and highlight misconceptions. The insights can lead to further exploration of the problem, presumably improving the quality of decisions taken by a more informed group, and modeling could then be seen as more of a process than a product.

People in many fields are drawn to and motivated to use systems thinking with the argument that it gives these benefits. As an idea, systems thinking permeates both popular culture and numerous scientific fields including education, business and management, public health, sociology, psychology, cognitive science, sustainability and environmental sciences, ecology and biology. The benefit stressed in the literature is that systems thinking makes it possible to pay attention to perspectives of different stakeholders involved, and evaluate a system from multiple levels of scale. Some claim that it may act as a bridge between the physical, natural, and social sciences. In a similar argument, Cabrera et al. (2008) hold that an advantage of learning systems thinking is that it is not content-specific; they suggest that because it is a pattern of thought, it can apply to any body of knowledge. It is also argued that systems thinking could be a valuable tool when people are to work with a common problem with the aim of reaching consensus. A framework like System Dynamics can provide a common "language," yet allow multiple perspectives of the problem at hand (Costanza & Ruth, 1998; Forrester, 1971).

However, there are also critics of System Dynamics. Disputes of a fundamental kind can be found in the field of econometrics, which uses data on past events and statistical analysis to find correlations. System Dynamics modelers base their primary approach on the assumption that persistent dynamic tendencies of a system arise from its causal structure, being generally unconcerned with precise numerical values of system variables at a specific point in time. This approach has been criticized, among others, by Naylor & Finger (1971), who argue from an econometrics point of view: “Simulation models based on purely hypothetical functional relationships and contrived data which have not been subjected to empirical validation are void of meaning [...] such a model contributes nothing to the understanding of the system being simulated.”

There are also critics of structured visual representations in general. Regarding visual representations in social theory, Lynch (1991) notes that the use of such representations with formal elements such as bounded labels, quasi-causal vectors, and spatial symmetries can give an impression of rationality that is not necessarily there. Critics of System Dynamics more specifically include the view of Brewer (1973), who states that System Dynamics applications have powerful uses but that they have been oversold. He warns against overconfidence in impressive looking models “that can give significance to the trivial and conceal uncertainties.” Gärdenfors (1982) points to the notion of the sensitivity of quantitative models, where a small change in one variable can have a large impact on the system as a whole. The importance of using correct input values in a quantitative model is also stressed, since a mistake in an input value affects the complete system. Thus, this critique is not aimed at the fundamental ideas of System Dynamics, but at what problems it claims to solve and with what accuracy this can be done.

Historical exposé

System Dynamics in academia, industry, and civil society

Model building is a common and essential task in science as well as in industry and civil society. A model can test the implications of theories, help the understanding of complex systems, and be used to support communication and education. System Dynamics is one of many modeling methodologies.

In 2007, System Dynamics celebrated its fiftieth anniversary as a scientific field. It has its origin in biology (General System Theory, von Bertalanffy, 1950) and cybernetics (Wiener, 1948), and gave birth to systems thinking as a trans-discipline in the 1950s. The field developed initially from the work of Jay W.

Forrester. His seminal book Industrial Dynamics (Forrester, 1961), focusing on problems arising in the corporate world, is still an important document of the philosophy and methodology in the field.

The book was preceded by an article in Harvard Business Review, presenting an "early stage of development" of System Dynamics (Forrester, 1958). The title was "Industrial dynamics: A major breakthrough for decision makers." He writes about: "understanding how industrial company success depends on the interrelation between the flows of information, materials, money, manpower, and capital equipment. The way these five flow systems interlock to amplify one another and to cause change and fluctuation" (ibid.). The name "Industrial dynamics" subsequently gave way to the general term "System Dynamics." Follow-up books, extending the idea of Industrial Dynamics, were Urban Dynamics (Forrester, 1969), and World Dynamics (Forrester, 1971). The span of applications has grown extensively since Forrester's publications to include work in corporate planning and policy design, public management, biology and medicine, environmental issues, and theory development in the natural and social sciences.

The Club of Rome, an organization consisting of an international group of professionals from the fields of academia, industry, and civil society, became closely associated with System Dynamics in the 1970's (Club of Rome, 2008). The common interest for the members of the club was the dilemma of extensive short-term thinking in international affairs and, in particular, the concerns regarding unlimited resources. The Club of Rome presented a new approach in addressing these concerns, focusing on the long-term consequences and applying systems thinking in order to understand the underlying mechanisms. The Limits to Growth (Meadows, Meadows, Randers, & Behrens, 1972), was a report commissioned by the Club of Rome written by a group of scholars at the Massachusetts Institute of Technology. It explored a number of scenarios with the aim of achieving sustainability within environmental constraints. The international effects of this publication had a significant impact, and it was translated into many languages (Club of Rome, 2008). With its focus on long-term vision and quite provocative scenarios, the book demonstrated the contradiction of unlimited and unrestrained growth in material consumption in a world of finite resources.

System Dynamics gained international ground, and the International System Dynamics Society was formed in 1985. Annual international conferences are held, and there is an active list-serve where members discuss subject-related issues year-round. System Dynamics books and papers are regularly translated into many languages (Forrester, 1996). Various software packages have been developed to support System Dynamics modeling, for both professional and educational purposes. One of the most well-known and used is STELLA (isee systems Inc., formerly High Performance System), which was introduced in 1985. It was a follower of Dynamo software, developed to construct quantitative System Dynamics models without having to define equations and without using programming language. Powersim, Mapsys, and Vensim are other examples of software used for System Dynamics modeling.

System Dynamics in schools

Dynamic systems are represented by differential equations which are known to be difficult, and this notion has previously stood in the way of teaching System Dynamics in K-12 schools. However, with the availability of visual computer-based modeling tools that do not require users to know the underlying mathematics in order to construct models, some of the barriers for teaching System Dynamics are reduced. Systems thinking and System Dynamics interventions for K-12 education have been implemented on a small scale and have grown slowly over the last twenty years. In the late 1980's and early 1990's a number of initiatives were taken to establish System Dynamics or systems thinking teaching in the school curriculum. System Dynamics researchers initiated projects where they applied the System Dynamics approach in the educational field as a tool for learning the principles of systems thinking, applied to a specific subject.

In the United States these educational efforts were initially focused on the computer software STELLA. In several school districts, teaching System Dynamics modeling with STELLA was established, aiming for the development of systems thinking skills. Projects such as STACI (Systems Thinking and Curriculum Innovation (Mandinach, 1989), and CC-STADUS (Cross-Curricular Systems Thinking and Dynamics using STELLA) (Waters Foundation, 1996), are two examples with an intention to promote systems thinking skills by using System Dynamics modeling. The modeling approach was applied to, for example, Mathematics, Physics, Social Studies, History, Economics, Biology and Literature. The idea is that students should be able to see generic structures, so-called archetypes, that could be used in many different settings, that is, that a small number of examples cover a wide range of situations (Forrester, 1996). When the structure is understood in one setting, the notion was that it could be possible to identify and understand it in other settings. This is often referred to as transfer in the area of learning sciences.

Since the middle of the 1990's, Forrester has been engaged in strategies to introduce systems thinking in K-12 education on a larger scale than the limited number of individual teachers involved in various projects in the beginning of the 1990's. In his keynote address to the 1994 Systems Thinking and Dynamic Modeling Conference for K-12 Education, he presented the idea of System Dynamics as a way to improve quality of life in general. He talked about what he believes could be the outcome of a Systems Education: "I believe we should give students a more effective way of interpreting the world around them. They should gain a greater and well-founded confidence for managing their lives and the situations they encounter." He then suggests three objectives of a System Dynamics education: "Developing personal skills, shaping an outlook and personality to fit the 21st century, and understanding the nature of systems in which we work and live" (Forrester, 1994a).

Barry Richmond, the founder and managing director of High Performance Systems and developer of STELLA software, shared Forrester's view that the System Dynamics community has something very powerful to contribute to addressing the serious problems that the world is facing. "We can offer a way of thinking, doing, and being that can help the planet's citizenry to achieve a much saner day-to-day existence, as well as a more promising longer-term future" (Richmond, 1994). But he acknowledged that this way of thinking has failed to involve a larger audience. Still in 2009 it does not have such widespread public visibility as the System Dynamics community hopes for.

Part of the reason for the slow growth is the lack of confidence the larger educational community has in these techniques to improve education (Zaraza & Guthrie, 2003). There is also the issue of educating teachers who will be able to use the techniques in their own practice, which takes time and resources. Although researchers have shown that systems thinking improves critical thinking and decision-making skills (e. g. Chang, 2001; Costello, 2001; Costello et al., 2001; Draper, 1991; Grant, Marín, & Pedersen, 1997; Hight, 1995; Lannon-Kim, 1993; Lyneis, 2000; Lyneis & Fox-Melanson, 2001; Stuntz, Lyneis, & Richardson, 2001; Waters Foundation, 2008), the broader educational community remains to be convinced of the value of systems thinking. Participants in the early K-12 projects recognized in a report (Lyneis et al., 2002) that in order to reach out to a larger group there is a need to develop curriculum materials using System Dynamics, developing good training programs for teachers, and building alliances with others in the area of interdisciplinary education. They are confident of the benefits of System Dynamics.

Often mentioned in the discussions about how to implement systems thinking in schools is the advantage of introducing this way of thinking in the early grades of educational systems, starting with basic, concrete exercises in the form of games and classroom activities (Quaden et al., 2008). In that way it is thought to build students' systems thinking skills, subsequently leading them to use this method of thinking more generally and in many subject areas. In higher education, the development and teaching of interdisciplinary System Dynamics courses at university level (Andersen & Richardson, 1980; Barlas, 1993; Hovmand & O'Sullivan, 2008) are not only seen as important for introducing university students to System Dynamics, but also for producing educators in System Dynamics through graduate education (Barlas, 1993). In Europe, a new European Master Program in System Dynamics has been established in cooperation with the universities of Bergen (Norway), Lund (Sweden), Palermo (Italy), and Radboud University, Nijmegen (the Netherlands) to meet this demand. Each university has had its own System Dynamics education for some time. Aiming to build on the various strengths of each of the four universities involved, the program will be launched in August 2010 (European Master Programme in System Dynamics, 2009).

Learning systems thinking/System Dynamics and the modeling tools

System Dynamics can be conceptualized as a special form of communication. Diagrams play a central role in both the practice and the core ideas of System Dynamics (Lane, 2008), and as in mathematics, the discourse is made special by its exceptional reliance on symbolic artifacts as its communication-mediating tools (Kieran, Forman, & Sfard, 2002; Sfard, 2001). Learning the formalism and the terminology attached to a certain tool like Causal Loop diagramming or a computer software constitutes a major learning task. It is even a prerequisite; without this knowledge it is not possible to complete a modeling assignment.

Distinctions can be made with regard to the different ways that models can be used in a learning situation. The most general distinction in the educational use of models is whether one learns by building models or by interpreting and using existing models, that is, the status of the model when the students begin their work. Alessi (2000) makes a "building versus using" distinction, discriminating between learning by either creating simulation models, or by having complete models to experience, explore, and experiment with a phenomenon. It is quite a different task to work with a model that is ready to start exploring, compared to if the model is to be constructed from scratch. In the same line of thinking, Bliss and Ogborn (1989) suggest that there are two types of activity in computer modeling: exploratory and expressive. Exploratory activity concerns learners investigating models constructed by others, and expressive activity describes learners building their own representations in a problem-solving activity. The case studies presented in this thesis concern the building, expressive activity.

Another distinction is whether there are predetermined answers to be found and accounted for in the task, or if there are multiple solutions depending on what perspective one takes. Many complex problems can be modeled in a variety of ways. The correctness is then based on how well the variables are chosen, how they are interrelated and how well the suggested solution is communicated to others, what could be called perceived feasibility.

Using models in an educational situation can also have different objectives. The objective can be the teaching of a subject matter, or it can be teaching the methods and practices of modeling itself. A focus on subject matter means constructing models in the process of learning a subject matter, or learning a subject matter with the support of using existing models. A focus on learning to model means learning the methods and practices of the modeling discipline, making the subject matter ancillary. Since a model always has to be about something, it means "borrowing" or using a subject matter in order to learn how to model.

Much work in artificial intelligence, psychology, and science education has concentrated on how individuals use representations in problem solving, rather than on the complex process of how they construct them. Most research into learning effects in the area of System Dynamics has focused on various modes of interacting with existing models, either with the aim of learning a specific content (Wheat, 2007), or learning systems thinking in general (Grösser, 2005; Jensen, 2005; Maani & Maharaj, 2004; Morecroft & Sterman, 1994; Moxnes, 2000, 2004; Romme, 2004; Sterman, 1989), rather than construction of representations by the learners. Furthermore, in the majority of cases, there is one single right answer that the students can be assessed upon. Many of the studies are carried out in an experimental setting. However, it is also important to examine how the learning process unfolds in authentic situations, which is the aim of this thesis.

Documented difficulties

A large amount of research work in the area of System Dynamics/systems thinking education has brought to the fore the complexity involved in successful learning of systems thinking. It is found that students have great difficulties in constructing dynamic models and that they have a hard time understanding system concepts (Pala & Vennix, 2005). Many studies in the field have shown that adults without special training perform poorly in dynamics tasks that are based on rather simple structures. Not only simple feedback structures fail to be recognized (Jensen & Brehmer, 2003; Maani & Maharaj, 2004; Moxnes, 2000, 2004; Sterman, 1989, 1994), but even systems consisting of not more than three variables prove too complex (Booth Sweeney & Sterman, 2000; Kainz & Ossimitz, 2002; Ossimitz, 2002). Individuals often presume situations as first-order linear systems with short time constants, rather than complex dynamical systems with long time delays and multiple ongoing reciprocal processes (Richmond, 1991; Sterman, 2008). This is not exclusively a problem for systems thinking, but a general difficulty of understanding causality (Sloman, 2005). Other aspects that seem problematic for perceiving causality include insufficient inquiry skills and reasoning skills in general (Sterman, 1994), and difficulties in making probability judgments (Sterman, 2008). The subject is continually been studied (Cronin & Gonzalez, 2007; Gary & Wood, 2005; Grösser, 2005; Jensen, 2005; Schaffernicht, 2005; Vogstad, Arángo, & Skjelbred, 2005). However, research has focused on the use of system models rather than modeling *per se*, and to a large extent on the quantitative modeling phase when students work with computer-supported modeling tools. Regarding situations when students interact with existing models, Ogborn (1999) shows that many novices have problems going beyond employing the model as an artifact instead of using it to understand a complex phenomenon. Similarly, Sins et al. (2005) found frequent evidence of students having a strong focus on adjusting model parameters to fit a given "right" graph, an approach that makes the model become an artifact that "just has to work" (Bliss, 1994; Hogan & Thomas, 2001).

When students are asked to construct a model of their own in a learning situation, they are often presented with a problem and then asked to construct a dynamic computer model right away, either from scratch or with available building blocks. Many of the difficulties found in students' work seem to be connected with the lack of dedicated time to conceptualize the problem. An intermediate step in the work of constructing a computer model could be to conceptualize the problem at hand using a qualitative model based on inductive reasoning. Sins et al. (2005), for example, conclude that students who do inductive reasoning do better in constructing models. Qualitative modeling (for example Causal Loop Diagrams and Stock-and-Flow Diagrams) could be a tool to be used to help in that process and prepare for the quantitative modeling work (Sherwood, 2002). It is suggested that this kind of tools encourages inductive reasoning and as such could be the preceding phase of computer modeling, thus helping students to avoid the common problems reported by many scholars.

Sherwood (2002) suggests that the first step in building a computer model should be problem analysis and drawing of a causal loop diagram that captures the key elements and the structure of the system. Computer modeling should start only after this has been very thoroughly done. Other literature supports this suggestion, stating that causal mapping is a valuable aid in structuring and understanding the problem and also an aid in identifying feedback loops (Grant et al., 1997; Williams, 2002). In a study investigating the link between systems thinking and complex decision making, Maani and Maharaj (2004) found that better performing individuals attempted to gain an understanding of the system structure before they proceeded to develop strategies and take action. They also noted that the structure was built incrementally, accomplished through an iterative process of conceptualization, planning, and action.

It is documented extensively that people have difficulties learning systems thinking, and it has been the object of an increasing number of research studies. The need for pedagogical interventions in teaching how to model is thus an important issue to raise. It has been done in student textbooks aimed at all levels in the educational system from kindergarten to university graduate level (Fisher, 2007; Quaden et al., 2008). Various tools such as conventions of how to graphically represent systems and computer software have been developed, and the organization marketing and selling STELLA software provides extensive tutorials and user guides (see Richmond, 2005). Study materials are available from the Creative Learning Exchange (CLExchange, 2008) and Waters Foundation (2009), organizations that support teachers who want to implement System Dynamics in education. In order to continue to develop effective and appropriate educational material, it is important to know about how students actually work, what resources they use in their meaning making process, and what difficulties they may have.

Learning to construct Causal Loop Diagrams – an example from LUMES Master program

Barry Richmond, the developer of STELLA software, expressed various ways of perceiving systems thinking:

"What do we mean when we say 'Systems thinking'? We can use the phrase to refer to a set of tools – such as causal loop diagrams, stock and flow diagrams and simulation models – that help us map and explore dynamic complexity. We can also use it to mean a unique perspective on reality – a perspective that sharpens our awareness of whole and of how the parts within those wholes interrelate. Finally, Systems thinking can refer to a special vocabulary with which we express our understanding of dynamic complexity. For example, Systems thinkers often describe the world in terms of reinforcing and balancing processes, limits, delays, patterns of behavior over time, and so forth." (Richmond, 2000).

Richmond pointed to three aspects that are equally important when students are introduced to the practice of System Dynamics modeling. These aspects are also present in the students' modeling tasks that form the empirical data presented in this thesis. Students learn how to work with the tool, the specific ways of framing a problem when using the tool, and the terminology used in relation to the tool. The normative working order will be presented in detail in conjunction with the task analysis (Chapter 4), while the elements and terminology of the tools will be presented in the following paragraph.

Elements and terminology of a CLD

In a Master's level course in System Dynamics, students are introduced to a set of tools to work with when learning about ways of thinking about and ways of expressing dynamic systems. The tools are Causal Loop Diagrams (CLDs) to be produced using pen and paper, and the computer modeling software package STELLA (isee systems, 2008). The goal of the course is for the students to acquire the capability to analyze the properties of a system and create models for it. They should become able to use models to analyze the effect of various factors acting on a system, in such a way that the relative importance of these factors can be understood. A second, more general goal, is to learn how to reach consensus and solve problems in collaboration with others.

CLDs are used to portray the causal relations and feedback loops at work in a system. The word causal refers to cause and effect relationships and the word loop refers to a closed chain of cause and effect (Ford, 1999). Words represent the variables in the system and the arrows represent causal connections. The arrows are drawn in a circular manner to draw our attention to the closed chain of cause and effect (ibid.).

Learning to model involves learning the rules about how to write and draw, that is, its spatial layout and organization. It also involves learning a specific terminology. The key terms and notations in a CLD are:

Variable: Can be a stock or a flow. Stocks represent conditions within a system, and are things that accumulate or diminish: water in a cloud, body weight, and anger (figuratively speaking). Flows represent the activities that cause conditions to change: evaporating/precipitating, gaining/losing, and again, figuratively speaking, building/venting anger (Richmond, 2005).

Link: The concept of causality depicted by an arrow. A causal connection (unidirectional causality) that can be positive or negative. The variable at the tail of the arrow has an effect on the variable at the head of the arrow, see Figure 5.

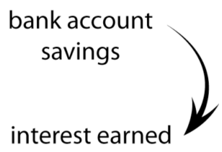

Figure 5: Link showing that the amount in the variable "bank account savings" affects the amount of the variable "interest earned".

Loop: A closed chain of cause and effect (multidirectional causality), see Figure 6. A feedback loop is accomplished if there is a mutual circular causality between variables, that is, when starting from a given variable and following arrows in the direction they lead, it is possible to get back to the start, without going through any variable more than once (Coyle, 1996).

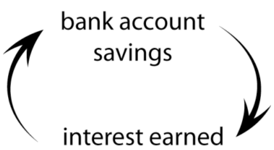

Figure 6: Loop showing that the amount of money in the savings account affects the amount of interest earned, which in turn affects the amount of savings.

Positive and negative effects (+/–): Indicate the effect of a causal relation with a plus or a minus sign. A plus (+) represents a so-called positive causal relationship, which indicates that both variables change in the same direction (that is, both increase or decrease), see Figure 7. A minus (–) represents a negative relationship, which indicates that the variables change in opposite directions.

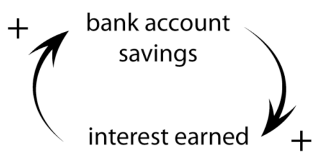

Figure 7: Positive effects, represented by plus signs (+). Loop showing that the more money there is in the savings account, the more interest is earned, which in turn increases the amount of money in the savings account.

In a causal loop diagram, there can be either reinforcing (R) or balancing (B) loops, see Figure 8.

Reinforcing (R): A positive or a negative feedback loop that amplifies change. Reinforcing processes compound change in one direction with even more change in that same direction. As such, they generate either exponential growth or collapse, effects that will make the variable increase indefinitely (meltdown in a nuclear power plant) or decrease until there is nothing left (radioactivity decay).

Balancing (B): a stabilizing effect. A balancing loop means that competing influences are balanced against each other. Balancing processes seek equilibrium – they aim at bringing things to a desired state and keep them there.

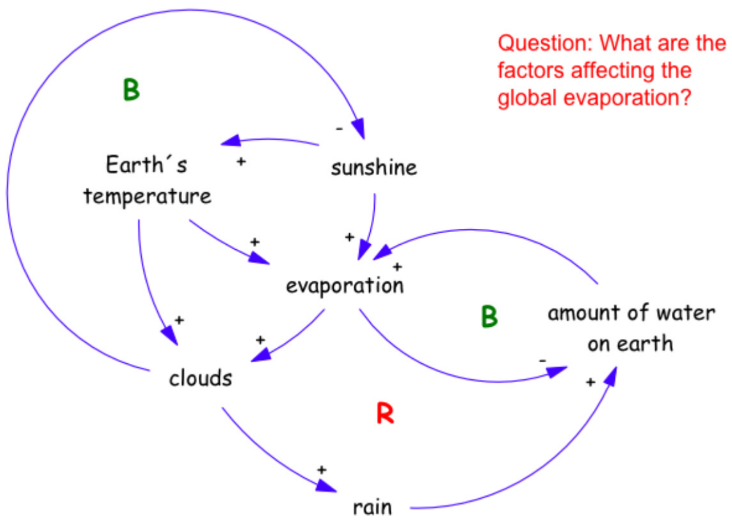

Figure 8: CLD illustrating an answer to the question "What are the factors affecting global evaporation?" (Haraldsson, 2003). Note the "R" and "B's." They stand for the concepts "Reinforcing" and "Balancing" which is the type of feedback loop they designate.

The terminology presented above and the related conventions for how to construct and graphically represent a model are introduced to the students in the LUMES System Dynamics course in traditional lectures. The collaborative project assignments that follow the lectures should be based on the System Dynamics framework. Aspects of how this framework is used and how it affects the students' work process are described and analyzed in Chapters 5 through 7. First, however, I turn to the theoretical perspectives underlying the empirical studies.

3. Theoretical framework

Using multiple perspectives

In order to understand the complex activity of learning and meaning making, I believe that there is a need to bring together various research frameworks. From a theoretical point of view, there may be problems when using multiple perspectives, among them running the risk of being perceived as eclectic, but on a practical level it may give us insight into an authentic learning situation with all its complexities. Where the socio-cultural research community looks at learning situations on a broad cultural and societal level, many cognitive perspectives, in contrast, focus on the individual and her abilities. Historically, there is a tension between the various perspectives.

I would like to bring several perspectives together, and look at a formal learning situation at the level of *the activity of constructing a joint model* in which students engage. My use of the term activity falls within common usage, that is, “a specified pursuit in which a person partakes” (The Free Dictionary), or “something that somebody takes part in or does, the work of a group or organization to achieve an aim” (Cambridge Dictionaries Online). I will use the term activity when referring to the work in which students engage in order to complete a course assignment. The social and historical aspects, as well as the individual’s role in this social activity will be taken into account. In my view, these perspectives can coexist, and using different perspectives is a matter of what ‘resolution’ one prefers. Research projects can be about individual cognitive abilities and how these affect learning, and they can be about looking at the broader cultural and historical situation and how learning takes place there. There are interesting findings at each analytical level, highlighting different aspects of learning and meaning making. In order to take both the social and individual aspects into account when doing analysis on the level of activity, it could be useful to apply several theoretical perspectives and thereby get a broader view of a learning process.

Although the approach taken in this thesis is conceptualized within a socio-cultural framework, the focus is on the site of engagement, defined as "the convergence of social practices in a moment in real time" (Scollon, 2001) and the immediate learning environment, rather than the broader temporal context. The central issue is how individuals engage in interactions in order to understand one another and the task at hand, and what cognitive and semiotic resources they rely on in this work. Research in the area of constructivism has been an inspiration in trying to take into account the individual, as well as acknowledge the relation between the social activity and the individual's cognition. As Alexander (2007, p. 67) argues, "frameworks and models espoused by many researchers cannot exist without recognition of the thoughts and reflection of the mind or without consideration of the sociocultural influences that exist in the world outside the mind."

While building on ideas of both cognitive and socio-cultural traditions, I do not discuss the great variation that exists within those broad groups of research traditions, but simply focus on some of their main characteristics. Although this summary treatment may seem overly simplified, the presentation is made in order to refer to their applicability in the data analysis that will follow in proceeding chapters, and subsequently to answer the research questions. The aim is not to make a complete description of those research traditions, but rather to present some assumptions about the nature of meaning making, social interaction and tool use.

The theoretical considerations that follow form a starting point in the method and analysis of how cognitive and semiotic resources are used and interact in the setting of a course in System Dynamics. The aim is to capture students in action, which implies that the study has a focus on the process rather than the outcome of students' work.

The socio-cultural perspective

The socio-cultural perspective provides a framework for understanding learning environments by emphasizing the socially situated nature of learning, and the critical role of tools in mediating the individual as well as the collaborative meaning making. It consists of quite a heterogeneous group of research traditions inspired by Vygotskian cultural-historical theory.

The socio-cultural perspective involves studying and analyzing learning activities, that is, studying how people interact with each other and various physical tools in the activity of learning. A fundamental assumption is that human activities like learning and problem solving are mediated by cultural tools (Wertsch, 1998; Vygotsky, 1986), categorized as either material (physical) or psychological. This implies that reality is not immediately exposed to us, but is conveyed or mediated through various socially, culturally, and historically crafted tools which we use to interpret phenomena in the world. Vygotsky connected material and psychological tools through their mediating function, that is, something is considered a tool if its function or its consequence is mediation (Vygotsky, 1978). The idea of "tool" is thereby interpreted to incorporate a wide range of technologies, artifacts (paper, pen, book, computer), and semiotic resources (language, symbols, subject-specific discourses).

Various tools, both psychological and material (Kozulin, 2003), scaffold a learning process, or a problem-solving process in different, more or less cognitive demanding ways. Mediated action theory (Wertsch, 1991) views cultural tools as carriers of culture, history, and ideology, each having its affordances and constraints (Wertsch, 1995; Wertsch, Del Rio, & Alvarez, 1995). Tools are seen as resources that we use in our meaning making processes, but from a sociocultural perspective, tools do not serve simply to facilitate mental processes. They also fundamentally shape and transform these processes. Thus, tools can help us make meaning, but they also constrain our thinking in that they are based on a certain ideology and a specific interface that designate the way to use the tools. In formal learning situations, these tools may include conversations and artifacts such as the representational tools that students use in the case studies presented in Chapters 5 through 7. Visual representations like CLD and a computer modeling software can support the creation of representational formalism that enables students to express their shared understanding of a situation or phenomenon. It helps them to structure their knowledge and directs their communication and actions within a certain framework.

System Dynamics is both a psychological tool and a material tool in a socio-cultural perspective. It is a tool that is used to represent causality and change in writing and drawing, and it comes with a set of concepts, a specific terminology. Also, it is a cultural tool that has developed to meet a specific need and a tool that has evolved over time as a consequence of users making adjustments and changes to it in their practices. The students taking part in the case studies presented later learn about nonlinear processes with a set of System Dynamics tools, that is, they learn to talk about, represent and solve problems within a System Dynamics framework. The aim of their course is to become able to use new tools to express their understanding of complex problems. What does the learning process look like, the process of becoming able to use these new tools, and what resources do students draw on?

Taking a socio-cultural perspective, a course in System Dynamics can be seen as the convergence of a long-term historical development of System Dynamics and the specific educational situation when forty novices gather to take a course. Or putting it more generally, in Scollon's (2001) words: "the convergence of social practices in a moment in real time." Students are presented with a "Systems thinking toolbox" comprising a normative working order, graphical objects that should be organized in a particular way, and a specific terminology that is part of a social practice. The toolbox cannot be taken for granted; the students have to make sense of it in the process of completing their assignments. In order to succeed they rely on a multitude of semiotic and cognitive resources, such as terms and symbols of the System Dynamic domain, verbal and nonverbal communication skills, and the ability to use abstract graphical symbols together with the spatial conventions that apply.

The role of language

Language is considered the tool of tools and is the most important artifact in human practices (Dewey, 1925/1981; Vygotsky, 1986). Words and linguistic expressions mediate the world and make it seem meaningful, and it is therefore of great interest in a socio-cultural perspective to study language as it is expressed in practice. Language, like the use of any tool, is developed through situated use and through constant negotiation with others. By communicating with others, individuals become involved in functional ways of describing the world, which makes it possible to interact with others in various activities (Säljö, 2005b).

Wittgenstein coined the concept of a "language-game" (Wittgenstein, 1968), to illustrate the manifold ways in which language is used. The concept has been picked up and used in several research disciplines. Research based on socio-cultural and socio-semiotic perspectives, for example Pea (1993) and Lemke (1997), has used it to provide insights about what is central in learning a new task. In a language-game, linguistic activities are intertwined with nonlinguistic activities in such a way that the meaning of the expressions can only be understood through a description of the whole situation, how the expressions are used in concrete situations and what the role and purpose of the language-game are. For instance, the terminology of System Dynamics cannot be fully understood without understanding how the terminology is used and what role it plays in the activity of modeling. Consequently, an expression does not have any meaning independent of the way it is used in a certain activity.

Whether person-to-person or between people and artifacts, interaction is central to understanding learning in a socio-cultural framework. Learning is about taking part in new language-games and therefore, according to this view, the learner must practice and exercise participating in these. In this line of thought, a major result of learning is the ability to master various ways of speaking and acting in a specific social context, and the ability to determine what is relevant and interesting in a certain situation. The term language-game denotes something wider than only linguistic behavior. Thus, this approach to learning is not restricted to spoken or written language but also applies to the use of diagrams, graphs, and mathematical symbols in the activities to be learned (Pea, 1992).

Using this perspective in the empirical part of the thesis, the first and third case studies in particular (Chapters 5 and 7), focus on the "language-game" aspect of the learning situation. Learning the normative working order, as well as the systems thinking terminology, is an integral part of learning systems thinking.

The role of visual representations

A widely used method for conceptualizing a problem is to make a graphic representation of it. The use of external, visual representations in the form of symbols and graphs is of special interest in this thesis, together with the students' spoken discourse. Taking the perspective of tool mediation, the focus is on the ways tools for making visual representations enable, mediate, and shape System Dynamics thinking. This section is therefore devoted to this particular category of tools.

The role or function of the visual representation can be seen in both an individual and a social perspective. Sketches and drawings are perceived as visual representations that reflect the conceptualization of reality (Tversky, 1999) that we can share with others. They can be used as an aid to our memory by "loading off" cognition to an external, physical artifact (Larkin & Simon, 1987). Visual representations constructed on a sheet of paper act as an external memory, holding information that we need, for example to solve a problem. They have a spatial organization which facilitates transformations and other manipulations, and they can remain displayed for a much longer period of time, compared to spoken language which is only there in the moment that it is uttered. This external memory off-loads individual cognition, but, of course, does not completely disclaim it. Each individual still has to construct her own meaning, supported by visual access to the paper, but also by personal interpretation of the visual representation.

A visual representation requires both a carrier, such as pen and paper or a software tool, and a formalism, such as a common language or representational technique (Suthers, 2001). The formalism of each kind of visual representation is theory-dependent, offering different interaction affordances depending both on their design and on individuals' earlier experiences. Tools are not considered neutral but as mediating certain world views, knowledge, and values. Research in the learning sciences suggests that the form of visual representations used by learners during collaborative work can have a significant effect on the discourse of the learners. The representations induce different types of knowledge and the structuring of that knowledge (Oestermeier & Hesse, 2000), and different forms of representations lead to different features of discourse. Moreover, each kind of representation requires certain strategies and can also help elicit certain strategies. This effect has been shown for both representations that are constructed by learners during collaboration (Suthers, 1999) and representations used as a medium of discourse (Baker & Lund, 1997; Guzdial, 1997; Wojahn, Neuwirth, & Bullock, 1998).

A tool for making visual representations enables learners to externalize ideas and share their individual knowledge with others in a formalized way. Compared to spoken language, representing ideas in a physical form makes them more easily accessible to criticism and discussion, which is an important prerequisite for collaborative learning (Hogan & Thomas, 2001). The common characteristic of visual representations such as graphs, is that, as Wertsch (1998) proposes, they can be revisited. Unlike spoken utterances, they permit "close reading." They can be interrogated, revised, regrouped, reinterpreted, and improved, and are therefore an important thinking tool (Suwa, Tversky, Gero, & Purcell, 2001). The creation of visual representations also supports cognition in that it may guide attention and provide a help to see patterns.

Research on collaborative construction of representations has rendered positive results for both learning processes and learning outcomes (Suthers & Hundhausen, 2003; van Boxtel, van der Linden, & Kanselaar, 2000; van Drie, van Boxtel, Jaspers, & Kanselaar, 2005). The visual representation is an object of reference that can facilitate discourse on abstract concepts and relationships. Expressing understanding in the form of a model, a graph, or a picture can facilitate tasks that are not supported by the vocabulary, the grammar, or the linearity of texts. The role of the visual representations in the case studies that will follow is to focus on the choice of variables to be used in defining and solving the problem and decide how these variables relate to one another and to the overall problem. In this way, the representation can serve as a touchstone for coordinating understanding (Schwartz, 1995). Participants can refer to the words and graphical objects in the emerging representation while verbalizing their ideas and negotiating meaning.

Graphical representations can also fulfill other, more abstract, functions in communication, by serving as "a useful tool for the identification of 'where are we now?', as a store of referents, as an external memory aid for the interlocutors, as an expressive way of underlining what is said, and as a representation of a whole problem discussed in the conversation" (Holsanova, 2008). External representations can thus have a meta-cognitive function in that they provide a support to think about one's own thinking and of the work process as a whole. Furthermore, external representations have a stand-alone function that makes them disconnected from the individual that created them. "To create representations is not merely to record speeches or to construct mnemonics; it is to construct visible artifacts with a degree of autonomy from their author and with special properties for controlling how they will be interpreted" (Olson, 1994, p. 169). Poetry and musical notation are lucid examples.

One example of an external representation, and one that is central in the empirical studies, is the Causal Loop Diagram (CLD), previously described in Chapter 2. The CLD is a tool for exploring causal relations, comprising both physical and conceptual aspects. It is a representational methodology to visualize the inter-connectedness and possible feedback loops of a system by drawing and writing, and it comes with a terminology and a way of reasoning closely linked to the work of constructing the diagram.

The models that the students create in the case studies is an artifact that allows explicit visual representation of complex relations. Mediational artifacts such as abstract models have the advantage of allowing us to extend the observable and the measurable, and can help us understand phenomena that are hard to conceive and describe with words. Learning the relevant language, symbols, and actions is not trivial. Rather it demands a substantial effort in most cases. We develop such knowledge by taking part in activities where these tools are used (Lave & Wenger, 1991), activities belonging to a specific semiotic domain.

The perspective of social semiotics

Researchers in the field of social semiotics have primarily been concerned with how humans produce and interpret spoken or written texts in various contexts. However, the application of social semiotics theory has expanded to include several ways of communicating. Visual representations such as photos, drawings, virtual two- and three-dimensional models, and symbolic representations such as tables, diagrams, formulas, numerical data, and programming code are also regarded as semiotic resources. The term "semiotic resource" is a key term in social semiotics. It originated in the work of Michael Halliday, who argued that the grammar of a language is not a set of rules for producing correct sentences, but a ”resource for making meaning” (Halliday, 1978).

Research based on linguistic analyses of subject-specific settings has sometimes assumed a “language learning” perspective on the acquisition of subject-specific knowledge. Competence in a subject is then equated with the ability to use the language in that subject (Lemke, 1990). Now there is an increasing awareness that meaning is not created by language alone. As Baldry (2000), Kress and van Leeuwen (2001), and Kress (2003) note, we live in a multimodal society where meaning is made through the use of a combination of semiotic resources. In line with the writings of van Leeuwen, I extend Halliday’s idea of a “grammar” to other semiotic modes, and define semiotic resources as “the actions and artifacts we use to communicate” (van Leeuwen, 2005), whether they are produced verbally, with a gesture or by means of technology, that is, with pen and paper, with a computer, or with a musical instrument.

In practices, local meanings and related actions are produced through specific ways of communicating verbally and through text and other mediational means that have emerged through history. These ways of communicating could be seen as various semiotic domains. Following Fairclough (1995), the New London Group argues that each semiotic domain has its own specific order of discourse that is “a structured set of conventions associated with semiotic activity (including language) in a given social space” (New London Group, 2000). Lemke (1998) suggests that these structured conventions consist of “words, images, symbols, and actions.” Thus, each semiotic domain has its semiotic resources and its highly specialized form of communication, which constitutes an important part of learning in a domain.

The concept of *resource* points to the mediational means that are used in situations. The concept of *semiotic resources* is used in the case studies analyses to focus on what resources students apply in their meaning making process to drive the work process forward, that is, what they do to be able to move on in the process of completing an assignment. The specific semiotics for System Dynamics modeling are used alongside the more general semiotic resources that we share with most people in our society, that is, the everyday type of language, concept of time and space, and the use of arrows and spatial conventions (up-down, higher-lower-middle). Roth and McGinn (1997) conceive of graphing as observable practices employed to achieve specific goals. Their perspective highlights the nature of graphs as semiotic objects and rhetorical devices, in other words, resources for making meaning. This stance permeates the three case studies presented in Chapters 5 through 7.

The perspective of constructivism

The main concern of constructivist theories is how people create meaning. The concept of constructivism is influential in the areas of psychology and education, but a clear definition of constructivism is nevertheless hard to find (Loyens & Gijbels, 2008; Phillips, 2000). However, it could be stated that the various forms of constructivism share the fundamental assumption that meaning is actively constructed by the learner.

In recent decades, the traditional focus on individual learning has extended to address the collaborative and social dimensions of learning. The different perspectives of constructivism can emphasize either individual cognitive processes in knowledge construction, such as cognitive constructivism, or social constructivism that stresses the collaborative processes (Windschitl, 2002). In a review of several constructivist perspectives of teaching and learning, Palincsar (1998) suggests a continuum for all variations of constructivism. At one end there is trivial constructivism, which stresses the individual as constructing knowledge, and is concerned with whether or not the constructions are correct representations. At the other end there is radical constructivism, which rejects the notion of objective knowledge and argues instead that knowledge develops from personal experience and as one engages in dialogue with others. There are many variations in between.

In the theoretical framework presented here, the learning activity that students take part in is viewed as an active, social constructive process. Within that process, the focus is on how the learner uses a range of cognitive and semiotic resources to make meaning with a new representational tool, which is part of a System Dynamics framework.

Constructivism and individual cognition

Although social aspects are predominant in the analyses conducted in this thesis, I believe that there is a need to take into account the role of the individual cognition and how it contributes to the social situation. Meaning making is not an activity that exclusively takes place in the individual's mind, yet individual cognition is important to recognize in a social, collaborative context.

Prior understanding plays an important role in the constructivist perspective. It is the fundament on which we can build new meaning, and thus an important resource in the meaning making process. A constructivist approach addresses the notion that students build more advanced knowledge from prior understanding

(Smith, diSessa, & Roschelle, 1994), regardless of the nature of that understanding. The basic stance presented by Smith et al. (ibid.) is that all learning involves the interpretation of phenomena, situations, and events through the perspective of the learner's existing knowledge. For example, we often speak of causality in terms of if-then statements. The concept of causality as an explanation for how we perceive events in the world is one example of this prior understanding that we build upon when faced by an unfamiliar situation. In the case studies that are presented in Chapters 5 through 7, there are many examples of students readily turning to well-recognized cause-and-effect explanations, earlier provided by, for example, school text books and media. Rain causes plants to grow, poverty causes people to starve, and merchants sell when the price on the market is high. The notions are so fundamental that we do not even make them explicit. However, when we are obliged to put them down in a structured way, for example in a model, we can become aware of inconsistencies in our own reasoning. Maybe the soil is drained of nutrients which makes the rain ineffective, maybe poverty leads people to grow their own food to a larger extent, and maybe the merchant has other goals than to maximize profit.

In a cognitive constructivist view, meaning making is perceived as individually constructed in the process of interpreting experiences in particular contexts, resulting in mental models. Mental models, as a concept first postulated by the American philosopher Peirce (1896), are psychological representations of real, hypothetical, or imaginary situations. A similar idea, proposed by Craik (1943), is that the mind constructs "small-scale models" of reality that are used to anticipate events, to reason, and to underlie explanation. An example of the importance of mental models is presented by Hestenes (2006), who brings forward the idea that "cognition in science, mathematics, and everyday life basically is about making and manipulating mental models" (p. 26). The concept of mental models is frequently used in the area of research on learning and instruction and in psychology when referring to a person's existing knowledge or the acquisition of new knowledge. But the status of these models is debated within the large research community. They can be perceived as static or dynamic, stable or constructed ad hoc, enduring or temporal, detailed or general, etc. Or they can be dismissed as completely irrelevant as a useful concept, as for researchers within the socio-cultural community.

In System Dynamics research it is often assumed that the individual has a mental model of the situation to be modeled (Gary & Wood, 2005; Hestenes, 2006; Larkin, 1983; Wild, 1996), even though the general status of the mental model is not well defined. Doyle and Ford even suggest a mental model construct proper to System Dynamics (Doyle & Ford, 1998, 1999). A high degree of similarity is thought to exist between mental content and the visual representations (e. g.

Larkin & Simon, 1987) and thus, making external representations is predominantly seen as a composite of individual cognitive abilities and skills (Berg & Smith, 1994). Understanding is viewed as the overt expression of underlying mental models, and a mental model construct is often used as an ex-post explanation for performance on tasks. A similar line of research that takes the visual representation as a starting point looks into how the formats of visualizing information result in different mental models, indicating that the form of visualization affects the structure of mental models (Schnotz & Kürschner, 2008).

I believe that the notion of corresponding internal-external representations should be used with caution. Expressing understanding could be dependent on the tools available as resources for reasoning among other contextual circumstances, and therefore we cannot draw conclusions about a person's understanding exclusively based on how this understanding is presented to us. As Wenger (1998, p. 41) writes: "Words like 'understanding' require some caution because they can easily reflect an implicit assumption that there is some universal standard of the knowable. In the abstract, anything can be known, and the rest is ignorance. But in a complex world in which we must find a livable identity, ignorance is never simply ignorance, and knowing is not just a matter of information."

The concept of cognitive resources is used in the case studies analyses to put the focus on the resources that students apply in their meaning making process to drive the work process forward, what they do to be able to move on in the process of completing an assignment. What is mainly referred to in the literature are the more general cognitive resources such as intellectual abilities, experience, creativity, memory, perception, and monitoring. Put into the context of the case studies, an understanding of causality is central for the System Dynamics domain. It is one example of such a cognitive resource, as well as the ability to reason in terms of if-then statements to represent causal relations. Other important individual factors that play an important role in problem-solving activities are the meta-cognitive abilities.

Meta-cognition

Even though there appears to be no uniform definition of meta-cognition in the literature, it has generally been defined as knowledge, control and awareness of learning processes (Baird & White, 1996; Thomas & McRobbie, 2001) and the ability to think about one's thinking (Gilbert, 2005). Meta-cognitive abilities may also include the ability to monitor the work process, and the regulative aspects of collaboration. These abilities are often not taken into account in the socio-cultural or other social perspectives, but are nevertheless important aspects of a collaborative work process. Side-by-side with the process of learning the formalism of the tool to express causal relations, the evolving representation also has a meta-cognitive function.

Students use the representation when looking back on the work process and to evaluate their work. A few examples are here taken from the work of two of the students participating in the empirical studies, John and Miriam. After going through an almost finished model, pointing to the words on paper and following the links between the words while reasoning, John asks critically:

```
*JOHN:   but does this make sense?
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Miriam quietly looks at their model and then starts to reason once more in the same way that they have been doing before. She perceives a flaw: a minus sign should be changed to a plus. John is able to follow Miriam's reasoning well, supported by their jointly produced diagram which they both refer to while Miriam talks and points. John quickly agrees with her suggestion and concludes:

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*JOHN:   that's what we did wrong
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The students also refer to the evolving diagram while monitoring and evaluating the work process. For example:

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*JOHN:   that looks how we wanted it to look doesn't it ?
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and

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*JOHN:   we are starting to see things here
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Moreover, it seems that the students, by being aware of the complete working order and using it to monitor the work process, adjust their present work to the steps ahead. This notion is especially distinct with regard to how the CLD should be constructed in order to be useful in the computer modeling phase. Students visualize the process beyond its present CLD framing and express it using prospective statements that involve the computer modeling terminology. John and Miriam evaluate their CLD and think ahead about how the variable "Total grain supply" eventually will be used in their computer model. The term "stock" is not part of the CLD terminology, but is used here to monitor how they have been doing so far. A stock is good to have defined since it is one of the building blocks of a computer model that has to be constructed later on.

```
*JOHN:   so we know we got (.) this to build a model
         [draws a circle around the variable Total grain supply]
*MIRIAM: mm
*JOHN:   stock
*MIRIAM: ya stock
```

The empirical data shows that the meta-cognitive aspect is present throughout the work process. It is often made explicit in the dialogue, but it can also be handled by the use of iconic gestures or making statements that implicitly refer to monitoring or regulating the work. An extended discussion about the notion of "thinking ahead," as well as aspects of evaluating and monitoring the work process will be presented in case study III, Chapter 7, and Chapter 8.

Constructivism and social cognition

Many researchers representing the social constructivist school of thought are in one way or another influenced by Vygotsky (Newman, Griffin, & Cole, 1989; Wertsch, 1991). Meaning making is seen not only as a personal, but a cultural activity as well. Several learning theorists have argued that learning is a fundamentally social activity (Dewey, 1916; Mead & Morris, 1934; Vygotsky, 1978) that takes place in a social and cultural context (Säljö, 1995, 2005a). This is done by imposing the patterns inherent in the culture's symbolic systems – its language and discourse modes (Bruner, 1990). Understanding is seen to be actively constructed, and dialogue is central in this process. Thinking is seen as a social action, mediated through language and other semiotic resources, and agency is understood as extending beyond the individual. "The extension takes two major forms: 1) agency is often a property of dyads and other small groups, rather than individuals, and 2) symbolic cultural tools that mediate human action are inherently connected to historical, cultural, and institutional settings, thus extending human agency beyond the given individual." (Kozulin, 1998).

The work presented here has interests in common with research in the area of Computer Supported Collaborative Learning, CSCL (Dillenbourg, 1999; Koschmann, 1996; Koschmann, Hall, & Miyake, 2002). The focus of CSCL research is often on the collaborative group that explores and reasons, addressing cognition and communication beyond just the use of technology (e. g. Crook, 1994; Dillenbourg, 1999). Research efforts in the field are in many cases guided by a constructivist approach, and much of current research involves analyzing interactions between students, as well as between students and the artifacts. A large body of research involving CSCL and modeling can be found within the area of science education (de Jong et al., 1998; e. g. Lindwall, 2008; Löhner, van Joolingen, Savelsbergh, & van Hout-Wolters, 2005; Roschelle, 1992; Tiberghien, 1994), and it is assumed that the representational format may be of influence both on the collaborative process and on the outcomes. The computer software and screen are, in my view, comparable to other representational tools and there are similar issues to address, be it collaboration on a computer screen or using a common piece of paper to write and draw on.

As many constructivists have demonstrated, the process of designing an artifact actively engages learners (Jonassen, Peck, & Wilson, 1999). Modeling tools could initially help to represent a view, or an interpretation of a confusing or challenging domain in order to share it with others. Based on that initial model, the tools can also be used to construct and examine alternate interpretations of a scenario, and in that process stimulate dialogue and discussion (Spector, 2000). Rouwette, Vennix, and Thijssen (2000) suggest that a collaborative approach to model building is effective in terms of improving understanding, based on the virtues of the tools.

Integration between social and individual cognition and the tools

Within the presented framework, meaning making is understood as the result of interactions between multiple agents in a social and cultural context, but at the same time acknowledging the importance of each individual's cognitive process. Cognition is here primarily studied as it is manifested in interpersonal interactions, rather than as situated in broader social institutional and cultural settings. However, given the view that both scientific reasoning practices and scientific concepts are cultural constructions (Driver, Asoko, Leach, Mortimer, & Scott, 1994), I approached a broader plane of analysis in Chapter 2 when describing the history and role of the tools used for introducing students into the practice of modeling dynamic systems. To acknowledge the individual cognition at play, I also rely on ideas that are central to studies of cognition, such as different forms of constructivism, in order to describe the processes of students' reasoning.

Using mediated activity as a focus of analysis is, according to Wertsch (1998, p. 17), a way to "live in the middle" of different theoretical perspectives, being neither purely psychological nor sociological in orientation. Thus, mediated activity includes both these components, which are organized into an integral whole. This prompts a focus not simply on the individual, but on the interaction with the environment, the action being both internal and external and linking cognition and culture (Plowman & Stephen, 2008). One example of this link is the double function of language: On the one hand, a social and communicative means, and on the other hand, as an individual cognitive ability.

Collaborative problem solving is common practice in educational settings, and there is a vast research literature on the topic. However, it is noted that in order for collaborative learning to be more effective than individual learning, learners have to achieve a sufficiently common frame of reference, or common ground (Barron, 2000). Negotiating common ground, or grounding, is a theoretical framework to understand a process that goes on during collaborative activity, which is pointed out by several researchers as an important aspect of collaborative learning.

The process of constructing shared understanding has been studied in psycholinguistics as the concept of grounding (Clark & Brennan, 1991). However, this theory analyses conversation on a micro or 'utterance' level and is not developed to describe the macro or 'knowledge' level, which is associated with meaning making. Building on the notion of grounding, Dillenbourg & Traum (2006), suggest that the concept could also be used for inquiries on the macro level. While the micro level focuses on short dialogue episodes, sometimes less than a minute long, the grounding on the macro level refers to the shared understanding that is constructed over a longer time as a consequence of the dialogue. To develop a shared conception of a domain like System Dynamics with its concepts, rules and procedures involves a deeper complexity of what is being co-constructed and works on a different time scale compared to a short conversation episode. The process of establishing common frames of reference includes an exchange of ideas, clarifying what is shared and discussing alternative interpretations (van Diggelen, Overdijk, & Andriessen, 2005). Also taking this wider approach to grounding, Baker et al. (1999, p. 33) argues that the common ground includes "mutual understanding, knowledge, beliefs, assumptions, presuppositions, and so on" that exist among communicating individuals, and that grounding is "the process by which agents augment and maintain such a common ground." (ibid., 1999).

In Roschelle and Teasley's words, the negotiation of a common ground is about constructing and maintaining a shared conception of a problem, a "Joint Problem Space" (Roschelle & Teasley, 1995). This activity is supported by various tools (language being one and visual representations another), by "integrating semantic interpretations of goals, features, operators and methods" (ibid., p. 229). Both individual cognition and social activity are at play in this work. Although primarily perceived as a social activity, investigating collaboration needs to take into account the individual perspective in the activity of creating the joint problem space.

Agency and learning can be perceived as co-constituted by the individual and the environment, and rather than exclusively describing a social activity, one may focus on the properties of individuals that make collaboration happen. Schwartz (1999) argues that the very notion of collaboration involves individual agency and the individual's ability to represent other people's agency. In the same line of thought, a common claim made by the authors in Dillenbourg (1999) is that for collaboration to occur, it is necessary for the collaborators to have the cognitive ability to conceive one another's thoughts, and ideally for the collaborators to have a shared conception of some issues. Weiss and Dillenbourg (1999) speak of this necessity with regard to learning: "The 'deep secret' of collaborative learning seems to lie in the cognitive processes through which humans progressively build a shared understanding" (ibid., p. 75).

In recent years, there have been several attempts to integrate the social and individual approach in the area of conceptual change (Hatano, 1994; Mason, 2007; Vosniadou, 2007). Hatano (ibid.) suggests a synthesis on individual and social in the area of conceptual change: "Exactly how conceptual change occurs has not often been discussed by its proponents. However it is frequently implied that the change is purely individual and cognitive in nature. Most investigators of conceptual change seem to hold the view that increased amounts of acquired knowledge automatically induce restructuring. At the least, virtually none of them has proposed conceptual change as induced in many cases by goal directed activities. Nor has it often been suggested that change may be initiated, facilitated, or consolidated by social processes, e.g., discourse among group members" (1994, p. 190)

Conceptual change, or learning, may also be initiated or facilitated by the use of visual representations. Ainsworth (2008) argues that psychological accounts, in addition to social semiotics, linguistics, and other social accounts, are useful tools to understand how processes of learning differ with the role of a representation, and how the use and construction of representations relate to learning. She suggests several levels of explanation that should be evoked, among them the cognitive, perceptual level, that is, the interaction between the representation and someone's individual capacities, knowledge, and skills. These factors depend both on the constraints of human ability in general and the individuals' personal experiences. For example, on a cognitive level of explanation, visualizations can serve as external memory and take advantage of visual-spatial working memory, whereas a meta-cognitive level of explanation looks at how representations can help learners "think about their own thinking" by revealing what learners understand.

When constructing a model such as a Causal Loop Diagram, students draw on a variety of resources. The semiotic resources of language and visual representations are mediating tools that support the collaborative work, as well as supporting the individual meaning making. Individual reasoning may originate from the activity structure given, from features of the ongoing discourse, and from the qualities of the tools in use. They can also originate from the individual's cognitive abilities, prior knowledge and assumptions, and personal history. The cognitive and semiotic resources interact in the process of creating a Joint Problem Space.

4. Research methods and analyses of the empirical data

This thesis explores the process of learning to create models of complex problems. Not only the physical tools like the models on paper or on the computer are of interest, but also the verbal and nonverbal actions in this process of interacting and making meaning. The theoretical grounds of the analysis are informed by the socio-cultural and socio-constructivist perspectives on interaction and learning (Cole, 1996; Resnick, Levine, & Teasley, 1991; Wertsch, 1985, 1991).

The theoretical considerations presented in Chapter 3 form a starting point for the method and analyses of how cognitive and semiotic resources are used during a course in System Dynamics. As the methodological approach is designed to study meanings as constituted in action, the empirical material consists of video recordings of collaborating students. The aim is to capture students in action, and the study has a qualitative approach which focuses on the process rather than the outcome of students' work.

Simply assessing the outcome of students' work does not give us enough information about how meaning is created and what pedagogical interventions are needed to support students in the course of the workprocess. In several research communities one finds a growing interest in the processes that lead to the result. Berger et al. write: "even the best pre-post and randomized designs" cannot provide an understanding of "what is going on while students are learning" (Berger, Lu, Belzer, & Voss, 1994, p. 476). This is written in the context of learning with instructional technology, suggesting that learning with computers compared to a non-computer-based situation may be significantly different concerning what processes are involved while students are learning. However, I think this suggestion applies to any learning situation since the process is not visible in any pre-post research design. In a similar argument, Goldman and

McDermott (2007, p. 27) note that "quantitative studies often provide researchers with assessments and global predictions, but do not aim to explain the inside story – the meaning that people ascribe to the events they experience in learning environments." A focus on processes rather than outcomes will also give us important insights into cognitive processes. A study comparing children with William's syndrome and Down syndrome (Bellugi, 1994, in Gottlieb, 2001), showed that in spite of both categories of children achieving similar outcomes in a task (equally poor), the processes that took place in order to achieve these outcomes looked very dissimilar. Although using different strategies, the two groups in the study performed equally. Likewise, in the case of reading and writing difficulties, Wengelin (2002) showed that the written outcome in the form of an ill-spelled or ill-structured language says little about the effort put into it. Individuals struggle with various issues, something which a pre-post design would not give any insight to.

By focusing on the meaning making practices developed by the interactants, the analysis will cast light on how the participants use cognitive and semiotic resources to collaboratively construct a model of a dynamic system. Rather than imposing predetermined categories (such as "age," "exploratory talk," "question," "explanation") onto the analysis of discursive data, the focus is on what participants orient to in their discussions (a discourse analysis approach, see ten Have, 1999). Thus, there is a focus on how activities and issues are managed and attended to by participants themselves. However, there is always the researchers' pre-understanding influencing what is made interesting and relevant. This approach is often used by ethnographers and in the learning research community by Lynch (1994) among others, who insists that empirical investigation does not need to involve an attempt to adhere to a particular notion of scientific method and proof. He suggests that we examine what people do when they engage in an activity, describing what people say and do, and then play these observations off against established versions of the activity. "[Such research investigations] are ordinary, and necessarily so, because they exploit, build upon, cooperate with, and conspire with the 'methods' through which the persons studied carry out their (and our) practical and communicative affairs" (ibid., p. 147).

A legitimate criticism of many research investigations of learning is that they do not allow enough time for substantial learning to occur and that learning is hard to measure when it comes to complex skills, such as learning to model. Learning of the kind that the students in the presented case studies engage in seems likely to need weeks or months rather than hours. Of course, learning could be evaluated after a completed course (teachers do so when they give grades), but it is impossible to draw conclusions about what particular actions in the learning process contributed to learning or understanding. I have therefore limited the scope of the thesis to an investigation of students' meaning making with tools. I have chosen to look at reasoning in the meaning making process which would seem to be important to learning, manifested in the ability to "go on" (Wittgenstein, 1980), which can be seen as of value in itself, rather than to claim to be investigating learning or understanding. Indeed, in practice, "understanding is like knowing how to go on, and so is an ability" (ibid, p. 308).

The main data source for the empirical studies is video recordings, supplemented with the students' diagrams on paper and their final report. A qualitative approach is taken to the analysis of this material. This approach allows the unpacking of the complexities within the interactions between users and the tool, and between individuals in a group. Video recordings of students working two by two and copies of their completed reports reveal how these students recognized various aspects of the problem they had to solve. Data also reveals the way students handle incompatibility between how they intuitively conceptualized the problem and what, as a matter of fact, was possible to represent using the tool. The model-building phase was studied with the help of a screen-capturing software that recorded the first hour of the model building, together with the students' verbal communication. As for the video recordings, the verbal protocols were fully transcribed, supplemented with remarks about students' interaction with the model.

Research questions

From an analytical perspective, the issue of how students collaborate and make meaning in the context of learning a new semiotic domain raises various questions. For example, the focus could be on an organizational level, on technological issues, on making a didactical analysis of the subject content, or a comparison with other representational formats. However, the focus here is students' activities when completing an assignment in relation to a representational tool and the kind of resources brought into play in the activity.

Two main research questions have guided the studies:

- How are cognitive and semiotic resources used in the tasks of analyzing and modeling complex problems using a System Dynamics framework?
- How does interacting with System Dynamic artifacts affect students in the process of completing their assignment – how are the features of the tool visible (or not visible) in the students' work process?

There are three different ways of perceiving systems thinking, according to Richmond (2000): as a set of tools, as a specific perspective on reality, or as a special terminology with which we express our understanding (see Chapter 2). To learn systems thinking involves all three ways. Inspired by this classification, three more specific research questions were subsequently formulated in relation to the overarching focus (the italicized text refers to Richmond's presentation).

- What role does the normative working order play in students' work process? (*Learning the rules of a tool*)
- How do students formulate their knowledge formerly represented in a specific format (e.g. an xy-graph) when they are forced to use a new representational format (CLD)? (*Applying a specific way of thinking*)
- How are the elements of the System Dynamics semiotic domain used, and what role do they play in the meaning making process? (An extension of *a special vocabulary with which we express our understanding of dynamic complexity*)

The following three case studies will illustrate one of these three aspects each.

Setting and course description

LUMES is the abbreviation for Lund University International Master's Programme in Environmental Studies and Sustainability Science (LUMES, 2008). The students entering the two-year program come from all continents and have various academic, cultural, and professional backgrounds. Ages are in the range of 19–45 years.

System analysis is a 7.5 credit compulsory course for all LUMES students. The course is the first one in the second semester, following core curriculum courses of 15 credits and the two selected courses of 7.5 credits each. The aim of the course is to provide the students with skills and insights in System Dynamics as a set of tools and skills that can be applied across a wide range of problems. It consists of four different parts: seminars, guest lectures, projects, and examination. A total of four projects are assigned in the course. The first project is individual, the second and third are done in dyads and the fourth is done in a group of four. The empirical data presented in the case studies concerns the project work for the second and third project when students work in dyads. Both projects involve issues of social and economic, as well as environmental sustainability.

In the case studies presented in this thesis, collaboration takes place between groups of two students engaged in a learning task. They are both in the same physical space, working on one and the same large sheet of paper. Collaborative learning refers to methods in which learners work together in pairs or small groups to accomplish shared goals (Slavin, 1992). As opposed to cooperation where it is usual to divide the workload and gather each contributor's work into a joint product towards the end of the work process, I consider the LUMES group work as collaboration, where there is no clear division of labor but a "mutual engagement of participants in a coordinated effort to solve the problem together" (Roschelle & Teasley, 1995).

Students' assignment and nature of the task

Each assignment starts with tutors presenting four different cases in class. The cases, each holding a problematic situation, can be in the form of a newspaper article, a scientific article, or a story written by the tutors. The assignment is to construct a model that represents the problem in the case, and further, to suggest which interventions should be made and how these could contribute to a solution. The topics for the assignment are considered to belong to complex and ill-structured domains. Significant for such domains is that they do not remain constant over time, they involve variables and constraints which are not well defined, and the influences are not easily predictable (Davidsen, Spector, & Milrad, 1999). The problems usually have more than one possible solution.

The tutors group the students two by two and assign them to one of the presented cases. The students are to create a model on paper in the form of a Causal Loop Diagram (CLD), based on the written case. As a second step of the assignment, they transform the CLD into a quantitative computer model using modeling software. A written report explaining the model and what consequences it predicts is handed in, comprising both the CLD and the computer model. Finally, a presentation to the class is given for each project assignment.

The total time available for each assignment is on average five full days. Group members work in a place of their own choice and decide upon their own work schedule. The only time for them to pay regard to is the deadline for handing in the assignment at the end of the working week. The tutors' role is to be available for discussion and to guide the students, but never to reveal any answers or do any modeling for them.

The examination, which occurs in the final week of the course, is an individually written paper demonstrating understanding of how to construct a model of a dynamic system. It consists of the construction of a feasible CLD for a problem, explanation of the feedback involved, and a proposal for a computer modeling strategy. The ability to reason on the basis of the model is strongly emphasized over numerical answers, and the students do not construct any computer models. The individual grade for the course is based on assessment of all four project assignments, together with the result of the final exam.

CLDs and computer models are two representational tools that the students use to complete their assignment. Constructing a CLD is a first step that involves decisions about what variables are relevant to include, and how each of these might influence the system. This working step is the focus of the case studies.

Unit of analysis

The studies of this thesis are explorative and look at problem solving in the context of university education. The unit of analysis is the students' mediated activity, specifically their interaction with their peer and with the evolving representation. The situation in which students engage is seen as both social and cognitive, and meaning making is seen to take place as a result of individuals' active participation in a social practice. The phenomena under study are the semiotic and cognitive resources by which students reason and coordinate their actions. This interactional process requires an understanding of language and other semiotic tools as both individual and social resources (Cole, 1996; Halliday & Hasan, 1989). The CLD is viewed as the primary mediational means upon which the learning situation in the empirical material rests. The empty sheet of paper on the table in front of the students, waiting for them to start to write and draw on, is the main reason for the students to sit down together.

Data collection and data analysis

Access to LUMES was gained through one of the tutors engaged in the System Dynamics course. The group of tutors at LUMES has a genuine interest in the area of teaching and learning, and discussions among colleagues on these topics are common. The enthusiasm for the research project was apparent, which presumably contributed to the willingness of students to participate in the studies.

Participating students were selected based on which case they were assigned to work with. The researcher picked a random case before they were presented in class. After the students were informed of who they were to work with (decided by the tutors), and if the selected case was chosen for them, the students were approached and asked if they would like to participate in the study. None of the students declined participation. Ethical considerations for the collection of data have been taken insofar that each participating student acted under informed consent. A consent form was signed by each individual and filed by the researcher. The participating students have been anonymized throughout the data material.

Four groups working with the second assignment in the course, together with four groups working with the third assignment, form the basis of the empirical data. The fictitious names are, for the second assignment: Miriam and John, Tom and Anna, Mark and Ellen, and Lynn and Brian. For the third assignment they are Anna and Stacy, Ben and Sarah, Lynn and Chris, and Ellen and Nathan. Anna, Ellen and Lynn are thus part of the study for both of the assignments, but working with a different student in each.

In order to analyze the interactants' discourse and actions, the group work sessions were video-taped during the first two hours of constructing the causal loop diagrams (CLD). The resulting models on paper were copied and filed to support the analysis, as well as the final version of the reports handed in. Field notes were taken during the days of the video recordings.

The complete corpus of video recordings was transcribed with regard to the spoken discourse. As a second step, when excerpts had been chosen for the three case studies, transcriptions of activities with regard to the interactions with the evolving graphic representation were added. The video films are considered as the primary empirical material. The transcriptions are regarded as working material that has been brought about by means of interpretations and attention to certain aspects of the interaction. Thus, "[t]ranscription does not replace the video recording as data, but rather provides a resource through which the researcher can begin to become more familiar with details of the participants' conduct" (Heath & Hindmarsh, 2002, p. 118).

The following transcription conventions apply in all excerpts (see also table 1, below): A short pause is marked by a period in parentheses (.), whereas a longer pause is marked with the length in seconds (e.g. (3)). Forward slashes (/ /) are used to indicate points of overlap in speakers' talk. In addition the equal symbol (=) is used to identify the immediate uptake or continuation of ideas. Referents to clarify students' deictic expressions are marked by [].Words enclosed in double parentheses (( )) indicate uncertainty regarding the transcribed section. As part of the transcription notation, additional information about observed activities, especially in relation to the evolving representation, is written in [*square brackets and italics*]. These annotations allow examining the way students coordinate their verbal activity with external representations.

(.)	short pause
(3)	longer pause marked with the length in seconds
/	points of overlap in speakers' talk
=	immediate uptake or continuation of ideas
[]	referents to clarify students' deictic expressions
(( ))	uncertainty regarding the transcribed section
[*italics*]	information about observed activities in relation to the evolving representation
[…]	excluded part of the dialogue

Table 1: Transcription conventions used in the case studies.

From the transcriptions and field notes, a synoptical analysis was done by identifying types of cognitive-communicative activity that the students were orienting themselves to (see Rainbow framework in data analysis section). Critical events were identified based on when features of the tool became visible in the students' work process. One such event, included in all three case studies, is the beginning of the collaborative work. This is the moment when the students have to establish the context and negotiate a structure for the task. Other events that were identified are the moment of transition from one working step to another (see Task analysis section), and the instances when students use the subject-specific terminology.

For the identified events, I examined more closely the transcripts and features of the artifacts to determine what role these played in students' meaning making in the process of constructing the CLD. Three different aspects that emerged in this material were chosen for three separate case studies, presented in Chapters 5 through 7.

To further illustrate the transcriptions of spoken discourse and actions taken in relation to the visual representation, the case studies also include freeze frames (photos) from the video recordings. The video camera was placed at some distance from the students in order to be as discrete and non-obtrusive as possible. This circumstance, and the fact that the light conditions were not optimal for filming purposes, affected the focus and the sharpness of the photos to some extent.

A collaborative activity involves many aspects that have an effect on the collaboration process and on the result of the joint work. There are questions regarding group dynamics and various roles taken by the group members. There are also questions regarding the members' cultural or educational background, sex and age and how these aspects can affect the activity. These aspects are put aside in the case studies that follow, acknowledging that they are important but not required for the data analysis in relation to the research questions, which focuses on how cognitive and semiotic resources are used by the observed students. The students represent a diversity when it comes to age, sex, personality, as well as educational background. One circumstance to be aware of is that English is not the first language for five out of eight students in the case studies. This is an additional aspect of the interaction and something that may affect it. The students participating in the case studies are reasonably good English speakers, and no specific problems relating to language difficulties were noticed. Instead of looking at single utterances to discern meaning, I have decided to concentrate on how meaning is actually expressed in the interaction, relying mainly on how the responding student acts on a statement, thereby trying to avoid speculations on how certain statements can relate to possible language difficulties.

The final model produced by the students is not included in the presented empirical material as the analysis of dialogue and actions focuses on the work process carried out by the students. However, when the aim is to understand the collaborative work and the actual learning that may have occurred, the solution produced can also be important as it is the result of the process and represents the achievement of certain objectives. Even though the issue is beyond the scope of this thesis, I would still like to raise the awareness to this notion.

Two methods for collecting and analyzing data were used: a task analysis method and the constructive interaction method, based on interaction analysis. They are presented in the following paragraphs, together with the results of the analyses.

Task analysis method

The task analysis method is extensively used in the area of Artificial Intelligence and Human Computer Interaction, for example in system design and interface design (Diaper & Stanton, 2004), and in the area of learning when it comes to designing instruction (Jonassen, Tessmer, & Hannum, 1999). The reason why this is an efficient method when designing instruction is that it can be helpful to articulate a model of how you would like learners to think and perform in a normative sense, and that design should follow on these articulations. Parallel to defining a normative model, it is also important to investigate what users actually do.

A task analysis attempts to ascertain what a user is required to do in terms of actions and/or cognitive processes to achieve a task. It consists of primarily identifying and defining a normative description of a working order and secondarily to confront that normative description with the corpus (Kirwan & Ainsworth, 1992). In the specific context of this thesis, the analysis aims for a description of the domain (creating a Causal Loop Diagram), focusing on the structure, characteristics and components of the task.

Even though my objective is neither to design an interface nor to design instruction, I find task analysis a suitable method for determining how the task is performed and what issues the students have to address in the work process.

Task analysis of the empirical data

The task analysis for creating a CLD will reveal how the normative working order is realized and what characterizes these steps. The following paragraphs describe the normative working order in short, and what actions students take to carry out the normative working order. Students are seen as a collective and the description includes all variations found within the eight groups that took part in the study.

The normative working order

The elements of activity and the working order that the students are taught when constructing a Causal Loop Diagram are:

Step 1: Reading the story

Step 2: Defining the relevant variables

Step 3: Sorting the variables into different categories
- Actors
- Factors
- Conditions

Step 4: Structuring (the set of relations among objects in the system)
- Defining causal links by drawing arrows
- Defining whether the causal links are positive or negative

Step 5: Structuring (interrelations among objects in the system)
- Defining causal loops (feedback)
- Defining whether the loops are balancing (B) or reinforcing (R)

To illustrate the various steps in the working order, a flow chart is used, see Figure 9 (first part) and 10 (complete). The left column shows the normative working order. The right column shows what actions students take, relative to the normative order.

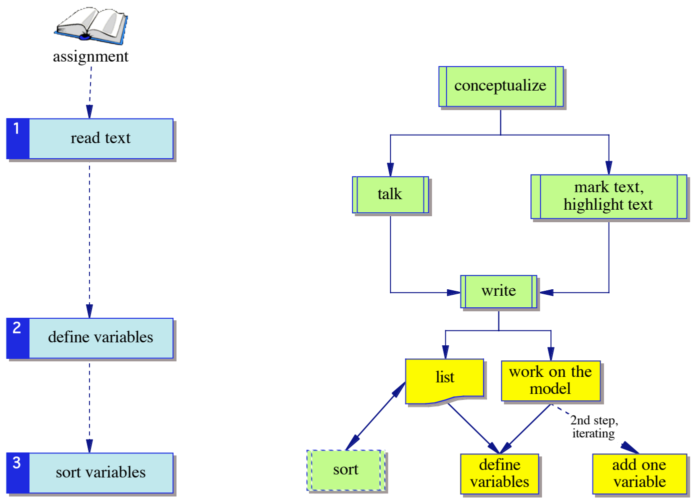

Figure 9: The first, second and third steps in normative working order to construct a Causal Loop Diagram (left), as taught by the tutors. The actions taken by the students are shown on the right.

How the working order is carried out

Step 1: Reading the story

The tutor hands out the assignment. Students read the text and conceptualize the problem on their own before meeting with their group member. Some students make notes in the margin of the text, and some use a pen to highlight parts of the text.

Step 2: Defining the relevant variables

The written story that the students will work with needs to be jointly conceptualized in order to collaboratively construct a model, an initial effort of what Roschelle and Teasley call creating a “Joint Problem Space” (Roschelle & Teasley, 1995).

Some groups talk for a while before putting anything on paper, while some groups start to write and draw almost immediately. Typically, the students start by telling the story to each other (for a shorter or longer time) checking whether they have the same comprehension of the scenario. During that process they suggest what variables to use in their model. One group in particular uses a marker to highlight important parts of the text they were given. This form of nonverbal activity supports the students’ memory and helps them see the important sections in the text before starting to construct their own model on a sheet of paper.

Spoken words are transient. Writing the variables down, either in a list or directly in a CLD, provides an external memory aid and makes the discussion easier to refer to, as pointed out by Holsanova (2008). When the students turn to the sheet of paper, they either start by writing down the variables in a list or start on the model (CLD) at once. If they start on the model at once, some groups are content with only two variables before proceeding to work on the structure. Others write down several variables without immediately defining causal relations between them.

When deciding on variable names, several observations can be made regarding the choice of how to label them. The students' discussions are about the use of positive/negative connotation (health or disease to show what affects a person's life quality), and the possibility to quantify the variables (hunger is harder to quantify than servings of food per day). Quantifiable variables are not so important during the CLD phase, but already at this stage students show awareness of the second part of the assignment, which is to construct a computer model where quantities will be needed.

Step 3: Sorting the variables into different categories (Actors, Factors, Conditions)

This is a step that is applicable only if a list has been made, and even with a list at hand this step could be omitted without constraining the move to the following working steps. Sorting as in the normative description above, suggested by the tutors, asks for a categorization of variables in terms of actors, factors, and conditions. This categorization is meant to be a help in the later construction of a computer model.

In none of the observed cases do students explicitly sort the variables that have been defined, for example rewrite the variable names and sort them in different categories as a separate step. One group makes headings when summing up, after the list is complete. They name one column "Business as usual" and the second "Consequences." Some other groups make a list of variables without a heading and a second list called "unknowns."

Steps 4 and 5: Structuring

The structuring phase involves addressing the most number of questions. Defining structure is done in two steps: one is defining links and the other one is defining feedback loops. Working with the structure of the model includes most decisions and subtasks, as can be seen in the flowchart, Figure 10. Having defined links and loops, there is also a need to define whether the links imply a positive or a negative effect, and if the loops are reinforcing or balancing. The main part of the students' time is spent on steps four and five.

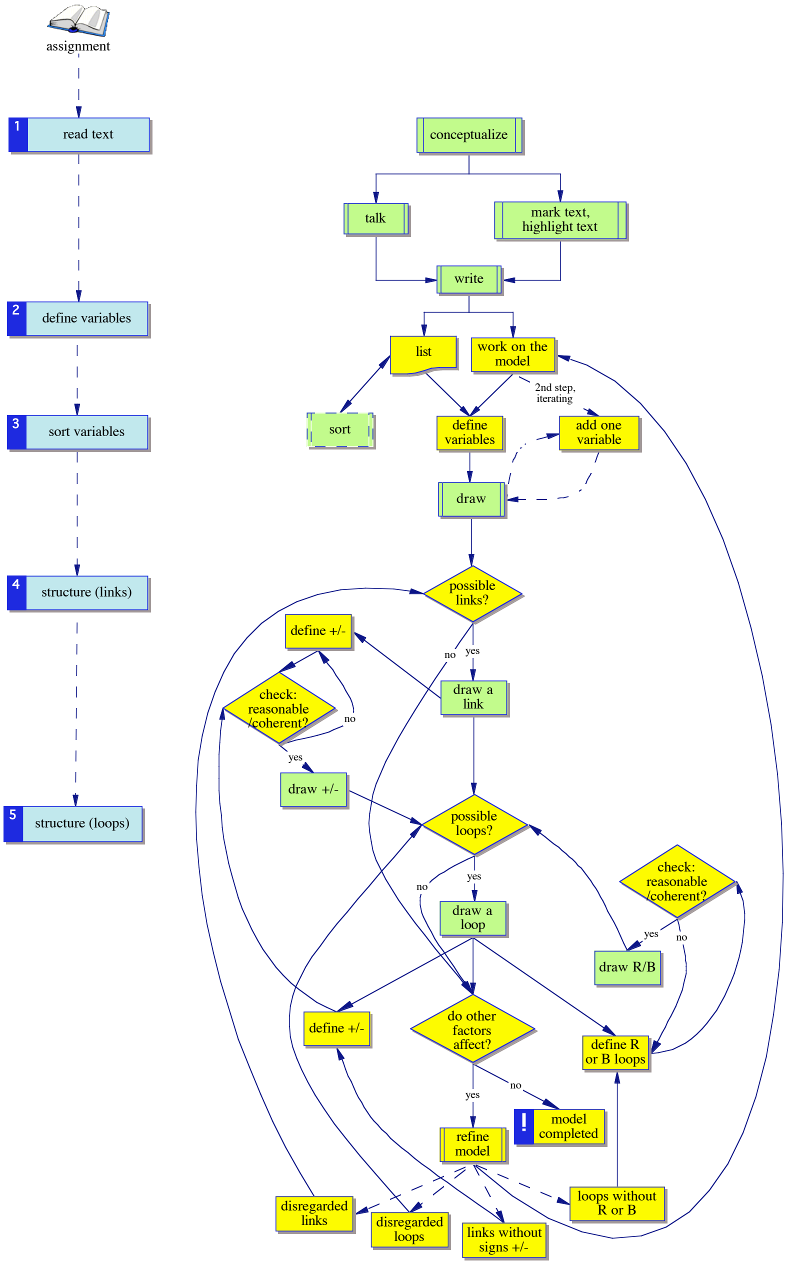

Figure 10: Defining structure is the fourth and fifth working step in the normative working order. These steps include most decisions and subtasks. B stands for Balancing, and R stands for Reinforcing. (For a definition, see the section Elements and terminology of a CLD). Working order as taught by the tutors in left column, The actions taken by the students are shown on the right.

Iterations

Tutors suggest to students that they start by constructing a small system with only a few variables, and then expand the model step by step by adding one or a small number of variables at a time, fitting them into the existing structure. Following this suggestion, the normative working order is carried out in several iterative cycles of reading the story (step 1), defining variables (step 2), fitting them into a structure (steps 4 and 5), and then going back to read the story once more, defining additional variables, fitting them into the structure, and so on.

Computer modeling as a second part of the assignment

Constructing a CLD is the first part of the assignment, and the students later proceed to constructing a computer model as the second part. Both the CLD and the computer model must be included in the final report. The focus of the empirical studies in this thesis is on the first part when students create a CLD. However, some observations relating to the computer modeling phase are presented in Chapter 8.

Constructive interaction method

Human thinking is not merely a matter of processing information or following cognitive rules. Thinking is to be observed in action in discussions, in the rhetorical cut-and-thrust of argumentation (Billig, 1991).

The method used for collecting data is based on the ideas of the constructive interaction method (Miyake, 1982). The data consists of natural speech between two students with comparable knowledge of the domain, wanting to solve the same problem. There is an emphasis on how students understand or develop concepts, as opposed to how they learn various procedures. Having an emphasis does not, however, imply that this dualistic division into concepts and procedures can be used to fully characterize a learning task. Learning a procedure is generally not possible without forming a concept of what the procedure is about. "Procedures are not thoughtless and mental activity is not disembodied" (Wenger, 1998).

To avoid the drawbacks of thinking aloud methods, the constructive interaction method is carried out by having two individuals perform a task together. The interaction usually leads to explanations and arguments about what to do and how to do it. This is considered to be a more natural interaction than that in the thinking aloud test, where the individual continuously verbalizes his thoughts while working on a task. As a data collection method, collaborative problem solving is attractive because it encourages learners to verbally express and substantiate their thoughts to each other, thereby making them accessible to the researcher without having to ask for them specifically. Miyake (1982; 1986) showed that having a pair of individuals discuss a topic while working collaboratively on a solution revealed much about their assumptions and understanding of the topic.

The method is used in order to describe the unfolding work process. It yields a rich set of qualitative data that can provide valuable insight into how individuals perceive situations, how they go about solving problems, and what resources they use to accomplish a task. The interaction between researcher and the observed individuals is minimal in the constructive interaction method, and therefore the results can be considered to be of relatively high ecological validity (Kahler, 2000).

Interaction analysis of the empirical data

The data analysis is inspired by interaction analysis (Jordan & Henderson, 1995). With its roots in ethnography, sociolinguistics, conversation analysis and other traditions that include nonverbal resources in interaction, the aim of the analysis is to identify how the participants make use of various resources, not only verbal, in the activity of constructing a dynamic model.

The aim has been to study the students' verbal and nonverbal actions of the activity in relation to the evolving model on paper. In order to structure the many hours of student activity on video, the first step of the analysis process was to look for types of cognitive-communicative activity that the students were orienting themselves to. Rather than assigning a category for each turn a speaker would take (one line in the transcript), segments of a period in time when the same topic was dealt with were identified.

Defining the categories was an iterative process starting from the transcriptions of students' dialogue and using theory-informed concepts from interaction analysis, specifically the Rainbow framework (Baker, Andriessen, Lund, von Amelsvoort, & Quignard, 2007). This particular framework was originally developed to analyze when and how students engage in an interactive knowledge elaboration in a Computer Supported Collaborative Learning (CSCL) environment. Although the principal methodological aim of the original framework was to enable functional categories of interaction to be quantified within an experimental approach, it proved to be useful also in a nonexperimental situation and with a descriptive approach. As Baker et al. suggest, such an analysis can help identify specific sequences that merit a more detailed process analysis.

The resulting categories were thus an elaboration of the Rainbow framework (Baker et al., 2007), modified with the aim of having a rich description of the authentic situation and being close to the data. The framework comprises eight principal analytical categories represented in the form of a decision tree, where the leaves are the categories.

A distinction was made between activities that are part of the given assignment and activities that are not, as well as between interaction-oriented and problem-oriented activities. The coding scheme was applied to the complete verbal transcriptions of the interactions, but not used for further analysis. The categories primarily served as a prelusive step in analyzing the ongoing discourse. They were used in order to find sections in the conversation where issues related to the research questions could be found. Each segment was coded as one of eight topics described below.

Off-task

Any interaction that is not concerned with carrying out the assigned task, including socio-relational interaction: for example, talk about the weather or where to go for lunch.

Interaction-oriented categories

Social relation: Socio-emotional aspects of the collaboration: for example, asking for help, tension release by telling a joke, giving positive feedback, keeping fellow group member focused on the task.

Interaction management: Coordination and regulative aspects of the collaboration: for example, who holds the pen when drawing the model, stating dissatisfaction with a dominant peer, asking a peer to participate more.

Task management: Procedural or practical aspects of the task: for example, discussing the assignment, organizing and planning the activities, management of the progression of the task itself, time management, establishing whether the problem or part of the problem was solved or not.

Problem-oriented categories

Particulars: Choosing and defining parts or nodes in the system. For example, deciding which parts are important to include in the model and information about them.

Structure: Recognizing and describing how the variables relate. For example, defining the causal relations between variables.

General idea: Interpretation of either the information given or interpretation of the constructed model (data and graphics). Recapitulation of the work in order to evaluate the feasibility. Suggestions as to how to proceed in relation to the problem.

Predictions: Formulating hypotheses, testing the hypotheses and evaluating them. Discussing implications of the constructed model.

The use of CLD terminology

A second investigation in the interaction analysis looked for instances where the specific CLD terminology was used. It could be noted that the CLD terminology was predominantly used in the problem-oriented activities, and especially in parts of the dialogue categorized as "General idea." There were also instances of the subject-specific terminology in parts of the dialogue categorized as Task management.

Summary and discussion of the data analysis

Constructing a CLD means applying a formal structure with precisely defined elements that constitute the overall structure. The rules about how to build models with this specific tool are strict and can be perceived as leaving little to one's own improvisation. Such a regulated work process may seem like a straightforward task that looks more or less the same for all modelers, but this is not the case. Even though the tool calls for sequentiality, including certain steps and certain actions that are meant to scaffold the modeling process, students must make cognitive and social efforts to make sense of the tool and of the problem they collaboratively have to solve using it. This is because the tool does not stand by itself. In the hands of any person it is something that she needs to make sense of – a sense-making that takes place in reflection and dialogue. Students need to make the normative working order operational, that is, apply it to the case and fill it with a content. Each task involves a number of subtasks and a number of potential alternatives available for each subtask.

The students follow the normative working order and act to a large extent in accordance with the norms. Part of the explanation is that there is a strong intrinsic sequentiality in the tool, in that some steps need to be taken before others can be dealt with. Students adjust to this notion without any outspoken reflection. Thus, the task analysis shows that the tool scaffolds the organization of the work process on account of its strict working order, and that the model evolves in small steps in an iterative manner, as suggested by the tutors. The iterative process that can be observed most likely depends on the nature of the problem, that is, that it is an ill-structured problem with many possible solutions. The problem is revisited several times before students are confident that the model holds the necessary and sufficient information.

The paper with the evolving CLD figures as the central semiotic object that holds the work process together and it is the object around which the students coordinate their attention and actions. The problem-oriented activities (Particulars, Structure, General idea, Predictions) were those that occurred the most. As regards the interaction-oriented categories, activities related to social relations and interactional management were observed quite seldom. Task management activities, which could also be categorized as meta-cognitive activities, could be noted on more occasions. Off-task activity was observed only in a few instances for each group during a consecutive two-hour session.

The analysis shows that students sometimes struggle to express their understanding in the specific form that the tool demands, which becomes observable when they work with the structure of the model. Moreover, it also appears that the specific systems thinking terminology is predominantly used in certain parts of the work process, particularly when taking a more holistic view of the evolving model and of the work process, that is, activities of a meta-cognitive nature.

Inspired by the three different aspects of systems thinking suggested by Richmond (2000), three major themes emerged from the task analysis and the constructive interaction analysis. The themes were formulated in relation to the overarching research questions of how cognitive and semiotic resources are used when learning a new representational tool, and how the features of the tools affect the working process.

The themes with the common denominator *"Learning to think in terms of systems"* will be highlighted in the case studies that follow:

- How the working order scaffolds the students' activity.
- The role of students' previous knowledge when representing a problem in a new semiotic domain.
- How the elements of the systems thinking semiotic domain are used, and what role they play in the meaning making process.

5. Case study I – Using the normative working order as a scaffolding resource

The first case study is about the work students undertake when constructing a CLD for the problem of desertification in the Sahel region in Africa. It is based on the work of students Anna and Stacy (fictitious names), starting to work on a CLD for the third assignment in the course. Of special interest is how the normative working order affects the students' interactions with each other and with the evolving model on paper. The working order is an integral part of using a specific tool for mapping and exploring dynamic complexity, one of Richmond's three aspects of systems thinking (Richmond, 2000).

The assignment: Sahel and the threat of desertification

Sahel, the narrow area of land south of the Sahara desert, has been the home of nomads for centuries. It has never been an easy place to live in but the nomads have survived amazingly well. In recent years, people acting for organizations like the UN decided to improve life for the nomads. These organizations did two major things. Firstly, they introduced modern medicine. They vaccinated the nomads against smallpox and measles and they brought malaria and sleeping sickness under control. Modern medicine greatly increased the life span of the nomads as well as keeping animal diseases down. Secondly, more water was made available. There are great supplies of underground water in the Sahel, which the nomads' hand-dug wells never reached. Deep wells were drilled using modern machinery. This large new supply of water increased the number of animals possible for the nomads to own.

Although the animals had water, their larger number soon ate or trampled the little grass available. A six-year drought further decimated the grass and the animals began to die of starvation. Because of the drought and the loss of animals, many nomads starved. The UN was faced with a more severe problem than the one it originally wanted to solve. The assignment is to explore the long-term dynamic forces that control and influence the Sahel region. (Excerpt from LUMES student assignment, 2005.)

Conceptualizing the problem

Anna and Stacy negotiate how to start with their assignment and decide to discuss the case before using pen and paper. Taking the first steps in the construction of a joint problem space, Anna suggests that the goal of the discussion is "to see if we understood the same thing."

```
*STACY:  so (.) like (.) should we discuss it first and then
         modeling or should we (.) is it easier for you to start
         writing straight away ?
*ANNA:   I don't know (.) it doesn't matter
*ANNA:   I think we can discuss for five ten minutes
*STACY:  okey
*ANNA:   to see if we if we understood the same thing
*STACY:  okey (.) mm
```

Anna and Stacy proceed by discussing the story and the issues as they perceive them. During the discussion, Anna makes gestures in relation to the paper showing spatially how the variables should be grouped. This action implies that she already has a plan for how a part of the model should be organized.

Anna and Stacy tell the story to each other checking whether they have the same comprehension of the scenario. During this initial discussion, they verbally introduce variables that they think should be included in the diagram. Moreover, the word balance seems to be important already at this stage when Stacy is explaining the problem and how it should be represented. (The word "balance" is marked in bold to highlight where it is used.) Anna agrees with Stacy's view of the problem and suggests which variables to use. Stacy comes to a close on the issue by proposing how to manage the task.

```
*STACY:  okey, so (.) the place is like sub saharan africa
*ANNA:   mm
```

```
*STACY:  and (.) what we have is like (.) an, a balance, it used
         to be a balance but it's not balance anymore because of
         (.) the introduction of technology and modern medicine
*ANNA:   mm
*STACY:  which took away the natural eh balance in fact of which
         were diseases and eh (.) what else was that (.) disease
         (.) diseases and drought =
*ANNA:   = and drought
*STACY:  drought (.) which used to balance the population of the
         nomads, of the nomads and most (.) of the animals
*ANNA:   yeah, I mean (.) how I saw it is that (.) first we have
         nomads and we have animals and grass or (.) vegetation
*STACY:  vegetation
*ANNA:   and when the number of nomads increases and wi, together
         with the number of cattle
*STACY:  yeah
*ANNA:   then (.) we have either diseases (.) or drought that
         reduces their number and
*STACY:  and they're (quite regular) it says that (.) every
         twenty or thirty they happen
*ANNA:   so the system is in balanced somehow
*STACY:  so the system, so what we should do actually is, when we
         start making the c-l-d like (.) make the system in
         balance
*ANNA:   exactly, without any medicine or technology or
*STACY:  and then model the the system (.) when it becomes (.) eh
         (.) im ba imbalanced
*ANNA:   mm
*STACY:  so (.) okey I mean we could start with with the balanced
         system it shouldn't (.) it shouldn't be very difficult
```

Balance, in this case, means that competing influences are balanced against each other. Balancing processes seek equilibrium as they aim at bringing things to a steady state and keep them there. Students are encouraged by the tutors to start with a small, balanced system before adding variables that affect the system in such a way that the balance is disturbed.

Anna and Stacy divide the problem into two parts: before and after the interventions by the UN. The situation before the intervention is represented as the balanced system, where disease and drought kept the population from growing.

The use of the tool-specific terminology is further discussed in case study III, Chapter 7, where the focus is on the language-related aspects.

Choosing and defining variables

(step 2 in the working order)

Defining variable names

The first thing that the tool (CLD) requires when starting to work is that a word be written down. This word commonly names a variable which the students see as a central part of the problem. They typically decide on either the first thing or the most important thing; the first thing being the beginning of a chain of events following a chronological order in the story, and the most important thing being what they perceive as the central variable in the model.

After the initial discussion, Anna and Stacy start to draw the model right away. They do not make a list of variables first, as suggested by the normative working order. In the conceptualization of the problem, Anna suggests three variables.

```
*ANNA:   first we have nomads and we have animals and grass or
         (1) vegetation
```

Fifty seconds later they are ready to start drawing the CLD. Stacy picks up the suggestion made by Anna previously:

```
*STACY:  ok so you have (1) there are here like some (.)
         variables that we should include like (.) human
         population animal population eh (.) vegetation
```

Anna and Stacy now move from using exclusively spoken language to include a visual representation as a resource in their collaborative work. When they are to decide on the variables to put in the diagram they change the terms, even though they basically are same physical entities as stated before. This seems to take place without any overt reflection. The names become formalized and generalized to better fit the terminology used in a CLD: Nomads become human population, animals become animal population and grass changes to vegetation.

Students generally also pay attention to the fact that they will have to assign quantities to the variables when constructing a computer model later on. This awareness is demonstrated by having discussions about quantities for each variable already at this early stage, and avoiding the inclusion of "soft" variables such as happiness and anger that are hard to quantify. This aspect will be discussed further in Chapter 8.

Using neutral variables

Next, Anna and Stacy expand the CLD by adding "Rainfall" and "Soil quality" to their model. One thing to keep in mind when choosing the names of variables is that they should not include value words like good, bad, more, less, high, low. Using adjectives in variable names increases the risk of causing confusion later in the work process as it will be difficult to proceed with making links and feedback loops and deciding if they are positive or negative. One such effect leading to confusion could for example be to use "less good soil quality" or "better soil quality". A more neutral term like "soil quality" fits better with the notation conventions and makes it easier to indicate if the effect is worse or better with + and – signs. Anna and Stacy run into this problem but resolve it quickly. The utterance "You cannot put the signs then" points to the notion of that it will be difficult to put a plus or a minus sign on a variable named "good soil."

```
*ANNA:   it's just good, good soil for plants to grow
*STACY:  okey, shall we put good soil ?
*ANNA:   okey, and we know what means and then we, we can change,
         mayb we can come up
*STACY:  with a better term, okey so (.) good, the better, no,
         but then you shou, you're not supposed to use the terms
         good here
*STACY:  that's, that's, that's why I put soil quality here but I
         can
*ANNA:   ah, okey
*STACY:  because good soil
*ANNA:   we can not, you can not put the signs then
```

There is also an issue of using variables with a negative or a positive signification since the choice of variables influences how the model is developed further. Medicine has a positive effect on a variable called health, but a negative effect on a variable called disease. Should the water availability be represented as a lack of rainfall or an absence of drought? Health or disease, rainfall or drought – which variable should be used? Students are aware that the choice will have an impact on the congruence of the final model and show it by coordinating terms with the requirements of the tool.

Another group, Ellen and Nathan, has a similar discussion to that of Anna and Stacy, concerning rainfall or drought, and disease or health:

*NATHAN: […] can be the good and bad [_points to their variable rainfall/drought_] rainfall and drought
*ELLEN: uhu
*NATHAN: (if) maybe it's good (.) heh and maybe it influencing
*ELLEN: I mean to make it more to make it more easy this is a bad thing [_points to the variable diseases_]
*NATHAN: yes but this is only bad this is a bad thing
*ELLEN: this is a bad thing
*NATHAN: but you need to call it a bad thing
*ELLEN: so let's just call it [_erases rainfall in the variable name_] drought then we have a bad thing here also

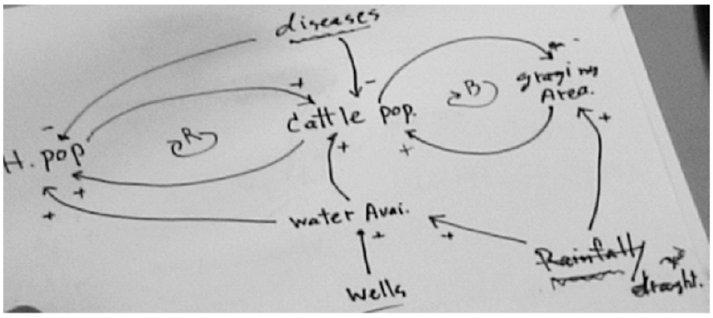

Figure 11: Ellen has erased rainfall and kept drought in the variable name.

*NATHAN: yes but I don't I'm no I'm not sure it's work or not (.) I just wonder what we have (.) maybe it's better (.) is it better if we have the good thing [_points to the variable disease_] and bad thing
*ELLEN: ah: let's call it human health (1,5) let's call this human health [_points to diseases_]
*NATHAN: so is that a good thing
*ELLEN: it's a good thing (.) and let's call this ehm rainfall [_points to rainfall/drought_]

Defining causal links and feedback loops

(steps 4 and 5 in the working order)

The next step that the students take, guided by the normative working order, is to decide the causal relations between the variables. This step is manifested in the students' active pursuit of causes and effects. Anna and Stacy concurrently work on both links and loops, meaning that as soon as a link has been defined, they consider a link "going back," that is, an interrelation between the variables.

The way to show a relation in a causal loop diagram is to draw an arrow from the word that has an effect to the word that is being affected. Thus, as soon as there are two words (variables) or more on the paper, it is possible to start creating a structure by drawing links from one variable to the other, to define a causal relation. If another link can be drawn back to the original variable, a loop is created. A tendency throughout the empirical material is that students immediately look for a link between variables as soon as there are two of them written down. Only in a few cases do students write down several variables before defining causal relations.

The rules about how to use the tool make it possible to draw arrows to and arrows from each word on the paper. There are thus decisions to be made regarding which arrows to draw, but also which arrows *not* to draw. This notion elicits various forms of discussion of issues first taken for granted, but then problematized as a decision has to be made regarding the structure of the model.

```
*STACY:  so the more rainfall (.) the more vegetation//
         [draws a link]
*ANNA:                                           //vegetation
*STACY:  this does not go back [points to vegetation and then to
         rainfall]
*ANNA:   and the better soil quality (.) also better vegetation
         [draws a link]
*STACY:  is this does this go back ? [makes a line with the
         finger between vegetation and soil quality]
*ANNA:   I think so and I think it's all re (.) it's all stated
         there somewhere [looks in the text] that (.) for the
         soil to improve sometimes yeah
*STACY:  but in soil qua, in terms of soil quality now we mean
         that (.) soil
*ANNA:   and nutrients ?
*STACY:  no soil that has not been desertificated
```

```
*ANNA:   ah, okey
*STACY:  so if if if we mean it like that (.) then definitely
         this vegetation will keep the soil from (.) becoming a
         desert
```

The expression "go back" is used to refer to a possible feedback loop, that is, that there is a mutual circular causation between variables. "This does not go back" signals that Stacy has considered a possible link from vegetation to rainfall, but concludes that there is not one. She uses the same kind of reasoning a second time regarding a possible link between vegetation and soil quality. This time it is formulated as a question, which Anna responds positively to after referring to the text they have been given. They agree that there is an interrelation between vegetation and soil quality.

Anna and Stacy use a counterfactual conditional mood to check whether their reasoning holds. A conditional sentence refers to a hypothetical state of affairs, or an uncertain event that is contingent on another set of circumstances. It indicates what would be the case if its antecedent were true. This form of reasoning is recurrent throughout the work process, both for checking single links and for summing up the work achieved so far.

Defining causal links as positive or negative

(step 4 in the working order)

The notation system in CLD includes putting plus and minus signs at the arrow heads of each link to define if there is a positive or a negative relation between two variables. A plus sign (+) or a minus sign (–) adjacent to the arrow head defines if the change in the variable at the tail of the arrow will cause a change in the variable at the head of the arrow in the same (+) or opposite (–) direction.

Anna and Stacy have defined five variables they find important to explain the problem. They have also defined the causal relationship between these variables by drawing arrows between the words on paper and defining whether there is a positive (+) or a negative (–) relationship between them. Having to put pluses or minuses on the arrows seems to help students in the process of telling the story when going through the model step-by-step, moving from one variable to the other.

```
*STACY:  so the more rainfall (.) the more vegetation [writes a
         plus]
```

and

```
*STACY:  and the better soil quality (.) also better vegetation
         [writes a plus]
```

Typically, the students use conditional ("if-then") statements with terms like "the more," "the better," and "the less" to define what sign to use.

Defining feedback loops as balancing or reinforcing

(step 5 in the working order)

Anna and Stacy move on to define if loops are balancing or reinforcing. Stacy makes a suggestion and draws as she speaks:

```
*STACY:  animal population they eat vegetation
         [draws an arrow from vegetation to animal population and
         writes a plus]
         more vegetation more animal population (.) and then more
         animal population less vegetation, right ?
         [draws an arrow from animal population to vegetation and
         writes a minus]
*ANNA:   mm (.) balancing
```

The balancing loop that Anna and Stacy are making implies that the stock of animal can grow if there is vegetation available to eat. Eating means reducing the vegetation, and when the vegetation becomes scarce it will reduce the livestock since the vegetation cannot sustain as many animals as before. The result is that the amount of vegetation and the number of animals have a balancing interrelation in this system.

Anna and Stacy's discussion has resulted in a diagram where the amount of vegetation depends on the amount of rainfall, and that animal population increases the more vegetation there is (Figure 12). Also, the larger the animal population, the less the vegetation since the animals eat the vegetation. Their diagram also rests on the assumption that human population can grow if the animal population grows, and in turn the animal population can grow if the human population grows.

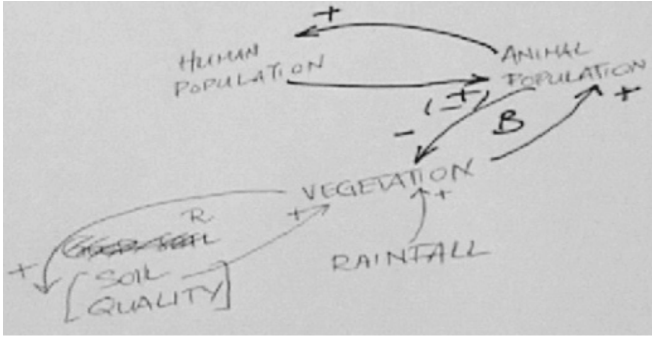

Figure 12: Diagram with a balancing loop including Animal population and Vegetation.

Expanding the model

Adding a variable and defining its place in the model

In order to take into account more information in the story, the students take action to expand their model. It is stated in the problem description that drought and early death by disease cut back on the human population growth, and this is the issue that Anna and Stacy address at this time.

*STACY: so (1) we should say what other factors affect this population (.) like (.) for example we said that (.) diseases and drought
*ANNA: mm
*STACY: [*writes the word 'diseases' on the top of the diagram*] so I think disease goes to both animals =
*ANNA: = animal and human
*STACY: so it's diseases here
*ANNA: but is it the same ?
*STACY: no it's not the same but we put it diseases in general
*STACY: it's not (.) some diseases are common for humans and animals
*ANNA: yeah this is (.) what I was thinking (1) okey
*STACY: you can you can separate human diseases and animal diseases but **it's not gonna make so much difference**

After all possibilities of drawing links to and from the first set of variables that they have defined, the tool calls for either putting an end to the work or adding new variables, thereby going back to step two in the working order. Stacy suggests that they should expand their model and find other variables than animal population that affect the size of the human population. She has two variables in mind and moves on, after being supported by Anna, to choose one of them: diseases. She writes the word "diseases" at the top of the diagram, see Figure 13.

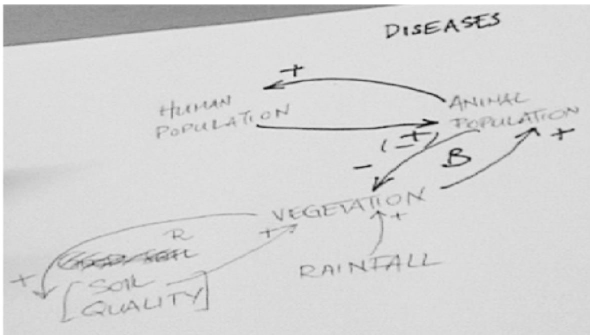

Figure 13: Expanding the model by adding the variable Diseases.

The next step that the students take, guided by the "demands" of the tool, is to decide the effects of the new variable diseases, proceeding to step four in the working order. Stacy says: "so I think disease goes to both animals" indicating that she wants to draw more than one arrow from diseases. Anna fills in: "animal and human," showing agreement. But then she has doubts. "But is it the same?" she asks.

Stacy is aware of her partner's doubt but doesn't find it necessary to make a distinction between human and animal diseases at this point. She acknowledges that in the real world they should be separated into two different kinds of diseases. But she also claims that there could be a reason for having diseases as just one variable: "some diseases are common for humans and animals." Anna seems fine with this explanation and ends the argument with "okey."

In reality it could be seen as being of great importance to define whether we are talking about human disease or disease that affects animals. Stacy states that "it's not gonna make so much difference." Whether or not it makes a difference depends on the level of generalization that is needed to explain the problem at hand. Stacy recognizes this. Defining that diseases can affect populations does not necessarily call for a detailed description of the kind of disease. The students express this generalization by following the rules of the tool: if you want to define that diseases affect human population and animal population in a causal loop diagram, there is no need to have more than one variable called disease. Having two variables does not add anything substantial to the explanation of the phenomenon that diseases have an effect on the size of both human and animal population.

Drawing several arrows from one single variable shows that it affects more than one variable in the system they are modeling, see Figure 14. The structure given by the rules of the tool makes it possible to draw an arrow to both human population and animal population claiming that disease will affect both populations.

Exploring the possibility to define a loop

Anna and Stacy continue to talk about how diseases should be represented in the diagram. They have agreed quite quickly (previous excerpt) on the claim that diseases reduce the populations. But is it also the other way around, does the size of the two populations affect how much disease there is? Is there a mutual relationship, or just a unidirectional causality? This issue has to be dealt with, in order to decide on which arrows to draw and which arrows *not* to draw. They are now dealing with the fifth step in the working order (see Task analysis section).

```
*STACY:  so (.) the more disease
*ANNA:   the less population
*STACY:  the less in in this both [human population and animal
         population]
```

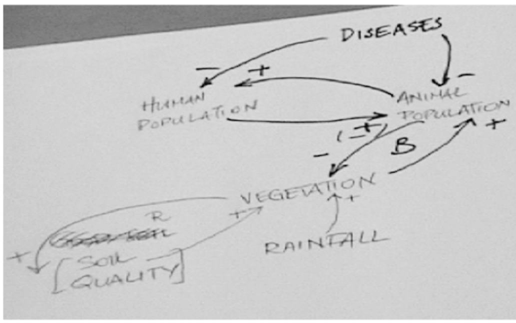

Figure 14: Stacy draws one arrow from Diseases to Human population and one arrow from Diseases to Animal population. She adds minuses to both arrow heads.

*STACY: and it doesn’t go the other way around
*ANNA: no [*takes the pen off the paper*]
*STACY: or you can say that if you have a more population is (.) well it could be
*ANNA: well it depends on what kind of disease you have
*STACY: if it's an epidemic disease it depends on the population but (.) you cannot assume that and
*ANNA: no let's keep it simple now
*STACY: but they are epidemic diseases
*STACY: it covers smallpox and things like that (.) which are (.) which are epidemic
*ANNA: cause then we have like an exponential growth in the population (.) in the in the (either) population for example
*STACY: in the what ?
*ANNA: if we will have here (.) eh (.) an arrow from human population to diseases (1) then they will grow it move faster than the the sick people (1) will grow faster than
*STACY: yeah
*ANNA: cause we will have more diseases and then less (.) or they will (.) yeah the human population will decrease faster
*STACY: yeah
*ANNA: I think we should have that

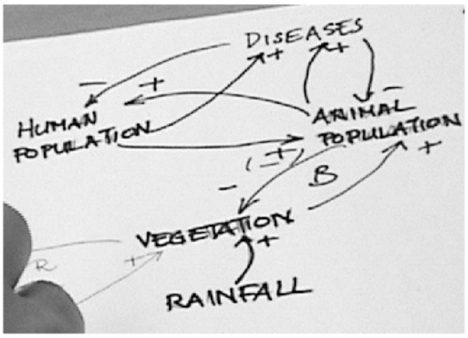

Fig 15: Stacy draws one arrow from Animal population to Diseases and one arrow from Human population to Diseases as a result of the discussion, thereby creating two loops. She adds pluses to both arrow heads.

The notion that there can be an interrelationship between all variables in the diagram (a variable can both affect and be affected by another variable) gives rise to discussions about issues that were first conceived of as unproblematic.

In this group there is first a quick consensus regarding one causal relation, stating that the amount of diseases affects the size of the population. They also state that the population size does not have any effect on how much disease there is, defining it as a one-way causal relation. However, in the next turn Stacy suggests the possibility of cases where diseases could increase based on the size of the population. An epidemic disease would have that effect. Anna wants to hold back on the complexity of the model and "keep it simple." Many arrows make the model hard to survey as it expands. Stacy insists on the fact that there are epidemic diseases and that this should be accounted for in the diagram.

Anna agrees after having reasoned about how disease can have a cutback effect on the population. She concludes by saying "the human population will decrease faster." Stacy draws an arrow from Human population to diseases (seen in Figure 15) and the question is settled. They move on to another topic.

Adding another variable

Stacy and Anna go on with the expansion of the model by introducing the other variable which has a decreasing effect on the population: Drought. This is, again, going back to step two in the working order.

```
*STACY:  okey so after diseases there's also drought
*ANNA:   drought yeah
*STACY:  mm (1) let me just (.) put it clearer [fills in the
         words with a black pen]
*ANNA:   drought is no water right ?
*STACY:  drought we have to connect with rainfall (.) less (.)
         less rainfall (.) the more drought and then you have to
         connect it to soil quality as well
*STACY:  yeah (1) but at isn't it drought (.) isn't it (1)
         between rainfall and vegetation
*ANNA:   cause if we have (1) less rainfall then have (1) more
         drought and then we have less vegetation (.) or the
         other way around
*STACY:  rainfall
*ANNA:   so I think it's here somewhere the drought [puts the tip
         of her pen on the arrow between rainfall and vegetation]
```

Figure 16: Anna points to Rainfall and then to Vegetation, following the arrow between the two words.

*STACY: rainfall (.) yeah it could

*ANNA: cause not (.) I mean it's not drought affecting the rainfall

*STACY: no no no

*ANNA: but it is (.) drought comes when we have

*STACY: yeah (.) yeah okey so [*scratches out the link between rainfall and vegetation*]

*ANNA: okey

*STACY: let's say (.) drought comes here

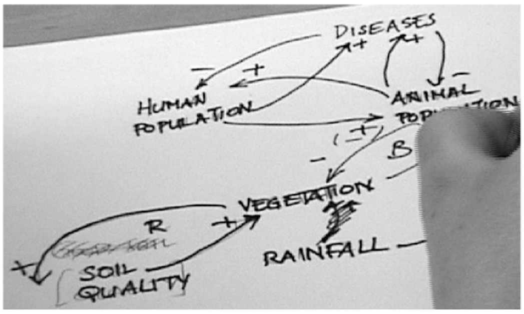

Figure 17: Stacy scratches out the link between rainfall and vegetation and draws an arrow from Rainfall to an empty space on the right. She then writes the word “Drought”.

*ANNA: yes

*STACY: and this comes here [*draws an arrow between drought and vegetation*]

*ANNA: okey

*STACY: because it (.) erase this here [*scratches out the link between rainfall and vegetation again*]

*STACY: so (.) more rainfall less drought [*writes a minus on the arrow going from rainfall to drought*]
*ANNA: mm
*STACY: eh less drought
*ANNA: less vegetation =
*STACY: = less vegetation
*ANNA: no
*STACY: no
*ANNA: more vegetation
*STACY: more vegetation (.) minus [*writes a minus on the arrow going from drought to vegetation*]
*STACY: mm (1) okey (1) more rainfall less rainfall more drought (.) more drought
*ANNA: more drought less vegetation

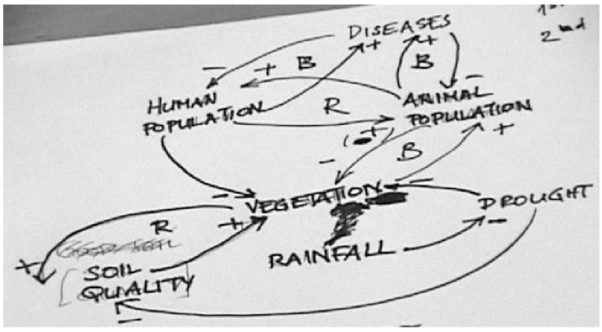

Figure 18: The result of the discussion of how Drought fits in the model.

The topic of this excerpt is how drought fits into the existing model. Anna first wants to explore the word ‘drought’. She says: “drought is no water right?”

To make the variables operational, as Anna is doing, clarifies what the drought does in the system and helps to see how it is connected to other variables. Stacy acknowledges a connection to the variable rainfall, which is one source of water.

Anna uses the spatial word “between” in order to argue for the place of drought in the ecosystem that they are modeling. There is a place for the new variable in the diagram, but one of the causal relations needs to be broken up. Later on she persists, pointing again to the arrow between rainfall and vegetation: “so I think it’s here somewhere the drought” (Figure 16). Stacy accepts the arguments. She draws an arrow from rainfall to an empty space in the diagram and writes the word “drought” saying ”let’s say (.) drought comes here” (Figure 17). She also draws an arrow to vegetation to keep the link between rainfall and vegetation, now indirectly instead of directly.

To test this new chain of causal relations, Stacy starts by saying "more rainfall less drought." Both the students continue the chain and state that less drought gives less vegetation, but note the error and quickly change to "less drought more vegetation." The students check whether the chain of causality seems reasonable by one of them pointing at a word on the paper and following the arrow to another word using "if-then" statements. In that way they relate their utterance to the graph to check whether the line of reasoning holds or not.

Summary and discussion

This case study shows a part of how the students' work process is carried out and what issues are dealt with, in relation to the normative working order introduced early in the course.

There are two major issues that the students address in this case study: 1) The situation of defining causal interrelations between variables, and 2) introducing a new variable in a diagram with already established causal relations. More specifically:

Issue 1: Is there a loop?
Is there a causal relation between Disease and Human population? And is there a feedback link from Human population and Disease, making it an interrelationship?

Issue 2: Expanding the model
How a new variable is introduced and how it gets incorporated into the existing model.

Anna and Stacy are constantly negotiating the Joint Problem Space (Roschelle & Teasley, 1995) by suggesting actions and confirming or rejecting the other's suggestions and actions, activities that aim at "integrating semantic interpretations of goals, features, operators and methods" (ibid., p. 229). They successfully engage in the language-game of System Dynamics by using the rules and conventions of the semiotic domain: by following the working order, using the terminology, and drawing in a certain way. They also show an understanding of the semiotic domain of CLDs, by taking into account the implicit conditions of the tool, that is, using neutral variables and variable names that are quantifiable.

The notion of causality is a fundament in the students' prior understanding. From early on in life, we learn to see things as causes and effects. The causal relations that the students are building their arguments on rest upon their individual prior knowledge and assumptions of what factors cause what in the situation presented.

There is no outspoken instruction from the tutors that the students should look for more information “outside” the story, that is, information not stated in the story, in order to be able to build a model. However, some students look for further information when starting to work with the computer model. That model needs quantitative data input, for example how much grass a cow eats per day, or how much milk a cow produces given that it eats a certain amount of grass, and students want to have adequate and reasonable numbers. In the qualitative modeling phase this is not necessary, however. No rain causes drought. Drought causes death of animals. These assumptions, based on prior knowledge and experience, are used when students build their qualitative models.

The causal loop diagram supports the students to think in terms of systems and exploring causal relations. The working order with clearly stated elements of activity may seem like a straightforward, mechanical process, both for the people working with it and for those people looking at the situation from the outside. However, looking more closely at interactional data of an actual problem-solving situation, it is clear that it is not a uniform process even though the major working steps are followed. Within each working step there are several issues to manage that are not so clearly defined as the major working steps. In an overall aspect, though, the tool generates structure and it has an important function in maintaining and sequencing conversations. It provides means to a kind of task regulation during the work process where the evolving graphical representation gives the students feedback on their ongoing work and discussion. The structured working order helps students decide on what to do next. Apart from the working order, the support for structure also includes a spatial aspect, noticeable for example by Stacy’s use of the word “between,” in order to argue for the place of a new variable in the evolving diagram. Moreover, by making a spatial distribution of words well separated when starting on the CLD, students create an action space to draw links or add more words to the model.

All of the students follow the normative working order that was identified in the task analysis to a very high extent (see “Data collection and data analysis” paragraph). All but one of the defined elements of activity suggested by the normative working order can be identified in the work of the groups taking part in the study. The activity that is excluded in the students’ work process is the one of setting up a list of variables, grouped as “actors”, “factors” and “conditions.” Some groups make other forms of lists, but not as a separate step that involves regrouping the variables once they are stated. Rather, they make one single list of things and people they find important in the story and use it as a memory support to check that all variables they want to use are included in the CLD. Others start with the diagram at once. Making a list could serve the function of creating a common ground before starting on the diagram. A first step for the students to conceptualize the problem is to talk about the story they have read. A list would be a second step to analyze the problem and agree on the key elements that need to go in the diagram and to plan ahead. Categorizing the variables in groups of "actors", "factors," and "conditions" would be a preparation step for the computer modeling phase. The reason for not using a list could be that the students feel that they have a good sense of what they want to put in the diagram after talking about it, and that they do not feel a need for a list. The reason for not categorizing the variables could be that they do not see the advantage of it at this early stage, thus postponing it until it is possibly called for.

The working order scaffolds the process, demanding that one step is taken before it is possible to proceed to the next. Other representational tools may not have this strict inherent sequentiality, thus the working order may not scaffold the process as strongly as in this case. A less inherently structured working order may require of the user that the steps must be memorized, and possibly also result in the working order becoming an issue that needs to be negotiated between peers. In the empirical data, there are hardly any remarks regarding the working order; the few observed occur in the very beginning of the collaborative work when students discuss whether they should start with a list or start on the CLD at once.

Having started on the diagram, a tendency that can be noted is that the students work with the structure early in the process. The normative working order is carried out in several iterative cycles: analysis, construction, and monitoring (reflecting on what they are currently involved in, summing up what they have done previously or planning what to do next). Or, to put in the context of the task analysis presented, an iterative process involving in particular steps 2, 4, and 5. The excerpts in the second half of this case study aim to show how new topics of discussion can be introduced because of the structured way that students are taught to work. For example, the introduction of a new variable shows the iterative nature of the work process when it opens up for a new discussion based on counterfactual conditional (if-then) statements, since the new variable needs to be fit into the structure. Which links are possible to draw, and is it possible to define any new loops? In order to make these decisions, they often use statements in the form of explicitly saying "if-then…," but it can also be implicitly stated in the form of "more of x, less of y," as in the presented excerpts.

It is unusual that students have defined all variables that are present in the final model before starting to sort or structure them. There are many examples in the full transcripts of students wanting to have causal relations defined between two variables at a time before proceeding to expand the model. Usually the variables are then added one by one (as in Anna and Stacy's case, by asking "what other things can affect…?") followed by the definition of the causal relations involving this new variable. In this way, the model is built in small iterating steps. The alternative would be to pick out and write down all variables first and then define the causal relations and feedback loops. The iterative behavior is consistent with Maani and Maharaj (2004), who in their study found that better performing individuals attempted to gain an understanding of the system structure before proceeding to construct models, and that the structure was built incrementally, accomplished through iterative steps. LUMES tutors stress this working order, that is, to start with a small system that captures the core of the system and seems feasible, and from there expand the model step by step. This can be noticed in the work of Anna and Stacy when they start with a small number of variables and a system in balance before proceeding to add variables that will disturb that balance.

The central problem that the students address when constructing a causal loop diagram, as implied by the name, is the issue of causality. First, however, the students must select relevant facts in the case and formulate them within a framework that is appropriate to use with the tool at hand (for similar discussions in Physics, see Chi, Feltovich, & Glaser, 1981; Devi, Tiberghien, Baker, & Brna, 1996; Greeno & Goldman, 1998). The reformulation step is important since students must take descriptions of the case and translate them into terms that are appropriate to use in this specific context. That is why nomads become human population, animals become animal population and grass is changed to vegetation.

Considerable work is done on defining and agreeing on relevant variables. The choice is based on information in the story as well as prior knowledge of causal relations in general. The students use terms that are recognized as standards in the modeling community, for example that nomads become human population. They use terms that can be quantified, presumably in order to be able to use them when constructing the computer model later on. Reformulation of terms in the story to terms to use in the CLD, or even more so in the computer modeling stage, happens quite effortlessly. Moreover, the use of value words like good, bad, more, less, high, low is avoided, well in line with general modeling guidelines suggested by Vennix (1996, p. 53). With regard to variables with negative or positive signification, Vennix also mentions that a variable with positive significance should be used, if possible. Students show awareness of these issues, indicating that they know the rationale of the tool. For example, a discussion in one group is about whether to use "disease" or "health" in their diagram. "Disease" would have a negative effect on the population, whereas "health" would have a positive effect. They finally chose to name the variable "health."

The graphical representation in front of the students plays a central role in the discourse. For every variable there are possibilities to draw an arrow between variables written down on paper and thereby defining the structure of the model. Drawing or not drawing these arrows requires a decision, which elicits different forms of discussion. This critical issue in the work process was discussed in the sections "Defining causal links and feedback loops." Having to put plus (+) or minus (–) signs on the arrows helps students in the process of telling the story when going through the model step-by-step, moving from one variable to the other. Typically, the students use conditional statements in the form of "if more of x, then more of y," to discuss hypothetical situations and their consequences and check the feasibility of their model. Some causal relations seem to be unproblematic (for example rain causes an increase of vegetation), but there are also quite a number of seemingly obvious causal relations that are problematic once the students need to draw a link and put a value sign at the head of the arrow. An example is Anna and Stacy's discussion about the relation between the population size and diseases spreading.

The working order supports the students through the work process. However, in order for it to be a help, students must be acquainted with it. This knowledge is realized on two planes: the individual plane as knowledge acquired (presumably) in the introductory lectures given by the tutors, but also on the social plane in negotiation with a peer about what to do (next). The formalism of the tool also has the qualities of scaffolding the process in that there are certain graphical objects that need to be put in the model to make it complete. If one or more of them are lacking, it reveals that a step in the work process has been overlooked.

6. Case study II – Applying prior knowledge in a new situation: Translating one representation into another

One aspect of learning systems thinking is learning to apply a specific way of thinking. This is exemplified by the following case study that focuses on the need for the students to convert, or translate, their prior understanding into a new way of thinking and expressing understanding. The case study is about the work students undertake when constructing a CLD for the case of Merchant Wang, a Chinese business man. It shows the work of Mark and Ellen (fictitious names) working on a CLD for the second project in the course.

The assignment: Merchant Wang

The case of Merchant Wang deals with how to manage food supply to avoid famine and starvation. It is described in an old Chinese story about a province experiencing food shortage. None of the farmers thought of taking care of the surplus of crops during years with good harvest, and considered leaving some of the fields unharvested. Merchant Wang asks them to harvest the fields and buys the crop at a low price. He stores it. As the people become more and more hungry during subsequent years with bad harvests, the merchant sells on three different occasions at rising prices, thereby making a very high profit. The people turn to the emperor and demand that Wang be decapitated, but arguments are raised that the situation would have been even worse if it wasn't for Wang and his granaries. The purpose of the modeling exercise is to analyze the situation and the dynamics of the system, and to draw a CLD for it.

Conceptualizing and reformulating the written story to fit into the representational format of a causal loop diagram

Choosing and defining variables

Ellen and Mark meet after reading the story of Merchant Wang on their own. They start by discussing the case in detail, going through the story together. As they speak, Ellen uses a blue marker to highlight key words or sentences in the text. They then proceed to make a list in the top left corner (Figure 19). Ellen suggests how they should manage the task to begin with:

```
*ELLEN:  I start a brainstorm thing here okey ?
         we just write down stuff that we have to come back later
         to (.) okey ?
```

She picks out four variables that she thinks are important to consider, based on the ongoing discussion:

```
*ELLEN:  so we have to distinguish between
         profits (.) prices (.) supply (.) demand
```

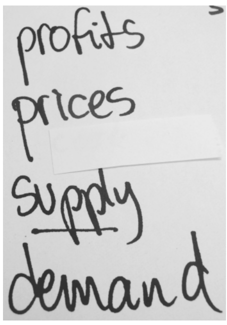

Figure 19. Making a list as the first working step.

The four words written down are variables that they keep throughout the CLD work that lasts for two hours. Two of them are picked out and used in the initial phase.

Mark begins on the CLD by writing the word "Supply" and then the word "Demand," two of the words on the list (Figure 20). "The first thing" seems to denote the central issue in the problem.

```
*MARK:   supply and demand
         this is the first thing
         that we connect together
```

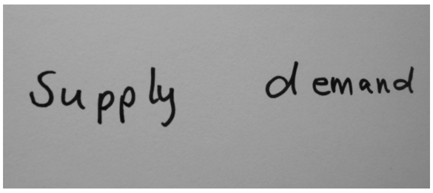

Figure 20: The first two variables in the CLD.

Defining links and loops, and determining a positive or a negative influence

With two words or more on the paper, the next step in the work process is to investigate the possibility to draw an arrow from one word to another in order to define a causal relation. This step elicits discussions about perceived causality, but also about which causalities do not exist. Thus, there are decisions to be made regarding which arrows to draw, but also which arrows not to draw. Issues that were first conceived of as unproblematic by the students can be objects of further discussion.

With just two words on the paper the assumption is that the words are selected with the notion that it is possible to draw an arrow from (at least) one of the words to the other. Mark draws an arrow from supply to demand and Ellen simultaneously says:

```
*ELLEN:  so (.) the higher the supply
```

Ellen indicates that she agrees that there is a causal relation between Supply and Demand. As Mark is drawing the arrow, she wants to define whether it is a positive or a negative influence. She signals this by using a counterfactual conditional mood in the opening of the sentence (typically the continuing part of the phrase above would be "… the lower/higher demand"). But then she stops without ending the sentence:

*ELLEN: but (.) can we connect those logically
aren't they both (.) independent of each other ?

The words dependent and independent are used to talk about causality. Saying "independent of each other," suggests that Ellen thinks that there should not be a link between Supply and Demand. But Mark argues for a link:

*MARK: supply (.) in the end (.) more supply means less demand

Mark puts his pen on the head of the arrow but does not write anything. He hesitates and signals uncertainty.

Neither agreeing nor refuting, but trying to find a resolution to this uncertainty, Ellen takes the focus off the two words on the paper and introduces another form of representation. She draws an xy-graph at the top corner of the sheet (Figure 21).

*ELLEN: the typical economic (.) thing is this one right
this is the (.) supply [*writes an s*]
this is demand [*writes a d*] and here we have the price
[*writes a p*]

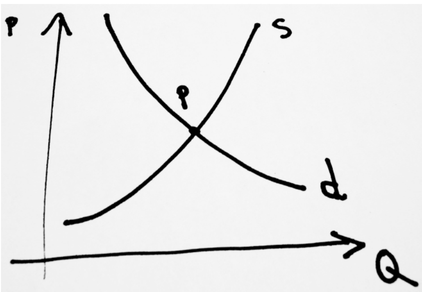

Figure 21: xy-graph of how supply and demand affect price. The graph shows that price is inversely proportional to quantity, but does not actually show a causal relation between supply and demand.

When Ellen draws the xy-graph, the word Price is introduced. Mark quickly picks this up and tries to find a place for it in their CLD. This indicates that he thinks that the two representational formats (the CLD and the xy-graph) are compatible in some sense.

```
*MARK:   okey
         we should put price here
         [points to an empty space to the left of demand]
```

Ellen ignores Mark's suggestion and Price does not go into the CLD at this point. Instead she tries to reason about causal relations on basis of the xy-graph, even though she is in doubt.

```
*ELLEN:  so the higher the supply (.) but how can we do that ?
         complicated
```

It seems that Ellen and Mark use the xy-graph for different purposes at this time. Mark is focused on identifying a new variable to put in the CLD, whereas Ellen is concerned with finding the causal relation between the two present variables: Supply and Demand.

The preconceived model of the market mechanism that Mark and Ellen quickly draw on when deciding what variables to use, works through the interaction between supply and demand. In economics, this interaction is commonly taught through comparative static analysis which does not really capture the dynamics involved in the market. Thus, the two representational formats (the CLD and the xy-graph) are not compatible. Models that represent the dynamics of market interactions are known to be hard for students to create (Wheat, 2007). The comparative static analysis represented in the xy-graph shows some correlation, not to be confused with a causal relation. A causal relation is where something (x, the independent variable) causes something else to change (y, the dependent variable).

The preconceived model of Supply and Demand gets in the way of thinking of the case as a dynamic situation based on causal relations. Two major problems surface. One problem is that the xy-graph may give the impression that there is a given corresponding value for Supply for a given Demand, thereby implying a (false) causality between these two entities. It is always possible to mechanically plot an xy-graph of two entities, even though there is no causality involved between the two. The other problem that the students face is the concept of Demand *per se*. When using Demand as a variable, the students find it difficult to define what effect it has on the Supply. Is demand the same as need or does it mean consumption? Or is it more like a wish and, in that case, how can a wish be operational?

Mark tries to convince Ellen that there should be a causal link from Demand to Supply and argues by using an example. Ellen agrees and tries to reason again, but her uncertainty remains:

```
*MARK:   well we could say demand
         when you
         if something you need
         if the supply
         is one (.) grain
         demand is very high
         everybody wants it
*ELLEN:  that's true
         [long pause]
         so the smaller the supply
         basically
         the [writes a plus, erases the plus and writes a minus]
         bigger the demand
*MARK:   yeah
*ELLEN:  and the bigger the demand [draws an arrow from demand to
         supply]
         the bigger the supply has to be [keeps the tip of the
         pen close to the arrow head]
         that's strange
```

Ellen agrees on the link from Supply to Demand and shows this by adding a value sign at the arrow head. She then draws a link from Demand to Supply. Trying to justify this action and in order to be able to put a value sign at the arrow head she says, "The bigger the supply has to be" (my italics), which is not a causal relation. Ellen talks of Supply as a kind of prerequisite for the Demand to rise, which is an issue that cannot be taken into consideration when defining causal relations. Rather, the causality should define what effect one variable has on the other. After drawing the arrow from Demand to Supply, Ellen keeps the tip of the pen at the arrow head as preparing to draw a + or – sign, but she does not write anything. Instead she says "that's strange," signaling that she is not sure of this line of reasoning.

Mark changes the focus somewhat and looks for something that could affect (increase or decrease) Supply if they choose not to keep the arrow from Supply to Demand. He suggests adding a new variable, Harvest, but takes it back:

```
*MARK:   supply is what [points to Supply]
         because then we have
         could have
         you know the harvest coming in here [points to Supply]
         or have it all in the same thing
         cause if we do it like this [makes a circle in the air
```

around Supply and Demand]
then it works
I mean
demand [*points to Demand*]
finish the supply [*points to Supply*]
*ELLEN: mhm

Ellen signals that she is listening by saying "mhm," but is not really engaged in Mark's argumentation. It seems as if she is already on to a new topic. To resolve the situation and to avoid the perceived problematic situation, Ellen suggests adding a variable to put "in between" Supply and Demand (Figure 22).

*ELLEN: mhm
or maybe if we put the price somewhere in between
[*writes Price*]
and say
the higher the supply [*draws an arrow from Supply to Price and writes a minus (–) at the head*]
but if we have
if we have a high demand [*draws an arrow from Demand to Price and writes a plus (+) at the head*]
then the price goes up

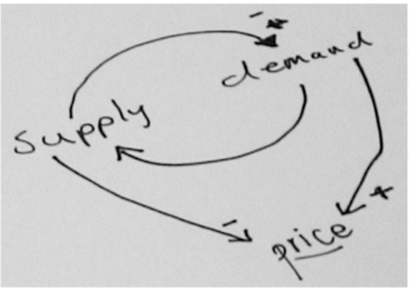

Figure 22: Variables with both indirect and direct links.

The spatial word "in between" is used in order to argue for the place of the new variable in the system. She writes Price below the words Supply and Demand. By putting something "in between" she can break the direct relation between two variables. In that way, she creates an indirect relation between Supply and Demand. (However, they keep the direct link previously drawn, but do not make any notice of it, see Figure 22.) Again, when talking about making or not making causal links she uses the word "connect" (Figure 23). But she is not confident of the causal relations between Supply and Demand.

*ELLEN: maybe we connect it like this
because I'm not sure how to connect those two directly
[*draws a circle in the air around supply and demand*]

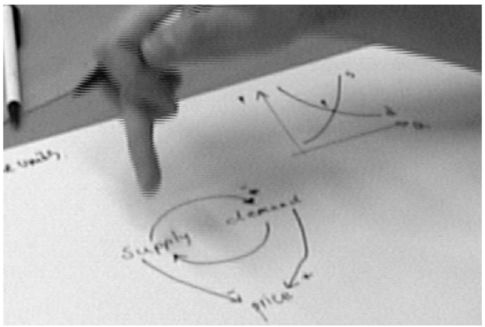

Figure 23: "I'm not sure how to connect those two directly." Ellen draws a circle in the air around Supply and Demand.

She then justifies the addition of the new variable and continues her reasoning using a counterfactual conditional mood. In a way this could be seen as running a simulation of the system verbally in order to share her understanding with Mark, or as letting the reading aloud from the model create a kind of feedback for them to relate to:

*ELLEN: because this is definitely the case
if we have a lot a lot a lot
the price is low [*points to the arrow between supply and price*]
if we have lots of grain
then
as
as we have in the first year
this case
lots of supply
very small price [*underlines Price*]
second time
lots of demand [*draws a circle in the air around Demand*]
very high price [*fills in the plus sign besides Price*]
*MARK: yeah
that's right
*ELLEN: so maybe we connect the two like this
even though it's not a loop then
but

```
          because those two [supply and demand] I don't know
          if we can connect them so directly
```

Saying "even though it's not a loop then," Ellen evaluates her suggestion and signals uncertainty: there are supposed to be loops in a causal loop diagram, and her addition to the diagram does not result in a loop. This is the first time that the concept of "loop" is used when referring to their own work.

Mark agrees to Ellen's suggestion of adding the variable Price, but they also keep the previous links. They end up with two kinds of relations: one direct and one indirect (see Figure 22). Not having a loop with the new variable included does not seem to be a big issue for them at this moment.

Ellen is still not satisfied with the direct link between Supply and Demand and adheres to the problem with the first loop they made. She suggests adding a new variable that influences the Supply, coming back to the issue raised before by Mark:

```
*ELLEN:   because basically the supply
          is also
          influenced by
          natural [draws an arrow to supply from outside the
          diagram]
          ahm
*MARK     productivity
          or
*ELLEN:   yeah
          by the environment
          by the weather and however the harvest is you know
```

Mark agrees and adds the variable Harvest (Figure 24):

```
*MARK:    yeah yeah
          but then we can have
          just harvest here
          it's easy [writes Harvest by the arrow going to supply]
```

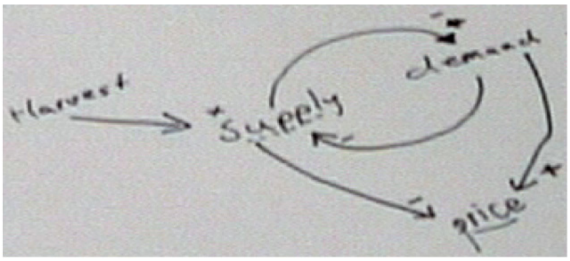

Figure 24. Mark adds the variable Harvest.

The reference to the xy-graph is no longer explicit. Ellen suggests finding a new variable that affects Demand and draws an arrow from an empty space on the paper to the word Demand.

*ELLEN: mhm
okey
and then we can
the demand is influenced by
[*draws an arrow from outside the diagram to demand*]
the hunger of the people
basically

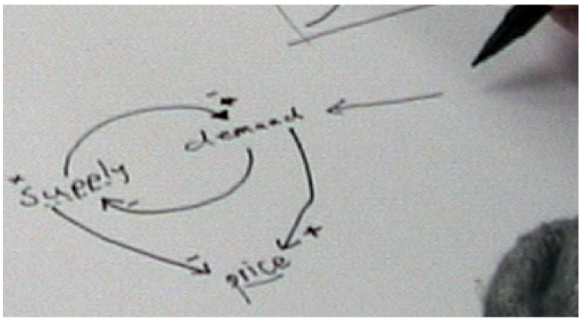

Figure 25: Ellen draws an arrow from outside the diagram to Demand.

*MARK: yeah
that's the supply

Mark sees the Hunger of the people as influencing Supply in the same way as Demand does, thereby making the Hunger of the people redundant in their model. Ellen does not accept this and looks for a definition and distinction between the variables, but Mark persists:

*ELLEN: the hungrier they are

```
*MARK:   but that's the supply
*ELLEN:  the supply is the grain that ahm
         is thrown on the market
         right ?
*MARK:   yeah
*ELLEN:  and the demand is what people really want
         to take from the market
*MARK:   yeah
         and that's I mean
         it's the same
         effect
         the hunger and supply
         I mean
         very little supply means hunger
*ELLEN:  that's true
         also
*MARK:   I think it's all right
         it just
         have it like this
```

Mark says "it's the same effect, the hunger and supply," referring to the effect that Supply and Hunger have on Demand in the model in front of them. A smaller supply of grain makes the demand go up, he states, and hunger also makes the demand go up. Mark signals that he thinks that it is no use adding the variable Hunger since they already have Supply that affects Demand. Ellen agrees with this line of reasoning and they keep the model as it is.

However, at the end of the first hour of work, Ellen is still not satisfied with the causal link between Supply and Demand.

```
*ELLEN:  more harvest
         more supply
         yep
         more supply
         less demand
         but ah
         I'm still not completely happy about this
         because it's not necessarily
         if you have more supply
         you don't
         it's not a necessary consequence to have
         less demand is it
```

Ellen and Mark spend two hours in total constructing their CLD. They do not resolve this problem, but keep the link between Supply and Demand in their CLD that they prepare to show to the other groups working with the same problem.

The following day during the meeting of all groups working on the Wang case, it turns out that all of the groups have included Supply and Demand and that they have similar problems. The tutors moderate the discussion and ask questions during this session, which leads all of the groups to eventually take Demand out of their models. The following day Mark and Ellen revise their CLD before starting to work on the computer model.

Summary and discussion

There are two major issues that the students address in this case study:

Issue 1: Is there a loop? Discussing an interrelationship between two variables
Is there a causal relation between Supply and Demand? And is there a feedback link from Demand to Supply?

Issue 2: Expanding the model: Introducing a third variable
How a new variable (Price) fits into the existing model and how it can resolve a perceived problematic causal relation between Supply and Demand.

Preconceptions are influential in the meaning making process. In a constructivist perspective, it is important to acknowledge that we always make new meaning based on prior knowledge and prior assumptions. In this case the assignment is about modeling a market economy situation. Although neither Mark nor Ellen has a background in economics, they immediately pick up the word-pair Supply and Demand as their first variables. They support their choice by drawing an xy-graph with two lines crossing, a commonly used model in economics and a representation that is demonstrably known to Mark and Ellen, see figure 26.

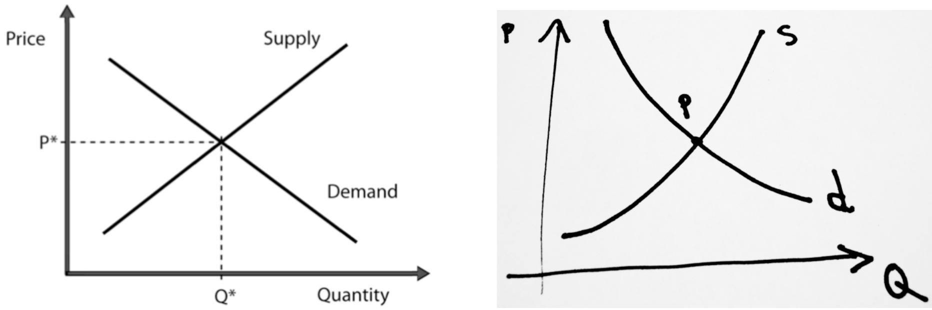

Figure 26: Supply and Demand curves, as shown in the graph to the left, play a fundamental role in economics. The price of a product is determined by a balance between supply and demand. The supply curve indicates how many producers will supply the product at a particular price. Similarly, the demand curve indicates how many consumers will buy the product at a given price. In the graph, the equilibrium price and quantity are indicated by the intersection of the supply and demand curves. On the right, Mark and Ellen's graph.

Earlier experiences of successfully constructing or using models in other representational formats tend to influence the structure of later constructions (Mats Svensson, personal communication). Part of the students' prior knowledge is the xy-graph that they seem acquainted with. In the process of creating a Joint Problem Space (Roschelle & Teasley, 1995), it is used as one of the main resources. However, the xy-graph clashes with the representational format of the CLD, and the perceived causal interrelation of the variables Supply and Demand gets in the way of constructing a CLD. Thus, students face a conceptual challenge when trying to translate the xy-graph based on a correlation, into a CLD based on dependent/independent variables. The semiotic domains do not match.

It is worth noting that the use of variables Supply and Demand hinders the work for quite a long time for three of the four groups in the study. The choice of variables was never questioned once they were written down, rather they were almost treated as given. It seems as if they felt confident in their choice, quickly moving on to the next working step of defining links and loops. One reason could be that the two words Supply and Demand were mentioned in the story that was handed out, which could have affected the choice of variables. Another reason could be that Supply and Demand are a word-pair that seems to be well known to the students. The xy-graph of Supply and Demand is such a pervasive model that the variable names are taken for granted to be included in a model. In other cases that the students work with, there are no pairs of words that are so strongly connected as in this economics case. Relying strongly on the preconceived xy-graph could also be the reason why there seems to be an implicit assumption of a causal relation between Supply and Demand.

The later CLD session, where student groups working with the same problem share and discuss their first models with each other, leads to a major revision of Mark and Ellen's model. The joint discussion together with tutor's comments and questions make them and all the other groups converge towards quite similar models where the original Supply and Demand structure is dismissed. Prior to the discussion in the CLD session, the Supply and Demand variables were used in more or less the same way by all four dyads that were videotaped. The original structure emerges from interactions within the dyad groups, but meeting other groups leads to a new negotiated common set of variables and suggestions of a structure. Consequently, this development of shared ways of talking emanated from distributed rather than individual achievements. This means that the unfolding activity allowed the development of a shared view and a common structure despite the fact that none of the groups originally held this. At the session where many groups met, a new structure emerged and Demand was taken out of the model.

If we were to use the concept of mental models to refer to a person's existing knowledge, what would we say about Mark and Ellen's mental model(s)? From the perspective that knowledge is mediated by and manifested in an external representation, it is not an appropriate question. Instead of making inquiries into their mental models, we have to acknowledge that Mark and Ellen use what resources they have in order to make sense of the story presented to them. Right or wrong, however organized, what the mental model looks like is irrelevant. What is relevant is what resources they draw upon in the situation and how they contribute (or not) to their meaning making. It is also worth noting that they were able to change their CLD into a feasible model after discussing it in a larger group, although no one in the group came to the meeting with a model that worked with respect to Supply and Demand. The discussion with a larger group of peers resulted in a new type of representation where the word-pair Supply and Demand was not used. Is this a result of a change in Mark and Ellen's mental models, or did they come to learn how to represent their understanding in a new representational form based on the same mental model?

According to cognitive theories about thinking and talking as based on mental models, the students' understanding of the expression 'supply-and-demand' could be a mental model. It would function as an instance of a standard concept to describe a market situation, represented by the specific terms of the case at hand, that is, supply of grain and demand for food. The idea of a mental model implies that these models have a certain stability and generality, and that they are used in the same way in different instances. Even though the students have trouble creating a model of the Merchant Wang case, we can not conclude that they lack an understanding of the economic situation with regard to Supply and Demand.

What we can say though, is that they have trouble with representing their understanding using the CLD formalism. If instead Mark and Ellen were assigned to draw an xy-graph that involved an interrelationship between the variables Supply and Demand, they would have succeeded and we would most probably conclude that they had an understanding of the mechanisms of Supply and Demand. The argument here is in line with Wenger: "Words like 'understanding' require some caution because they can easily reflect an implicit assumption that there is some universal standard of the knowable. In the abstract, anything can be known, and the rest is ignorance. But in a complex world in which we must find a livable identity, ignorance is never simply ignorance, and knowing is not just a matter of information. In practice, understanding is always straddling the known and the unknown in a subtle dance of the self. It is a delicate balance" (Wenger, 1998, p. 41)

The assignment to construct a CLD based on a subject matter not well known to the students highlights a possible problem of learning to model *per se*. The idea underlying systems thinking and the CLD is that students should be able to see general structures underlying the behavior of a system, and generic structures that could be used in many different settings (so-called archetypes). A modeling course focuses on the practice of modeling and being able to identify archetypes, whereas in a modeling task in the corporate or institutional context presupposes that the people involved have certain special subject knowledge to contribute. In this learning-to-model situation, students rely on the story handed out, together with their intuitive understanding of a market situation, and use terms that they have come across in the general economics discourse. It is a dilemma worth considering when the main goal is to learn how to model and the subject area is of less importance.

7. Case study III – The use of terminology and other semiotic resources

Systems thinking can refer to a special vocabulary with which we express our understanding of phenomena, one of the three aspects of systems thinking also suggested by Richmond (2000). The third case study has this specific aspect in focus. It is an investigation and analysis of how students express their understanding of a problem they are assigned to work with, but takes a broader approach than that of language alone. An extension of this aspect will be made, as several other semiotic resources are included.

The case study will illustrate the students' use of language and other semiotic resources in the process of constructing a Causal Loop Diagram (CLD). It will show how language, gesture and the visual representations are used as integrated resources to express understanding of a problem and its solution. It will also show how the tool supports them in structuring their knowledge and directs their communication and actions in order to create a Joint Problem Space (Roschelle & Teasley, 1995). The study investigates the work students undertake when constructing a CLD for the problem of desertification in the Sahel region in Africa (as in case study I). It is based on the work of students Nathan and Ellen (fictitious names), starting to work on a CLD for the third assignment in the course. Additional examples to further illustrate or supplement excerpts from Nathan and Ellen's work process are taken from the complete transcribed material of eight groups working during two hours each.

The assignment: Sahel and the threat of desertification

The case of Sahel has been described previously in case study I, chapter 5. It is the story of an area of land south of the Sahara desert where the UN introduced modern medicine and made more water available to make life better for the nomads in the area. These interventions increased the lifespan of both nomads and their livestock, and the water availability made it possible to sustain more animals. However, the larger number of animals ate or trampled the grass, and a drought further decimated the vegetation. Many animals died of starvation. Because of the drought and the loss of animals, many nomads starved. The area was faced with a more severe problem than the one before the intervention. The assignment is to explore the long-term dynamic forces that control and influence the Sahel region.

The story is an example of a phenomenon called The Tragedy of the Commons, first published in an article by Hardin (1968). The article describes a dilemma in which multiple individuals acting independently in their own self-interest can eventually destroy a shared limited resource, even though it is not in anyone's long term interest.

Conceptualizing the problem

Nathan and Ellen have a map of Africa in front of them as they start their work recorded on video. The map is brought in spontaneously, and is not part of the project assignment. Nathan and Ellen show right at the start that they are aware that they are being filmed. However, apart from a single reference to the camera, they do not take any further notice of it during the two-hour session that they are filmed. On that single occasion, it seems as if Nathan and Ellen not only turn to the camera to show awareness of it being there, but use it for a short while as a third party in the group. Part of the initial work that needs to be done in the negotiation of a joint problem space is to put the problem at hand into context. In doing this, Ellen and Nathan bring in the camera as a member of the group to show and explain things to, at the same time as they show and explain to each other.

*NATHAN: we have a map [*lifts the map from the table and shows it to the camera*]
*ELLEN: yes (.) africa is on tape (.) alright (.) there we are (.) this is our home [*takes the map from the hands of Nathan and pulls it closer to the camera, at the same time leaning into the camera eye herself so that her face and the map are visible to the camera*]
*NATHAN: ((nomads)) yes

```
*ELLEN:  hehehe
*NATHAN: ((especially here)) [points to the Sahel region on the
         map and makes a circle movement with index finger]
*ELLEN:  mhm (.) ok (.) so we both read the text now finally
         [puts the map aside so that an empty sheet of paper is
         visible to the camera]
*NATHAN: yes
*ELLEN:  and now we can start to (.) look for some important (.)
         factors in here [takes the project assignment and starts
         to turn the pages]
```

Ellen has made notes and has also used a blue marker pen to highlight parts of the text in her project assignment, but no direct reference is made to it. Instead she turns to a section in the text with instructions, and she reads them aloud. Ellen then suggests that they start by defining "some important factors," and they agree to make a list.

```
*ELLEN:  it says (.) in the questions first of all [reads from
         the text] keep it simple of course that's what we have
         to know (.) and identify the major parameters (.) we
         will start with that ok
*NATHAN: yea
*ELLEN:  maybe we just write down some (.) some major parameters
         and then later we put them in causal loop or
*NATHAN: some major (.) I think there are only two major
*ELLEN:  two ! (.) you think ?
*NATHAN: major (.) major what I mean is major
*ELLEN:  really (.) go ahead which ones
*NATHAN: nomad eh human population and eh herd
*ELLEN:  the cattle population
*NATHAN: yes
*ELLEN:  let's start with that
```

As suggested by Nathan, the two variables put down in the list are Nomad population and Cattle population. Nathan checks whether Ellen agrees and backs his suggestion up with an argument for the choice they have made, together with an iconic gesture to refer to the entire model they are about to construct. Ellen suggests how the two variables could fit into the structure. They both refer to the variables by pointing at the words in their list and use the term "connect" when talking about causal relations.

*NATHAN: do you (.) do you think so (.) you agree is there another and (ahm) and I don't
*ELLEN: I think these are important ones but yea (.) maybe the other ones we have they are only **reducing** or **increasing** these populations [*points to the words Nomad population and Cattle population*] yes
*NATHAN: it it **connect** I think it **connect** to every variable (.) a I think [*makes an iconic gesture on the empty paper in the form of a circle*]
it's **connect** to ev every other variable in this (.) in our boundary
*ELLEN: aha
*NATHAN: so yea this have to **connect** to these two [*points with his pen to the words Nomad population and Cattle population*]
*ELLEN: mhm
*NATHAN: so this is the main (.) the factors [*points to Nomad population and Cattle population*]

After some discussion, Nathan and Ellen agree on a third variable: Desertification (Figure 27). When Ellen wants to define what desertification means, she turns to the map and makes gestures in relation to it (Figures 28 and 29). She uses the project assignment to support her suggestion.

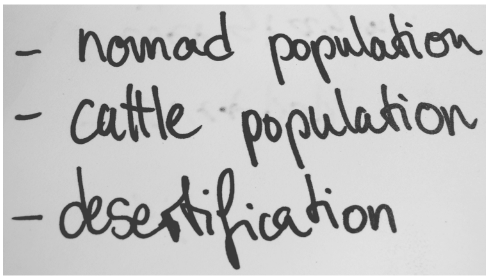

Figure 27: Ellen adds a third variable to the list: desertification.

*ELLEN: let's let's define it //
*NATHAN: // yea
*ELLEN: a little bit because what (.) what is it (.) because I think (.) it means (.) that the (.) ok [*brings up the map in front of them*]
we have the (.) sahara here which is a real desert [*writes with the pen in the air on top of the map*]

```
*ELLEN:  and we have the sahel here which is not a real desert
         but kind of desert right [points with her whole hand on
         the Sahara region on the map]
```

Figure 28: "we have the sahara here which is a real desert (.) and we have the sahel here which is not a real desert but kind of desert right."

```
*ELLEN:  and desertification means that (.) the desert is
         expanding [makes a gesture starting with hands together
         and then pulling them apart, showing spatial aspects of
         something small becoming bigger]
```

Figure 29: Ellen makes an iconic gesture: "desertification means that the desert is expanding."

```
*NATHAN: a: you mean that
*ELLEN:  that (.) yea I think that's it's like the spreading of
         sand dunes it said somewhere in here (.) m: hmhm
         [looks in the text]
```

They agree on the definition of desertification without any difficulties. Later, in the sixth minute, Ellen starts writing a new list in order to conceptualize the problem from another point of view. She divides the problem into two categories: before and after the intervention, a similar approach to that of Anna and Stacy (see case study I). The concept of “natural system” denotes the situation before the intervention.

*ELLEN: I just I just think ok what we have is in the beginning
we have a (.) we have a **natural** (.) **system** [*writes Natural system*]
right (.) that's what we start off with (.) basically
(.) and the problems (.) only start when human help
comes in (.) foreign aid [*writes Foreign aid below Natural system*]
and foreign aid brings [*makes two branches from Foreign aid and writes Well technology in the top branch, followed by the word Water in parentheses and an up-arrow*]
well technology

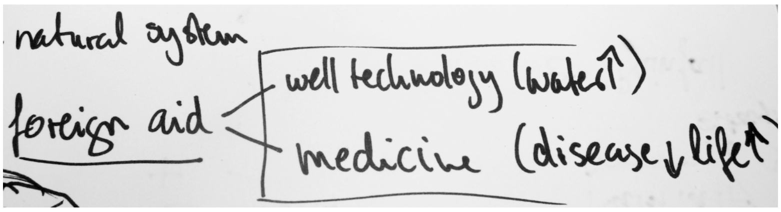

Figure 30: The second list with added notations.

[…]
*ELLEN: and ehm what do they also bring [*writes medicine in the lower branch*] modern medicine **which leads to** =
*NATHAN: = long lifespan
*ELLEN: = less disease exactly [*writes diseases in parentheses, and a down-arrow*]
and therefore (.) longer life [*writes life in the same parentheses, and an up-arrow*]

Ellen clarifies the effects that the variables have by writing them in parentheses, as seen in Figure 30. Arrows pointing up or down denote an increase or a decrease of the variable, a notation that is sometimes used in a CLD. Thus, she combines a traditional list with notations belonging to the CLD, thereby including an aspect of the problem that is not easily expressed in writing.

Managing the task

In the eleventh minute, Ellen comes back to the conceptualization of the problem and uses the list they created earlier. She also formulates the goal of the assignment. When suggesting how to manage the task, she uses the systems thinking term "balance."

```
*ELLEN:  ok but I think our question still is (.) what our main
         goal is (.) do we want (.) to because what I was
         thinking of first is (.) first of all we establish the
         natural balance situation (.) then we introduce the
         factors (.) that come from foreign =
*NATHAN: = effects
*ELLEN:  countries (.) and suddenly nothing works anymore (.) the
         natural balance is destroyed
*NATHAN: that's right yea
*ELLEN:  and then our question is what can we do to reestablish
         this balance (.) even though foreign aid has messed up
         the system
```

She later concludes, supporting her argument by an iconic gesture and underlining one of the words in the list:

```
*ELLEN:  I think it's quite important that we (.) show somehow
         that in the beginning (.) we have an easy balanced
         system [makes a circle with her hands in the empty space
         on the paper]
         and only when (.) this comes in [underlines Foreign aid
         in the list] …
         (a change of topic follows)
```

Eller suggests some steps to develop the model in an iterative manner. She implicitly refers to what the tutors have encouraged them to do: start with a small, balanced system before adding variables that affect the system in such a way that the balance is disturbed.

Laying out the model

Nathan and Ellen start on the CLD after thirteen minutes. When Ellen starts to write their variables down, she keeps the term Cattle population that they used in the list, but changes the term Nomad population in the list to Human population.

This was already suggested by Nathan when they defined variables in the initial list (see figure 27).

*NATHAN: nomad eh human population and eh herd
*ELLEN: the cattle population

The adjustment to the more general term Human population is not explicitly noted by either Nathan, nor Ellen. Ellen puts down Human population although Nomad population is written in the list, and Nathan does not object.

The spatial layout of the model is taken into consideration when they are to add a second and a third variable in the model. Nathan shows how he would like the model to be laid out. He suggests that the second variable should be written beside h. pop, but with some empty space in between (Figure 31).

*ELLEN: let's call it human population [*writes h. pop*] and cattle population
*NATHAN: [*points to an empty space on the paper, to the right of h. pop*]
*ELLEN: here ?
*NATHAN: yes we (can then have) then you can uh [*points to the right of h.pop to show that he would like some space in between*]

Figure 31: Nathan shows where he want the second variable to be written down, to the right of the first variable, but with a space in between.

*ELLEN: cattle population [*writes c. pop to the right of h.pop*] ok (2,5) then (.) which factors do we have that **influence** these populations (.) we have water availability (.) I just put it somewhere ok

```
*NATHAN: yea maybe you can (put inside) because it affects the
         cattle population [makes a sweeping gesture to the right
         of where Ellen started to write]
```

In the preceding excerpt, Ellen takes the next step in the work process: to find more variables in order to expand the model. She suggests water availability, and starts writing below H. pop (Human population), but Nathan stops her. She erases what she has started by drawing a line over the text. Nathan signals that he wants her to write it below the other two words, but in the middle of them, so that they form a right-angle triangle. This is suggested presumably because it is more convenient to spatially have factors affecting one another close together. Nathan proposes that water availability affects both human and cattle population, and having the words laid out in this manner make it easy to draw links from both H. pop and C. pop (Cattle population) to Water availability. Ellen complies with this suggestion. The terms "influence," "rely," and "affect" are used to talk about causal relations.

Planning the next step

Looking for loops

Twenty-one minutes into their work, Nathan and Ellen have constructed a CLD with several variables, and they have made a structure by drawing links, see Figure 32. The next step in the working order is to define interrelations between the variables. At this point, Nathan discovers that their structure does not show any loops, and he shows concern for this fact. Ellen agrees and suggests that "it would be nice to have a balancing loop in the beginning," referring to the normative working order that suggests to start with a small model "in balance" before adding variables that disturb this balance.

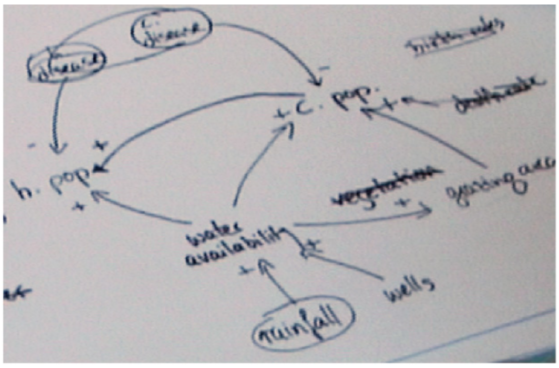

Figure 32: Nathan and Ellen's model: Many links, but no loops.

*NATHAN: we have to (.) I want to define a **loop** (.) there is no **loop**
*ELLEN: no **loop** at all
*NATHAN: yes why
*ELLEN: m:
*NATHAN: we have to
*ELLEN: it would be nice to have a **balancing** one in the beginning
*NATHAN: ah yea
*ELLEN: would be nice to have a **balancing loop** in the beginning
*NATHAN: right right true
*ELLEN: let's try to create a **balancing loop** [*takes a new sheet of paper*]
*NATHAN: ye:s about here
*ELLEN: yes (.) mhm
*NATHAN: ((there is)) no balance (.) there is no **loop** at all no **loop** no **loop** no **loop** no **loop** (.) no **loop** no **loop** no **loop** [*points to the different variables in the model one by one*]

Ellen finds a reason why there are no loops, and uses their model as the accounting device.

*ELLEN: but the thing is of course there is no loop (.) because this comes **from outside** [*circles with the pen on top of the word rainfall on the previous sheet of paper*]
and this comes **from outside** [*points with the pen to the word disease on the previous sheet of paper*]
and we cannot **link** (.) the rainfall eh something **back** to

```
         the rainfall [makes a gesture as to draw a link to
         rainfall] you know what I mean
*NATHAN: maybe we can create a little loop here [draws a link
         from h.pop to c.pop]
         more cattle
*ELLEN:  yes
*NATHAN: more population [follows the link with the tip of the
         pen]
         more population more cattle
*ELLEN:  m: this is nice
*NATHAN: [writes a B in the loop]
```

The expression “link back” refers to the possibility to draw a link in the opposite direction from the previous one, in order to define an interrelation between two variables, that is, a loop. This is one example of how to identify possible loops in the evolving diagram. Other expressions to denote an interrelation are “go back” and “the other way around.” A variable that “comes from the outside” denotes an exogenous variable that only has an affecting role, and not something that can be affected by variables in the defined system. Rainfall in Nathan and Ellen’s model is one such variable. The amount of rainfall is considered to be given, that is, impossible to control by the modelers, in the system that they are modeling. With this definition, it is not possible to include Rainfall in a feedback loop.

Summing up and evaluating the work

Thirty-five minutes into their work, Nathan and Ellen take a new sheet of paper to make another, tidier, CLD. This can be perceived of as summing up and evaluating the work so far, with the additional aim of correcting possible mistakes made in the prior model(s). Since they are using a black permanent pen, the need to start over from scratch is possibly called for because the model becomes messy after a number of changes.

When deciding which links to draw, reasoning based on counterfactual conditional statements is often observed. This type of reasoning is widely used to check and validate the CLD, for example when students review what they have done so far and look at their model in a global manner. It can be in the form of explicitly saying “if-then …,” but it can also be implicitly stated in the form of “more of x, less of y.” They check if the chain of causality seems reasonable, often by pointing at a word on the paper and following the arrow to another word using counterfactual conditional statements simultaneously. Or, as in the following case, they draw as they talk. In this manner they can actually hear whether the line of reasoning holds or not, an action that could be perceived as producing a kind of verbal feedback for themselves on the model they have constructed.

A strategy to detect flaws in the model is, in the same manner, to look at the external representation at the same time as verbalizing the effects of each variable. Nathan and Ellen have talked about the central phenomenon that their assignment is an example of, that is, the tragedy of the commons. They want to make sure that the mechanisms that result in the tragedy are represented in their model. Ellen starts drawing the new CLD by writing down the same two variables that they started the previous model with: Human population and Cattle/herd. She proceeds by defining the causal link between the two by drawing an arrow from Human pop. to Cattle/herd (Figure 33) at the same time as she reasons using counterfactual conditional statements. The interplay between the dialogue and the external representation is strong. They also use their previous CLD to refer to when one of the links in the new diagram causes confusion.

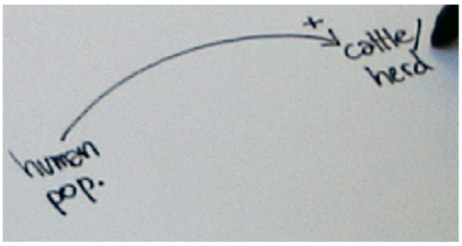

Figure 33: A causal link between human population and cattle/herd, reading: The bigger human population, the more cattle.

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*ELLEN:   […] so the more human population [writes a plus at the
          arrowhead pointing to cattle/herd] the more cattle this
          is the first
*NATHAN: nomad (.) the first (loop) for that one
*ELLEN:   yea the first step of the tragedy of the commons already
          [follows the line with the back of the pen]
*NATHAN: uhu uhu uhu yes
*ELLEN:   these [circles human pop. with back of the pen] want to
          maximize their benefits [makes swooshing sound and
          follows the arrow to cattle herd] they put their cattle
          in into the grazing area right
*NATHAN: mhm
*ELLEN:   shall we maybe put the grazing area here [puts tip of
          the pen to an empty area to the right of cattle/herd]
```

*NATHAN: mmm grazing area connected to water (.) and
connect(unintelligible) [*points to the previus CLD*]
*ELLEN: let's try this (.) here we put the grazing area [*writes grazing area*]
this is basically the commons [*draws a square around grazing area*] here right (.) the commons the I mean the the the open access area we have (.) so **the more** cattle [*draws an arrow from cattle/herd to grazing area*] **the more** they eat [*writes a plus* at the arrow head]
right
*NATHAN: mmm
*ELLEN: and **the more cattle** [*draws an arrow from cattle/herd to human pop.*] **the more population** (.) or not yea
*NATHAN: yes yes I can (unintelligible)
*ELLEN: think so ? [*writes a plus at the arrow head*]
*NATHAN: yes (.) more food more people
*ELLEN: ya ya more people ah ok (.) so here we already have a dangerous situation going on [*wites an R in the loop human pop. and cattle/herd*]
right
*NATHAN: yes
*ELLEN: the more grazing area (2) the more cattle
*NATHAN: mmm yes
*ELLEN: heh why did we have this step (.) differently here [*points to previous CLD*] **more grazing area more cattle** [*erases the plus at the arrow head and writes a minus*] **more cattle less grazing** aha:: little mistake here [*draws an arrow form grazing area to cattle/herd*]
more grazing more cattle [*writes a plus at the arrow head*]
so here we have a balancing loop right [*writes a B in the loop grazing area and cattle/herd*]

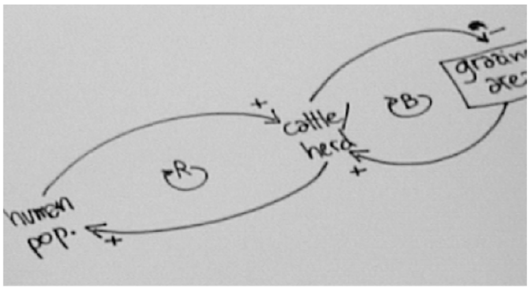

Figure 34: New diagram with two loops. The plus sign at the arrowhead pointing to grazing area was changed to a minus after consulting their previous CLD.

*NATHAN: m:
*ELLEN: so we already have two loops
*NATHAN: so this I think that's what I think this is the eh limit of growth [*points to the balancing loop*]
*ELLEN: mhm (.) it's right here [*taps pen on grazing area*]
*NATHAN: because this is the (.) bala eh reinforcing
*ELLEN: uhu
*NATHAN: it do if don't have this loop [*covers the balancing loop with his hand*] the population will go up
*ELLEN: yes (.) yes like no limit (.) endless

Ellen interprets their model and concludes that they have succeeded in expressing their idea in the diagram by saying: "so here we already have a dangerous situation going on." Nathan does the same when confirming that the model captures the idea of the "limit of growth." The model shows what they want it to show.

Ellen makes an evaluating remark when saying: "so we already have two loops," pointing out the positive feature that their diagram shows loops (Figure 34). Both Nathan and Ellen also interpret their reinforcing loop and connect it to the real-world phenomenon: the loop shows that the population increases indefinitely if there is not something in the system (death) acting as a limiting force.

Another example of using counterfactual statements is when Ellen, working with Mark (case study II), takes out an empty sheet of paper and starts to draw a new CLD, based on the former one that she and Mark have developed. She argues while drawing and concludes by positively ascertaining that there is a feedback loop.

*ELLEN: […] I'm just trying to make it a little bit more
more (.) more more (.) clear
buy

```
        the more he buys (.) the more he stores
        [draws an arrow from Buy to an empty place in the model
        and writes the word Stores]
        the more he stores (.) the more
        the less he sells
        oh the less he sells (.) the more he stores
        [draws an arrow from Sell to Stores]
        so then (.) then we have this loop here
```

Not necessarily taking a new sheet of paper, students recurrently sum up their ongoing work, typically in conjunction with closing a sub-topic of the assignment. This step often includes a kind of evaluation of their the model, resulting in either confirming it or becoming aware of flaws. Nathan and Ellen sum up their work on several occasions by checking the feasibility of their model.

The concepts of balancing and reinforcing loops define whether the feedback mechanism has a stabilizing effect (B) or an effect that will just make the variable increase indefinitely or decrease until there is nothing left (R). Ellen uses these terms when summing up the work and validating her and Nathan's model. She also makes a connection between the abstract model and the actual problem: "what causing the problem is this reinforcing loop…," thereby using the representation as an accounting device. She points to the variable names when referring to them.

```
*ELLEN: so here we have a balancing loop (.) which is fine (.)
        here we have our good old reinforcing loop (2) the more
        humans the more cattle the more cattle the more humans
        (1) reinforcing loop (.) basically the problem is (.)
        what is causing the problem is this reinforcing loop
        right (.) so (.) what I I separated into rainfall (4)
        because rainfall is influencing all three (.) this
        [points to the word vegetation]
        this [points to the word cattle]
        and this [points to the word humans]
```

At a later point in time, Ellen reads off their diagram to check whether it says what it should say according to the story, thereby evaluating their work. The term "reinforcing" is used to back up the reasoning and to make an evaluation, and she concludes that the model depicts "a reasonable problem."

```
*ELLEN: according to this our problem would be that the
        vegetation area is getting smaller and smaller and the
```

desert area bigger and bigger (.) because this is **a reinforcing loop** here (3,5) that w (.) would be I think a reasonable problem

This use of subject-specific terms can be noted in other student groups as well. Anna and Stacy (case study I), also use the words "balance" and "loop" when evaluating and checking the feasibility of their model. Here, the result of Stacy's reasoning is that there is a need to define another loop in order to better fit the diagram to the story, and she uses an iconic gesture in relation to the model on paper to clarify her argument. For reference to their graph, see Figure 18.

*STACY: okey [*reads in the project text*]
nature kept humanity's actions in check through a variety of harsh yet effective mechanisms (.) every twenty or thirty years the drought would cut back the human and animal population giving trees and grass a chance to recover (.) so (.) **we need to establish a balancing loop** [*makes a circle on top of their model*]
including drought [*points to the word Drought*]
and the same of course happens with diseases but the diseases we have already [*makes a circle with her index finger on top of the loop that includes the variable Epidemics strike, former disease*]
it's a, it's the drought that we're missing (3) **we need to have a loop down here** [*makes a circle in the lower left corner of the model where the word Drought is written*]

Later, Anna uses domain-specific terminology when summarizing her and Stacy's work, and to signal that she thinks they have a problem. The concept "balancing loops" is used to explain her concern, and Stacy agrees. By the agreement she signals that not having a balancing loop is a valid argument when wanting to indicate that something is wrong with their model.

*ANNA: but we don't have any **balancing loops**
*STACY: I know

They recognize that their model is not finished unless they have a balancing loop that involves the water and food availability. This leads them to go through the model and discuss the links that they have defined. It also leads to a discovery of a flaw, and by finding a missing link the problem is resolved and the model shows a balancing loop.

Summary and discussion

Learning the formalism and the concepts tied to the System Dynamics semiotic domain constitutes a major learning task for the students, within the task of constructing a model for a particular problem.

When directed to work with a new tool, students draw on a varied range of cognitive and semiotic resources in order to make sense of the problem at hand and how it should be resolved. In this case study, the students' exploration of the System Dynamics domain is exemplified by the close interplay between verbal and nonverbal activities, and external representations. The study also pinpoints phases in the work process where the domain-specific terminology is predominantly used.

Using various forms of representations when exploring a semiotic domain

Students use a multitude of external representations to create a joint problem space and to complete the assignment. The written story is one such resource. They depend upon it and return to it throughout the work, as it gives them instructions and information about the case to be modeled. Some students make notes in the margin, and some use a pen to highlight parts of the text. Lists are used, predominantly in a brain-storming phase where the variables for the diagram are picked out. The list itself is mainly used as an external memory to make sure that none of the important variables are forgotten. Other external representations are brought in spontaneously. In the case of Sahel, Nathan and Ellen use a map of Africa in the initial work of putting the case into a context.

The CLD serves as an offload for the individuals' memory, as it can capture more parameters and greater complexity than what the human mind can hold in one specific moment in time. The evolving model also serves as an external memory of the collaborative process, and makes the discussion easier to refer to when looking back at the process, and when planning ahead.

The visual representation also seems to support the students when they want to clarify or emphasize what is said, that is, as an accounting device. The iconic gestures and acts of pointing seem to play a similar role in the dialogues. They too are used to clarify and emphasize, but they also play a role in the planning of the layout of the model. This is in line with Crowder (1996) and Roth (2001), who note that gestures are particularly frequent when students construct an explanation in the moment, and that they also appear to help students to predict, revise, and coordinate elements in a model. Students draw in the air, just above the paper, to explain how they think the model should be laid out spatially, and they also verbally state "this variable should go here," pointing to a specific place on the paper. This indicates that they have a vision of a larger part of the model than the one worked on for the moment, and that the formalism of the CLD makes this planning possible since the students share the common ground of how a CLD should be laid out. The extensive use of iconic gestures shows that the spatial aspects are important and considered throughout the model building process.

The analysis of the verbal discourse reveals that the terminology relating to the CLD is used to express features of dynamic systems, but in addition there are also many instances of the use of informal everyday concepts to denote CLD concepts. Similar observations are noted in the research on learning to program, in that beginner programmers show a rich variety of common-language associations to programming concepts (McKeithen & Reitman, 1981). Learning with the programming language Logo shows that learners use a hybrid of Logo and natural language when talking through problem-solving strategies (Noss & Hoyles, 1996). The language of the medium (in this case the computational system) "affords a half-world in which effective communication and precision can be approached, where articulation and rigor can be made to converge" (ibid., 1996). For the LUMES students, expressions like "connect," "go back," and "independent" are used when talking about causal relations. By noting which expressions are used it is possible to gain insight into the issues they are currently addressing.

For example, when students talk about loops (interrelations), a number of different expressions are used:

`*EVE:` oh yea sure (.) pretty good link eh:e (.) yea and **the other way around**

and

`*JOHN:` I don't know if we should **go back and forth** cause it's (.) I am not sure

and

`*STACY:` this does not **go back**

and

`*ANNA:` is this (.) **does this go back** ?

The introduction of new variables opens up for a new discussion on how they fit the current model. Every new variable introduced in the model needs to be incorporated in the structure. This in done by drawing arrows between it and the existing variables. Drawing or not drawing these arrows calls for a decision, often made by using counterfactual conditional statements. The suggestion to link two variables is an articulation of prior knowledge and assumptions regarding causal relations. So are statements regarding effects on the variables (more of this, less of this). The effects are indicated by plus signs (+) or minus signs (–) at the arrow heads of the links. These signs seem to help students in the process of telling the story as they go through the model step-by-step, moving from one variable to the other. The CLD on paper does not produce any interactive feedback, as in the computer model, and using counterfactual conditional statements could be perceived as their own production of feedback from the model they are constructing.

```
*STACY:  animal population they eat vegetation
         [draws an arrow from vegetation to animal population and
         writes a plus]
         more vegetation more animal population (.) and then more
         animal population less vegetation (.) right ? [draws an
         arrow from animal population to vegetation and writes a
         minus]
*ANNA:   mm (.) balancing
```

Quite often it is observed that students take turns, building on each other's contributions in this kind of reasoning, collaboratively constructing one complete utterance, what in conversation analysis terms Lerner (1991) calls a collaborative completion. This is what Anna and Stacy do when deciding how the new variable Rainfall will fit with the existing model, and Stacy draws as they talk.

```
*STACY:  the more rainfall [draws an arrow from rainfall to
         drought and writes a minus]
*ANNA:   the less drought
*STACY:  the //less drought
*ANNA:           //less drought more more vegetation
*STACY:  more vegetation [draws an arrow from drought to
         vegetation and writes a minus]
*ANNA:   yes
```

Spoken language is often used in conjunction with nonverbal actions like making gestures, drawing and writing in relation to the evolving graph. Many gestures are of the iconic type, that is, gestures that refer to a physical aspect of its referent. Iconic gestures are often used to illustrate what is being said, for example drawing with the hands in the air to illustrate the form of a physical item that is talked about. In the case studies reported here, iconic gestures are made primarily when students formulate suggestions, discuss and plan the layout of part of the model or the entire model, as a precursive step to using the pen to draw. Drawing and other nonverbal actions related to the model on paper are also used to support and strengthen an argument. In these cases gestures can be perceived as the link between spoken language and the visual representation, or, as differently stated by Vygotsky (1978): gestures can be regarded as mediating devices that link the social and the psychological.

Using domain-specific terminology to plan, summarize, and evaluate work

The students use the System Dynamics terminology as a resource, especially when accounting for and evaluating their own work and making plans for how to go on, that is, "do we agree on what have been done so far?" and "do we agree on what to do next?" This is an important part in negotiating a joint problem space. Thus, the complete transcribed data reveals two types of situations where the specific CLD terminology is predominantly used: One type of situation occurs when students plan how to go on, that is, the next step in the work process. This could be labeled as opening up a new topic in the conversation. The second type of situation where the terminology is used occurs when students are approaching a closure to a part of the model, just before starting a new one. In this case they use the subject-specific terms to summarize and evaluate what they have done so far. In discourse analysis terms, CLD terminology is mostly used in conjunction with a topic opening and a topic closure. In both situations the language is a means for the collaborators to check whether the common ground needed to proceed is there.

Both of the types of situations described (evaluating/summarizing and planning) are examples of stages in the work process when students have a meta-approach to their model and the assignment, that is, they "zoom out" from individual issues, in order to look at the model in a holistic manner. It is on these occasions that the domain-specific terminology is predominantly used. It is also used in situations when students plan the management of the task, yet another meta-level of their work. This may possibly be because it is on these occations where students (implicitly) match their model against the goals of the course and envision a judgement from a tutor, which are situations when the subject-specific terms are typically used.

It can sometimes be difficult to distinguish between parts of the dialogue that are about closing a topic and those that are about opening up a new topic, especially when showing just a short excerpt of the complete dialogue. However, the full transcriptions, where it is possible to have access to the preceding and following dialogue, help in determining what is what. For example, utterances of the form “we-ell,” “O.K.,” etc., operate as a possible precursive action to end a topic and can help to distinguish an upcoming closure (Schegloff & Sacks, 1973). After such a possible preclosing there is a place for initializing a new topic. For example, Anna closes her and Tom’s current topic by saying “well…” followed by a suggestion how they should proceed, and Tom agrees:

```
*ANNA:   well as and I was thinking (.) how to close this loop to
         make a simple thing and //
*TOM:          // mm
```

In addition, when summarizing or coming to a conclusion, the discourse marker “so” is often used (Blakemore, 1992).

`so we have our balancing loop start here`
and

`so it’s another negative loop`
and

`so that’s balancing as well`

The way language is used to develop knowledge is very much taken for granted in research on learning, and the relation between use of language and understanding of subject matter is not very much investigated. At the same time, it is a rather common observation that students may have learned to use terms and expressions within a knowledge domain, without having developed a corresponding understanding of the subject matter (Svensson et al., 2009). Although an evaluation of students’ understanding with regard to the subject matter is not taken into consideration in the case studies presented here, the shallow or deep use of systems thinking terminology can be seen in the light of this discussion. In situations when students interact with existing models, Ogborn (1999) shows that many novices have problems going beyond employing the model as an artifact instead of using it to understand a complex phenomenon, an approach that makes the model become an artifact that “just has to work” (Bliss, 1994; Hogan & Thomas, 2001) or look good. There is a possibility that a strict working order might encourage a procedural effect, with students focusing on the sequence of construction rather than on analyzing the systemic structure of the problem.

The CLD terminology is easily adapted and used in the discussion with peers, but it takes considerable time for the subject-specific terms to be used as structural elements that give behavior in the system. For example, students focus on making loops and deciding whether these are reinforcing or balancing, but often there is no explicit notion of the importance of having a reinforcing loop as a driver of the system. Thus, the notions of link, loop and the other domain-specific terms can remain abstract and a vague ideal (surface), or can be terms that actually mean something on a deeper, conceptual level (understanding why a loop is needed). For example, the utterance "we don't have any loops" could be signaling that the person knows that CLDs should have loops in a visual, layout manner, or on a deeper level signaling that there need to be loops in order for the system to show dynamic behavior. A proper understanding of feedback loops requires a dynamic perspective in order to see how things evolve over time.

An analysis of the dialogue may reveal on what level the terms are used. However, an utterance can give the observer the impression that the term is used in a superficial way, which is not necessarily the case since it can imply a deeper understanding without an overt expression. Thus, caution should be taken before assigning superficiality to the use of a term. To distinguish uses of the terms on a deeper level, when students explicitly show an awareness of the functions the various terms have in the model, is more conceivable in the dialogue. For example, there are situations where students express an understanding of what roles balancing and reinforcing loops have in the system that they are modeling by supporting their argument with additional explanation of the consequences of defining a loop in a certain way, or what it does to the system as a whole.

A related issue is the student's use of the rule to assign an "R" or a "B" to a loop. This rule requires counting the number of pluses in a loop; odd numbers denotes a balancing loop, whereas even numbers notes a reinforcing loop. There are two general strategies that students use to apply this rule: prior or subsequent to reflection. Some students reflect on what kind of loop it is and use the rule to confirm their idea. Others expect the rule to make a decision for them. In the latter case, students reflect on the result that the application of the rule came up with. It is noted that it is easier to adjust the story to a mistaken loop in the second case, and generally, that this way of working results in a comparatively longer time for the students to detect a mistake.

8. Switching tools: the quantitative modeling phase

The second phase in the students' assignment concerns the construction of a quantitative computer model. The case studies reported in Chapters 5 through 7 deal with the construction of a CLD, which forms the first phase of the students' assignment. It is intended to work as a blueprint and to be a stepping stone in the process of constructing a quantitative computer model using STELLA software (isee systems, 2008). Students thus have to switch tools half-way into the assignment, although continuing to work on the same problem.

Supported by observations and a qualitative analysis of the empirical data, the aim of this chapter is to highlight some characteristics of working with the two tools. The first part of the chapter will report on how the tools differ with respect to their inherent qualities, and point to issues that students perceive as harder or easier to deal with. It will also illustrate how students handle the transition of their model from one tool to the other. In the second part of the chapter, the characteristics of the tools will be illustrated based on five recognized criteria that constitute a good learning environment (Larsson, 2002), together with examples from the empirical data.

Learning a new tool and a new terminology

The tutors' experience is that the computer model turns out to be of better quality when students construct a CLD using pen and paper as a preparation step before turning to the computer (Mats Svensson & Harald Svendrup, tutors at LUMES, personal communication). This is why the assignment is divided into two separate parts: making a CLD and, after that has been completed, constructing a computer model. The purpose of the CLD is to help students focus on the choice of variables and their respective causal relations. The second step involves translating the CLD into the new representational format that STELLA postulates.

The computer software tool

A dynamic system is a system that evolves over time and is mathematically represented by differential equations. However, the user interface in the computer software makes it possible to construct models without having to solve or even write the underlying differential equations, let alone master a programming language. Instead, there are standardized symbols for constructing dynamic models; the symbols can be chosen from a toolbar at the top of the screen and then placed in the model with a mouse click. By double clicking on an object, it is possible to assign a value or a formula to it. The computer carries out the calculations.

The software uses a somewhat different terminology from the CLD. *Stocks* illustrate causal agents in the simulation. Savings in a bank account are such an agent (Figure 35). *Flows* convey the effects of these agents on the others. Deposits to and withdrawal from the bank account are flows. The distinction between stocks and flows is not made in a CLD, but has to be defined in the computer model. *Converters* can hold values for constants or be coefficients or ratios, for example interest rate, that influence flows. They generally do not need to be included in a CLD. *Connectors* are the lines that show the directional effect of factors on each other by the use of arrows, equivalent to the links in a CLD.

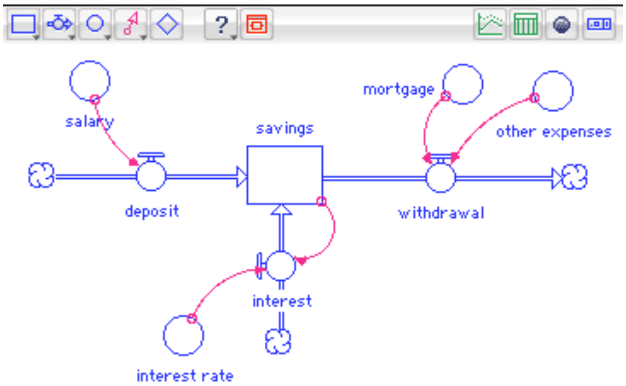

Figure 35: Bank account model made in STELLA, showing relations between savings and variables that affect it. Note the reinforcing loop involving savings and interest, which is the part of the model that makes it non-linear. The various objects that could be used to construct a model are visible in the toolbar at the top of the screen. The four most frequently used objects from the top left to right: Stock, flow, converter, and connector.

Differences in the tools

The CLD and the quantitative model in STELLA differ with respect to how information can be expressed, but the quantitative model also needs information additional to what is represented in the CLD. For example, users have to distinguish between stocks and flows, assign quantities to each variable, and convert entities so that they become mutually coherent and computable (that is, using the same time scales and the same entities for weight, currency, etc.).

Analyses of the empirical data show that there are issues that students perceive as harder or easier to deal with in the different tools, partly depending on the differences in the representational format. Converters are such an example. They can sometimes be hard for the students to represent in the computer model, since they can have a well constructed CLD without taking into account how entities will have to be converted. How the interest rate affects the savings (as shown in Figure 35) may not be hard for students to represent, but there are other, more difficult problems. In the following example, Ben reasons about how Rainfall becomes Vegetation:

```
*BEN:    well how about this (.) surface water we want to say
         that a certain (.) percent of the rainfall is going to
         vegetation
*SARAH:  yeah
*BEN:    so we'll do water in and water out
         […]
*BEN:    the thing is how does water become vegetation
         how do you associate that (.) I mean how does it
         magically become vegetation
```

In a CLD, this issue does not ask for resolution. The relation can be represented by an arrow from the word Water to the word Vegetation, with a plus at the arrow head, stating that the more it rains, the more vegetation there will be. In the computer model, however, students need to convert, or translate, the amount of rain into area of vegetation, or kilograms of vegetation, depending on how the model is constructed. Thus, having a feasible CLD of the system does not give all parameters for constructing a complete quantitative model. The students must be aware that a converter that takes care of the transformation from one entity to another is needed in addition to the variables in the CLD.

Two different aspects of perceiving conversions can be discerned in the empirical data: first of all, the bare notion of the need for a conversion between two variables with different entities, which is problematic for some groups. Secondly, how the nature of the conversion is perceived; as a linear transformation, that is, an increase of variable x affects variable y linearly, or if a nonlinear function is assumed. Examples of groups of students using both linear and nonlinear functions can be found in the empirical material.

Another issue is the use of “soft” variables such as anger or happiness. They are quite easy to incorporate in a CLD, but become problematic when quantities have to be assigned to them in the computer model. For example, it is quite straightforward to draw a causal link between a good harvest and the farmer being happy, but how much more does he need to harvest to be one unit happier? Students are aware of this difficulty and try to avoid variables that are hard to quantify. This can be exemplified by Ellen’s argument for staying with the variable Demand (Merchant Wang, case study II), but not expanding their model with “soft” variables, even though she and Mark have discussed factors such as hunger and happiness.

```
*ELLEN:  we don't put any feelings and stuff like that inside
         I mean it's (.) we just look at the market
         in the demand of course implicitly there's some kind of
         (.) happiness and hunger and all that
```

Presumably, Ellen knows that variables like happiness and hunger will be hard to quantify when they later construct a computer model, and she makes her suggestion based on this awareness.

The translation between the CLD and STELLA raises problems since the computer model requires a somewhat different structure than the CLD, and requires that all the variables be quantified. However, some aspects of the problem seem easier for the students to work with in the computer model than in the CLD. An issue that the students need to address in their models is how to represent a so-called “trigger” for a certain variable to start having an effect on another. For example, Merchant Wang (case study II) does not start selling off the grain in his store until the market triggers his action by signaling that it is prepared to pay a certain amount per kilo. Before that, he holds his store and is not an actor on the market. This kind of decision model involves the concepts of necessary and/or sufficient conditions.

In STELLA, a trigger may be conveyed by writing a formula based on an if-then statement, or, as an alternative, by pointing and clicking in an interactive xy-graph to define specific values for certain points in time, as shown in Figure 36.

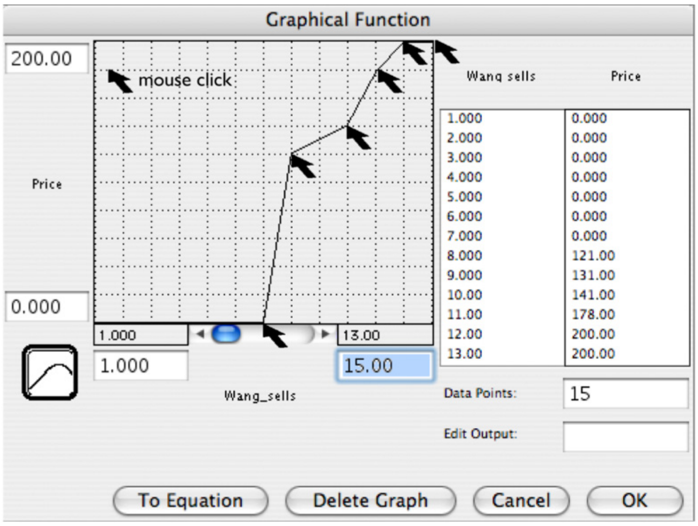

Figure 36: An input graph in Stella allows the user to define the relationship between variables by pointing and clicking in a graph instead of writing mathematical formulas. This is a big advantage because it does not require extensive knowledge in algebraic calculus.

Students have learned how to represent this kind of conditional action in the computer model, and they seem to handle it well. However, in the earlier phase when they are drawing a CLD, conditional actions raise problems for some of the groups since there is no way of representing a trigger. Either you define a causal relation by drawing a link, or you do not. Some students address this problem by making several diagrams: one for each scenario. The result may be one CLD without a causal relation between two variables, and another with the causal relation where the effect has been triggered by the sufficient conditions. The reason why the students choose this strategy could be that they have overlooked a fundamental feature of systems thinking, the fact that there are general structures underlying the behavior of a system. Two groups working with the Wang assignment (case study II) fail to recognize this until quite late in the work process. They make a deconstruction of the Wang situation in different years with one CLD per year, thus overlooking a general structure that could hold for all years. When it comes to using the CLD as a blueprint for the computer model, it is problematic to have several diagrams with different structures.

Thinking ahead – using the terminology of an absent tool

The shifting of representations from CLD on paper to a quantitative computer model is characterized by a transition of one representational form to another. This kind of transition happen twice for each case: first when constructing a CLD, and then again when making a computer model.

The initial task is to take descriptions in the case text and translate them into terms that are appropriate to use in the specific context of a CLD, as shown in the case studies. The formalism of a computer model is different from the CLD, which forces the students to adapt once more: this time from the CLD to fit the new form of a computer model. However, the interaction analysis shows that the adaptation starts even before it is demanded, seen in the light of the normative working order. When students construct the CLD, they already use terms of the computer modeling tool. This can be yet another aspect of planning, or thinking ahead, previously discussed in case study III, a phase in the work process that notably involves the use of System Dynamic domain-specific terms more than other situations in the work process. Thus, subject-specific terms for the tool at hand are not the only ones used; students even use the terms of a tool that they will work with at a later stage.

One observation made in the constructive interaction analysis concerns the way that students express notions of the future computer model already when working on the CLD. Besides working on a CLD and trying to make the best of it, they are aware of where they are going next and take certain actions to be prepared for the computer modeling work. That is apparent by their use of specific terms that belong to the computer model, even though they are not needed in the first working phase. Thereby the two representational formats are sometimes intertwined. There are many examples in the empirical data of students using terms that belong to another tool than the one used at the moment. When students make a list, they talk about links and loops (CLD terms); when they work on a CLD they use the STELLA terms stock, flow, and converter, even though these kinds of concepts cannot be represented in a CLD. Sometimes they also express a reaction, even frustration, over the fact that some information that they want to include in a CLD cannot be represented in the same way as in a computer model. For example, Anna (in case study I, working with Stacy) has the computer model in mind when suggesting variables for the CLD. She is frustrated about how the two representational formats do not match (STELLA terms in bold).

```
*ANNA:   I think we have three major (.) things (.) human
         population animal population and vegetation
*STACY:  and then we have exogenous exogenous factors
*ANNA:   and this is are like (.) stocks I think
*STACY:  okey yeah
*ANNA:   and then the other variables influencing this
*STACY:  yeah (unintelligible) no I do not
*ANNA:   well I cannot (.) no (.) I can't do this anymore (.)
         yeah I'm thinking this is stock inflow outflow and then
         I have a converter coming in
```

Anna and Stacy address the incongruence between the two tools on a number of occasions. Another example is when they discuss whether there is a need to have a specific disease variable for humans and another one for animals. They acknowledge the difference between the two representational formats and conclude that the division is not necessary for the CLD, but it is necessary for the computer model that they are going to construct at a later time. They end up having only one variable for disease in their CLD.

```
*STACY:  […] you can separate human diseases and animal diseases
         but it's not gonna make so much difference
*STACY:  you're just gonna have one disease here and
*STACY:  I'm always thinking in terms (.) in stella terms cause
         when we put in stella then we can not have the same
         disease for both
*ANNA:   no no you're right
```

Tom, working with Anna in the second assignment, is also more comfortable thinking in terms of the computer model. He and Anna are not satisfied with their feedback loop in their CLD (Figure 37, left), and he is frustrated. Tom suggests that a linear layout of building blocks in STELLA is easier to use in order to represent the problem (Figure 37, right). He also suggests variable names that are different from the ones they have in the CLD.

```
*TOM:    I find it easier to think in stella for this
         because you've got a stock of grain and you've got
         things coming in (.) and things going out
*ANNA:   mhm
*TOM:    thinking of a CLD is actually harder
```

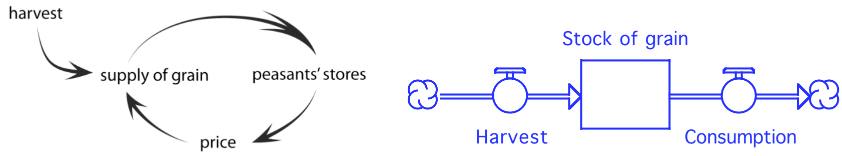

Figure 37: The CLD that Tom and Anna are working on (left), and a fabricated STELLA model showing what Tom is referring to when "finding it easier to think in stella" (right). The variable names are not the same, and "thinking in stella" does not involve a feedback loop. The two models are not compatible, but "thinking in stella" seems to help Tom and Anna to conceptualize the problem.

Tom and Anna find it easier to reason in mathematical terms rather than to make a qualitative model based on causal relations:

*ANNA:	I'm thinking that (.) what Wang buys is **supply minus stores** //
*TOM:	// **minus stores** I'm thinking in stella as well!
[…]	
*TOM:	It's terrible (.) some things are easier to think in stella than CLD (.) **supply minus peasant's store times price** equals Wang's reserves
*ANNA:	yepp! [laughter]
[…]	
*ANNA:	doesn't help us with this (.) no this is only Tom this is CLD (.) no stella!

Later, Tom comes back to using STELLA terminology when suggesting a new variable that can have a negative effect on the supply (that is, the stock of grain). Anna is going along with the line of reasoning and they are both very aware that they are thinking in terms of the computer model. They are also aware that it is not something that they immediately can apply in their CLD, and Anna giggles when noting that they are using STELLA terminology again.

*TOM:	I think we do need something there (.) cause supply is more like (.) like a **stock**
*ANNA:	and harvest is what (.) what comes into like
*TOM:	the **stock**
*ANNA:	a **flow** into the **stock**
*TOM:	stella stella stella
*ANNA:	yeah yeah [giggles]

Using STELLA terms seems to help the groups to conceptualize the problem, even though the specific terms are not applicable in the CLD phase that they currently work in. It also indicates that they make early adjustment in order to be sure that what they put down in their CLD is useful for the computer modeling phase.

Narration, simulation, interactive feedback, and collaboration

Tools that are used in problem-solving activities have different qualities in that they support various actions and interactions. In a study of computer-based tools developed for the K-12 curriculum, Larsson (2002) suggested five factors that, in order to provide a good learning environment, could be considered when inspecting and evaluating educational software available on the market. It was suggested that the tool should address different learning styles, be situated in a narrative framework, offer interactivity, involve feedback to the user, and support collaboration between learners. These factors could be used not only to evaluate digital material, but also when comparing and contrasting other kind of tools that support learning and problem solving. The CLD and STELLA used by the LUMES students do not address different learning styles. The ways of having feedback presented as a graph or a table in STELLA could apply to some extent since it is likely that this form of symbolic format is preferred by some individuals, while others prefer alternative forms. The remaining aspects, however, could be useful to distinguish qualities of these two tools. The purpose is not to evaluate them to determine whether they have the features and whether one tool is better than the other, but only to note differences between them.

Narration

Narratives are used to put information into a context, a feature that, compared to trying to memorize isolated facts, is perceived to motivate us and enhance our capacity to remember (Gärdenfors, 2006). The spatial structure of a CLD seems to support the creation of a narrative, often applied by the students when conceptualizing the problem. Narrations are also observed as students assess their model-in-construction, for example when they validate a match between the story in the assignment and the diagram. To have a shared understanding of the story is an important part in the construction of their Joint Problem Space. In one situation, Brian is confused about the model that he and Lynn have constructed for the Merchant Wang assignment. They decide to start on a new CLD from scratch and think the problem through again. Brian holds the pen and Lynn encourages him to tell the story.

```
*LYNN:   just do it one more time
         and then (.) like (.) just tell the whole story because
         (.) it's so important that we get this (.) that we
         really really really understand this problem
```

Narratives are important resources in our meaning making process and when we communicate, noted for example by our extensive use of metaphors and associations when we want to understand something unknown to us (Norman, 1993). Lakoff and Johnson (1980) suggest that metaphors not only make our thoughts more vivid and interesting, but that they actually structure our perceptions and understanding. An example of metaphor use in the empirical material is when Mark explains to Ellen (Merchant Wang assignment, reported on in case study II) what function the variable Harvest has on the market and why it is needed. By referring to systems in general, he suggests that they put Harvest in their CLD as an exogenous factor. Such a factor, he argues, will act as the "driving force" in their system, "feeding," and being the "core" or the "nuclear" of it.

*MARK: the harvest is (.) it's like a fuel (.) nothing happens
if that
if eh I mean the system will
to change the system (.) you have something change in
the system
you have to have (.) that's the **driving force** here
going up down going up down
that **feeds the system** (.) that's the main problem
it's at the **core** of the system (.) the **nuclear** of the
system
that makes it (.) turn differently
but it is going because of the harvest

The act of creating narratives is more frequently observed in the CLD phase than in the computer modeling phase. It is used when the model is constructed, but also when it is evaluated. The use of narratives appears to some extent again in the computer modeling phase when students, after running their model, are presented with interactive feedback in the form of a graph. Referring to the graph as they speak, the narrative is used to check the feasibility of the computer model, that is, to check whether it tells the story they want to tell. This form of discourse is less observed during the actual construction of the computer model.

Simulation

The construction of an interactive computer model forces the students to quantify the qualitative CLD model and stresses the need to be clear about what the various variables in the model really stand for, and make them quantifiable. Interactive computer models have advantages in that they can be used for experimentation and let users test various scenarios in order to see their consequences for the system as a whole. It is possible to compress time and space and allow interventions to be tested in a shorter time than it would take to test them in real time. Furthermore, experimenting on a model can avoid causing harm to an actual system, if the interventions prove unsuccessful. Thus, it is possible without any risk to test a variety of interventions and see their consequences. Computer modeling tools also take advantage of the fact that a computer model can be of much greater complexity, can handle the underlying differential equations and carry out more simultaneous calculations than the human mind is capable of (CLExchange, 2009).

The cases that students work with are about complex phenomena. In many other learning situations that do not include interactive simulations, students' assignments can be to describe situations and suggest actions as a final step. With the introduction of a computer model, however, another step is included: that of testing and analyzing consequences of these actions. The quantitative computer model that the students create provides means for them to see how a dynamic system will change due to different interventions. It is possible to test assumptions and relationships by running the simulation and observing the result in the form of a graph, a table, or an animation. This is a major difference between CLD and STELLA, as the CLD on paper does not support interactive simulation.

The group negotiations to construct a model that can run simulations include, among other things, how to transform the qualitative model into a quantitative one. This involves aspects presented earlier, such as deciding parameter values and converting entities between separate factors and between subsystems. For example, students are observed to have difficulties when discussing issues of how to convert rain into vegetation or how to handle quantitative estimations of abstract concepts such as beauty, peace, or anger, issues that are not applicable in the CLD.

Interactive feedback

An observation when comparing CLD work to STELLA work is the change of the topics raised by the students due to the fact that the feedback provided when using the computer software is different from the feedback generated by a visual representation on paper. The feedback in STELLA is interactive and can be presented in the form of a graph or a table, and when the structure or the input data in the model is changed, so is the graph and the table. It is immediately apparent that the CLD on paper provides a static picture that the students can relate to, but it does not provide any interaction. The interactive and visual aspects of alternative representational forms can become a considerable resource to bring the students' work process forward and a help to evaluate the constructed model. Students seem to compensate for the absence of interactive feedback in the CLD by reasoning aloud, often in the form of a narrative, while pointing at the various symbols on the paper, thus creating a kind feedback for themselves.

One point in the work process that was specifically noticed in the interaction analysis was right after students had run the simulation for the first time and had seen the result in the form of a graph on the computer screen. In all observed cases, this activity resulted in reactions that indicate that students have expectations of what the graph should look like, that is, they had formulated a hypothesis (albeit maybe on a very general level, and maybe not explicitly). The feedback results in a reassurance or a conflict with this hypothesis: either the graph meets the expectations, or it does not. The students react to this feedback, often referring to the story they want to tell. Prior knowledge and individual cognitive abilities such as the capability to form a hypothesis based on a number of facts are resources drawn on in this process.

Ben and Sarah, working with the second assignment, have revised the input data after noting that their first graph indicated a flaw, that is, it did not meet their expectations. They change the input data for one of the variables and run their model once more. This time it seems to meet expectations, and Ben reasons with support of the graph:

```
*BEN:    see now grain for sale is good
*SARAH:  [mumbles]
*BEN:    it's up to (.) fourteen ? [.] units of grain for sale ?
*SARAH:  mhm
*BEN:    should have been twelve (.) shouldn't it ?
         but since we did one and divided it into parts so (.)
         it's okey I reckon
```

Ellen and Mark (case study II) use the graph to relate to the story they want to tell. Ellen first perceives a problem in their graph, but is then reassured by Mark:

```
*ELLEN:  oh wait (.) waitwaitwaitwait
*MARK:   that's right
*ELLEN:  yeah that's right
```

… and later:

```
*ELLEN:  at least the harvest looks good huh ?
         there's grain coming in (.) in september
         [long pause]
         okey here we have a lot of coming in (.) half again and
         half again coming in
*MARK:   it works
         taking ten (.) always ten off the market
*ELLEN:  mhm (.) so the grain is gone before the next harvest
         so they already have a problem
*MARK:   yeah that's right (.) because we have a consuming of ten
*ELLEN:  mhm it's logic yeah ?
```

In the situation where the reaction is that something is wrong with the graph, there can be at least two reasons: 1) expectations of an anticipated pattern in the graph are not met, and 2) no specific expectations were present, but the result is perceived as obviously incorrect. Two different things happen in the groups with anticipated feedback: Some groups note a falsification of their expectations, but rely on the generated data and the software and do not take any action to resolve the discrepancy. Other groups note it and address it as soon as the graph is generated. The groups that address the discrepancy can resolve the situation in different ways: they can question the structure, or they can question the quantities and formulas that they have put in. The analysis shows that students do not easily abandon the structure of their model when the simulation does not run as expected. They rather try to find mistakes in the quantification. Instead of sacrificing the structure that they have invested so much time in, they seek an easier solution by changing the values of the parameters.

The interactive feedback brings in a new dimension of the modeling work. It makes it possible for the students to build the model more based on a trial-and-error strategy than in the CLD phase. They take small steps in building the computer model, running it and receiving feedback in each step.

Collaboration

It is often stressed that the virtue of systems thinking and System Dynamics is that the tools can be used to collaboratively make visible different perceptions of a problem in order to get a richer comprehension of it, and thereby make better informed decisions. Both tools support collaboration in this way. However, a prerequisite is that all the people involved share the common ground of how the tool works and what input is needed. The strict working order of the CLD seems to reduce discussions about how to manage the work process, something that is more observed during the computer modeling phase. In parallel with discussions about what the model should include and be constructed, there are also discussions about the management of the computer and the software itself.

Students adapt their communication in form and content to the situation during the work process by reacting to the demands of the two tools. That is, the decisions that are made and the issues that are in focus in the collaboration differ between the two phases. This is natural since the tools are used at different times of the work process where some issues need to be dealt with earlier than others regardless of the tool, but it also depends on the type of input the tool calls for. As mentioned previously, storytelling is primarily observed in the CLD phase when the tool calls for variable names and causal relations between them. It is often done in a collaborative manner whereby the group members take turns, build on each other's utterances and create the narrative together. The discussions when working in STELLA concerns how to transform the CLD and how to quantify variables and apply mathematical functions such as ratios and triggers.

The lack of interactive feedback in the CLD phase is compensated by students telling a story and in this manner producing their own verbal feedback from the visual representation on paper as the model develops. With the interactivity offered in STELLA, there is more of a trial-and-error strategy, where various inputs are assessed by running a simulation. The discussion that follows is a reaction to the feedback: either to go back and revise, or to ensure that they are on the right track.

When working on the CLD, it is observed only on one occasion that each of the students in the pair has a pen and that they work on the same model simultaneously. In all other cases, it is one student at a time holding the pen and the other one sitting alongside. When working on the computer there is one person in charge of the mouse through the entire recorded period. For practical reasons it is not possible to work simultaneously on the computer screen, but it would have been possible to switch places so that both students could work on the computer at some time. However, in both cases, the evolving model figures as the central semiotic object that holds the work process together. It is the object that mediates their discussions and physical actions.

Summary

The CLD and the computer model enable the students to have different, yet coherent, views of a dynamic system. Each tool can be used to represent a system, but each emphasizes different aspects of it. They use different terminologies and different ways to graphically represent a system, although they both share the focus on feedback structures (Sterman, 2000). While the CLD puts the focus on the causality in a qualitative sense, STELLA focuses on quantification of the variables and offers an interactive simulation of the system behavior. A computer model also provides consequence analysis of suggested interventions, and interactive visual feedback in the form of graphs, tables, and animations. The tools requires different actions and input by the students, which have to be learned. After presenting a CLD in class and having it approved by the tutors, students turn to the computer. By observing the work students do when transforming their model from one representational form to another, it is possible to discern what the two different tools contribute in their work process, and to note potentially problematic situations.

Some aspects seem easier for the students to work with in the CLD, while others seem easier to work with in the quantitative model. It is not required to quantify variables in a CLD, thus "soft" variables such as beauty, peace or anger are not problematic. For example, it is quite straightforward to make a CLD showing that the more moles there are in a garden, the angrier the landlord is. In STELLA however, it would be required to define a mathematical relation between the number of moles and the intensity of the anger, thereby quantifying the anger. This is a difficult issue for the students, and they try to avoid using variables of this nature as much as possible.

On the other hand, students have trouble representing conditional actions in the CLD, which they find easier in STELLA. A difficulty observed is when the system involves activities that take place only under certain conditions. To include conditions like these in the CLD would require verbal elaborations or visual codes added to the diagram. In the computer model, however, this is dealt with by writing a formula based on an if-then statement. Computer modeling involves mathematics, which some of the students feel well acquainted with. Not being able to apply math, as in the qualitative CLD phase, causes frustration for some of them.

Students concurrently use terms belonging to the two different tools, using a computer modeling term when constructing a CLD, and vice versa. An assumption is that a term is used because it is helpful in that specific moment, to support a suggestion, an explanation, or an argument. An additional assumption

about why a STELLA term is used in the CLD phase is that it may indicate early adjustments in order to be prepared for the computer modeling phase. Although using the terms verbally, students do not, however, sort the variables in the categories Actors, Factors, and Conditions and write them down in a list, a working step suggested by the tutors to facilitate the transition from CLD to STELLA (see Chapter 4, Task analysis of the empirical data).

Students use narratives to a great extent when working with the CLD. One use of narratives is to create feedback by telling a story while assessing the model. In this way they check if the story that could be told based on their diagram matches the story in the assignment. Since there is no interactive feedback, it is harder to detect flaws. In STELLA, where simulation with interactive feedback is provided, storytelling is observed as the students get the result of their simulation in the form of a graph. It is easier to detect flaws but it is hard to find where the flaw is. Students tend to change numerical values rather than scrutinizing the structure of the model.

In addition to making meaning of and using the new representational format in a tool like STELLA, students may experience general technical problems not directly related to the assignment. This is often noted in studies concerning computer-related tasks. Especially in experimental studies where students have limited time for the task, the technical problems get in the way of drawing important conclusions regarding the students' actual work with the assignment (e. g. Rueda, Arruarte, Elorriaga, & Herran, 2009). Much time is spent on understanding how the software works or dealing with general technical problems related to the computer hardware and software. This type of problem is also noted for the LUMES students, but only on very few occasions. Thus, this does not seem to be a big issue for them, most likely due to training sessions with the software prior to their modeling assignments, a high level of general computer skills among the students, and helpful tutors.

To conclude, students handle the translation from the CLD to the computer model without any major difficulties, that is, they make the necessary adjustments to fit the CLD to the new representational format of STELLA. However, this adjustment does not happen only when changing the representational format, but is observed throughout the CLD phase, for example by choosing variables that are suitable for the quantitative computer model, and by the use of STELLA terms when assessing their CLD work. Students anticipate the next step and prepare for it. Moreover, it is observed that the computer modeling phase adds a new dimension of the model building process in that it gives them the opportunity to test their model by running simulations and getting interactive feedback. This seems to give them a greater confidence in the quality of the model since they get feedback based on their own input. It is harder to detect a flaw in a CLD due to the lack of interactive feedback.

9. Summary and conclusions

Tools have profound effects on how we think and communicate with one another. Some of them, like our native spoken language and basic drawing techniques, are so much taken for granted that we seldom reflect upon them. Others need to be presented to us explicitly, often in an educational setting. People encounter various resources, or tools, for reasoning throughout the educational years. In a socio-cultural perspective, getting acquainted with a new representational tool means learning to think and express understanding of a given problem in a form that has been developed in a social and historical context. The alphabet is perhaps the most frequently used; in mathematics there are formulas, tables and graphs, and in music there are musical notations. Not only do we have to learn a subject content that has to be represented, but also the representational tool itself. Thus, we learn to think in terms that are supported by, and match, the representational format. A fundamental question for the science of learning concerns how this is achieved.

In the LUMES Master program, students are introduced to systems thinking and the method of creating causal loop diagrams and interactive computer models for analyzing and solving complex problems. They learn how to use the terminology, symbols and methods of a specific semiotic domain, in order to later be able to apply the method in numerous situations. In socio-cultural terms, they are introduced to a set of psychological and physical tools (Wells, 1999; Wertsch et al., 1995).

Having access to a particular tool can make us approach a problem in a certain manner. Schoultz et al. (2001) argued that children's expressed understanding of astronomical concepts, such as the shape of the earth and gravitation, is highly dependent on the tools available as resources for reasoning. It was shown that explanations of gravity differed between situations when children had access to a globe and situations when there was no physical object to relate to. Another example, from the theory of science, is the argument made by Poincaré (1908), that measurement conventions profoundly influence theoretical conceptions. In particular, he claimed that the curvature of physical space is not a fact of nature independent of how measurements are defined. It is based on a certain perspective of the world.

To think in terms of systems is to apply a specific perspective on the world. The semiotic domain of systems thinking builds on causality as a fundamental concept. Causality is also the main explanatory principle in our every day life that we use to explain why we are tired, why our colleague smiles just now, how snow becomes water or what makes the employment rate go up. Hence, one can presume that the idea of systems thinking is not unfamiliar to us. However, when we are directed to use specific tools to represent causal relations, we need to adjust our apprehension to fit into the representational format of the tool. That is, even though we think we have a clear apprehension of the phenomena that we want to explain, the tool dictates how this can be done. This is both a constraint and a support. It can be a constraint if the tool does not support expressing something that we want to express. At the same time, it can be a support as it forces us to deal more systematically with a problem. When we are required to express our understanding in the form of a visual representation we can detect possible incongruence in our chain of explanation, or make ambiguities in our line of reasoning visible. The reason why we use a tool is in many cases because we believe that it can make us more competent and because we want to communicate our understanding to others.

Opening up "the black box"

This research project aims to contribute to the body of research in the area of tool-mediated (learning) activity. It has taken the opportunity to collect and analyze data of the *work process*, rather than evaluating the *product* of the process, which is usually the main source of information for a tutor to evaluate students' work.

In most formal educational situations, there is a pedagogical intention behind an assignment. However, every tutor knows that a learning activity cannot be arranged in detail; the learning situation is contextualized, and the interaction, as well as the tools available to express understanding, affect how meaning is made. Although, for example, the normative working order for a specific tool tells us what the students' overall work process will look like, the specific issues that the students address are not conveyed until we open up "the black box" and investigate "the nature of qualitative understanding and associated learning processes" (Roschelle, 1991, p. 2). Having many students to attend to, a tutor only has occasional insights into their work process, which are occasions that often are initiated by their need of help with a particular issue. The instances of helping students give the tutor only limited information about what goes on during the time in-between tutoring. An analyst's contribution could be to systematically sort, to abstract trends and patterns, and to draw conclusions on the basis of a number of observations that last for longer periods in time, in order to give a richer description of the work process.

The research questions that have guided the analysis of the empirical data of this thesis concern how interacting with systems thinking tools affect students in the process of collaboratively analyzing and modeling complex problems, and how cognitive and semiotic resources are used in this process. Three theoretical perspectives have been applied: the socio-cultural perspective, the social semiotic, and the constructivist perspective. The aim is to provide a *conceptual lens* with which to discuss and perceive the complexity of learning to express knowledge with new representational tools: both its visual and spatial formalism and the related terminology. The underlying assumption is that meaning making may be revealed through the ways in which a tool is attended to in people's activities, and that to understand human meaning making, we need theories with both individual and social perspectives. The sociocultural perspective is applied to emphasize the use of tools as a part of human learning. It puts focus on the mediating roles of language and other tools in a social context, which is in many ways connected to the social semiotic perspective. To view systems thinking and System Dynamics as a semiotic domain accentuates the use of specific terminology, symbols and gestures to express understanding. Furthermore, the constructivist perspective is used to put focus on the role of individual cognitive abilities and prior knowledge.

In the case studies presented here, the students' exploration of the System Dynamics domain is characterized by the close interplay between verbal and nonverbal activities and external representations. The case studies show how individual cognitive abilities, language, gesture and the visual representations are used as integrated resources to express understanding of a problem and its solution, as illustrated in Figure 38.

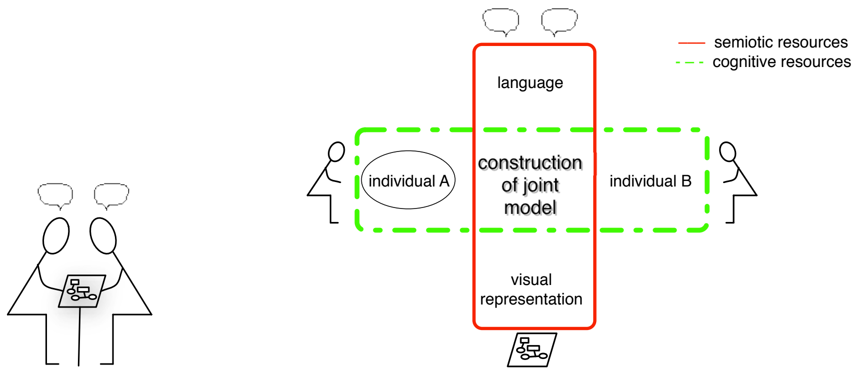

Figure 38: Interacting features of a collaborative situation when learning to represent problems within a System Dynamics framework. When required to use tools of this specific domain, students draw on a range of cognitive and semiotic resources in order to make sense of both the tool and the assignment at hand.

Each semiotic domain has its own specific order of discourse based on a structured set of conventions (New London Group, 2000), including words, images, symbols, and actions (Lemke, 1998). Tools that are developed in a semiotic domain build on these conventions. In a collaborative situation, they mediate the interactions between learners by providing pre-defined structures that aim to support particular (learning) activities. Tools thus scaffold a work process by shaping an activity, in promoting the performance of certain actions, communicative or physical, and making other actions impossible or less likely to be performed (Suthers, 1999). The normative working order for the CLD exemplifies such a scaffold and is part of the specialized actions in the systems thinking semiotic domain, as illustrated in the task analysis in Chapter 4 and in the Chapter 5 case study. As an educator it is important to consider the working order when introducing a new tool: How explicit and how structured is it? Is it negotiable? What issues are dealt with within each working step?

A closer look at the work process

A strict working order can act as a supporting feature for the students to guide them through the work process, as shown in Chapter 5. In the case with the CLD, the normative working order is imperative since certain objects must be defined before others. The observed differences between groups concern the length of the iterative cycles of defining links and loops, where some groups define a number of unidirectional links first, and then go on to look for loops. Other groups look for a link back (that is, a loop) as soon as they have defined one single unidirectional link. Other than this variation, there is little room for altering the working order. However, there are issues to consider and decisions to make within each working step, which are much more left to the students' free elaboration. It is important as an educator to be aware of the nature of these elaborations as it furthers the understanding of what students themselves focus on, or find problematic. Gaining this understanding would make it possible to act more proactively when arranging learning activities and giving instruction.

The task analysis in Chapter 4 aimed to deconstruct the working order to identify the various subtasks within each step, and point to the types of decisions that have to be made. The first issue in the process concerns the choice of variables, an important decision as it determines what is possible to express with the model. The choice of variable names indicates that they have the second phase of the assignment in mind: they want them to be easily computable in the posterior, quantitative model.

The resources that students draw on are mainly the story that they have been given, together with their individual prior knowledge of the subject matter that they share and discuss with their peer. Experience from previous assignments can also influence the choice. Moreover, the graphical structure and the working order in the CLD seem to elicit the production of narratives, both in order to find the right variables and in order to produce a kind of verbal feedback once the model starts to take form.

The steps that follow involve the definition of causal relations and the nature of these (positive or negative), as well as the definition of feedback loops. The demands of the tool elicit various discussions about causal relations and feedbacks, illustrated in the case studies. The basis of these discussions is the students' active pursuit of causal relations. Evidently, the name "Causal loop diagram" implies that there should be causal loops and, subsequently, causal relations are tried for each pair of variables. This can sometimes result in inappropriate relations, coerced by the tool. One such example is illustrated in case study II, Chapter 6, where students run into difficulties due to the choice of variable names, in combination with this active pursuit of a feedback loop; prior knowledge of an xy-graph representing a relationship between the two variables "Demand" and "Supply" gets in the way of creating a CLD. To reconsider the choice of variables and to challenge prior understanding in order to get out of the conflict is difficult. Although the problem in this case depends on confusion regarding correlation and causality, it advances the difficulties of transferring information from one representational format to another, and understanding what is possible to express, and what is not.

The relevance of prior knowledge and ways of perceiving a system

A related issue is the relevance of prior knowledge when learning to model. In the LUMES course, the tools are used to learn about System Dynamics. The tools are in focus, compared to a situation where the problem is the focus and System Dynamics tools are applied to solve it. A reason for some of the problems that the students encounter can be a lack of content knowledge. The nature of an assignment is to construct a model, and the subject matter is generally not well known to the students. In the course it is even made a point that models can be constructed for a wide range of problems, and that students should be confronted with a variety. This highlights a possible problem of learning to model *per se*. A modeling task in the corporate or institutional context presupposes that the people involved have certain subject knowledge to contribute. Students with little or no experience of the content area use their prior knowledge and assumptions about the presented case. Having an extensive prior knowledge of the subject to be modeled certainly affects the learning situation, but to study this is outside the scope of this thesis. Some remarks on how students approach their task can nevertheless be made.

Parallels to what can be observed in the case studies can be seen in other areas where distinctions between novices or experts are made in relation to how they solve problems. In an inquiry learning environment, it was shown that students with high domain knowledge employed a theory-driven strategy, whereas less knowledgeable students started off in a data-driven mode of inquiry and gradually shifted to a theory-driven strategy (Lazonder, Wilhelm, & Hagemans, 2008). Concerning the way in which novices and experts construct representations for physics problems, Larkin (1983) showed that the main difference between the groups is that the novices' representations are constructed mainly in terms of the entities given in the problem, whereas experts' representations are more in terms of theoretical entities which are needed to solve the problem. In the area of programming, it is well established that beginners use cues that they recognize in the problem description, while experts use larger chunks of the problem based on the problem definition (Anderson, Farrell, & Sauers, 1984; McKeithen & Reitman, 1981; Soloway, 1986). In a similar vein, Adelson (1981) showed that the programming novices used a syntax-based organization, whereas the experts used a more abstract hierarchical organization based on principles of program function. The empirical data from LUMES confirm these findings. Students primarily use entities given in the problem description and apply a data-driven strategy.

Another aspect of the relevance of prior knowledge concerns how the concepts belonging to the domain of systems thinking are perceived by the students. While sketching a model using standardized symbols like boxes and arrows seems rather straightforward, the underlying conceptual features of dynamic systems remain difficult for students to understand, as documented extensively (see Chapter 2). Students are, for example, fairly good at identifying structural feedback loops, but more seldom discuss dynamic feedback processes. By observing the collaborative work and listening to students' conversations, it is possible to draw tentative conclusions as to how systems thinking concepts are perceived, but this could be more thoroughly examined by interviewing students about the core ideas of the domain. A phenomenographic approach could be taken, with the aim of presenting analytical categories that give a description of qualitatively different potential ways of understanding or experiencing dynamic systems. The categories could be taken into account when organizing learning activities and used by teachers in coming to understand students' need of support. Another research project could be to use the collected empirical material supplemented by interviews to build on the research project that focused on the contextual character of meanings of language units used by students (Anderberg, Alvegård, Svensson, & Johansson, 2005; Johansson, Svensson, Anderberg, & Alvegård, 2006). Assumptions concerning the use of language are often implicit, without differentiating between the use of language and understanding of subject matter (Svensson, Anderberg, Alvegård, & Johansson, 2009). This differentiation would be interesting to explore with regard to the systems thinking domain.

Scaffolding and constraining features of the tools

The rules on how to create a representation in the form of a Causal Loop Diagram help students to identify aspects of a problem that need to be explored, and provide them with a concrete representation. It is a representation of students' shared understanding, although shaped by the affordances and constraints of the modeling tool. In a socio-cultural perspective, this is an important note: the possible ways to express understanding are dependent on the tools at hand. When assessing a student's performance it is important to be aware that it is not an assessment of his understanding of the subject *per se*, but his ability to express his understanding of the subject in a particular form. As pointed out in Chapter 8, students were well aware of the market mechanisms that held Merchant Wang back from selling his grain until a certain price was paid, but they had problems representing this fact in a CLD. However, when moving to the computer model, they had no problem at all. If we were to assess the students based on the CLD, the diagram would give us the impression that they did not have the understanding we were looking for. Assessing their STELLA model, we would have concluded that they had.

The rules that apply to the spatial layout of the diagram are part of the semiotic domain and need to be taken into account. Students show, with both language and gestures, that they are familiar with these rules when discussing how the model should be laid out. The extensive use of iconic gestures, observed in the video recordings and reported in Chapter 7, shows that the spatial aspects are important and considered throughout the model building process. They are mainly used when students formulate suggestions, discuss and plan the layout of part of the model or the entire model, as a precursive step to using the pen to draw. Even if they do not use the appropriate terminology such as “link,” “loop,” and “feedback,” drawing on the visual display and gestures as resources, they are able to communicate in a way that their peer understands. For example, a finger moving along a hypothesized line on the surface of the paper requires the peer to imagine a line behind the finger. As the finger moves, the utterance can describe the movement as “connecting to this.” The formalism of the CLD makes this communication possible since the students share the common ground of how a CLD should be laid out. Thus, communication is distributed over three modes of expression: the perceptual ground, gestures, and utterances, suggested and nicely captured in Roth’s (2001) analyses of activities in a science classroom.

The dialogue and the physical model are tools to accomplish a goal: to learn systems thinking. The external representation serves as an offload for the individuals’ memory, as it can capture more parameters and greater complexity than the human mind can hold in one specific moment in time. The evolving model also serves as an external memory of the collaborative process, and makes the discussion easier to refer to when looking back at the process, and when planning ahead. Students maintain a joint obligation throughout the work to bring the process forward, and concepts that are specific to the semiotic domain are particularly used in this work. As presented and discussed in Chapter 7, their use of the terminology that belongs to the semiotic domain can for the most part be observed during meta-cognitive activities such as monitoring, planning and evaluating work, and much less when the model is actually constructed. Possibly this can be so because it is on these occasions that students (implicitly) match their model against the goals of the course and envision a judgement from a tutor.

Students learn to work with two different tools: the CLD and the computer software. Although working on the same problem, they have to switch tools in the middle of the work process. The aim of Chapter 8 was to discern characteristics of working with the two tools, and to note potentially problematic situations when transferring between them. Critical issues include the fact that the transfer is not a one-to-one relationship when it comes to graphical objects. Additional objects, such as converters, are needed in the computer model, and sometimes the structure needs to be altered to some extent. Moreover, students who seem to be more mathematically oriented like to think in quantitative terms already in the CLD phase, and are sometimes frustrated by not being able to assign formulas and conditional actions in the qualitative CLD. The possibility to run simulations in the computer model affects students' monitoring and planning. Trial-and-error strategies are applied to a large extent when constructing the model, by building it and running simulations in small, iterative steps.

It would be interesting to further study the transition from the CLD to the quantitative computer model. By using the same kind of analysis methods as in the case studies, it would be possible to discern whether, and if so, how, students change the model due to new or additional requirements of the quantitative modeling tool. It would also be interesting to study the student's generation of graphs and how they affect the work process, as it is an example of a kind of interactivity offered in many educational software packages.

Concluding remarks

Richmond (2000) pointed to three aspects that are equally important when people are introduced to systems thinking and the practice of System Dynamics modeling: Systems thinking can refer to a set of tools that help us map and explore dynamic complexity. It can also be used to mean a specific perspective on reality, and, as a third aspect, it can refer to a special vocabulary to express understanding of dynamic complexity. All three aspects are present in the students' modeling tasks that form the empirical data presented in this thesis. The analysis shows how their understanding of systems thinking is manifested. It shows that students successfully engage in the language-game of System Dynamics by using the rules and conventions of the semiotic domain: they comply with the working order, use the terminology, and follow the conventions for the spatial layout.

On a general level, this thesis addresses the issue of learning with support of representational tools and the way that the evolving representation mediates the collaborative work process. The research is an attempt to bridge multiple perspectives, and the contribution lies in the analysis of what cognitive and semiotic resources students draw upon in this process. The case studies may help to identify the ways in which tools both provide the means to and constrain the way we can express and think about a phenomenon, and thus make educators more informed and prepared when supporting students in a learning activity. However, much work remains to be done to fully see the implications of tools and the larger context of learning environments, and to understand how it affects meaning making.

For the community of System Dynamics educators, I believe it could be worthwhile to think of the systems thinking/System Dynamics domain in terms of cultural, mediated tools and of what implications such an approach may have for how learning activities should be organized, and what kind of support students need. In order to help teachers when planning learning activities that involve systems thinking, it may be helpful to be aware of how students tackle the task of learning to express their ideas of causal relations, and what cognitive and semiotic resources they rely upon. To be aware of critical issues or events in the work process may also be helpful in order to inform teaching practice, and thereby promote students' learning.

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