Does teaching students how to explicitly model the causal structure of systems improve their understanding of these systems?

If students really understand the systems they study, they would be able to tell how changes in the system would affect a result. This demands that the students understand the mechanisms that drive its behaviour. The study investigates potential merits of learning how to *explicitly* model the causal structure of systems. The approach and performance of 15 system dynamics students, who are taught to explicitly model the causal structure of the systems they study, was compared with the approach and performance of 22 engineering students, who do generally not receive such training. The task was to bring a computer simulated predator-and-prey ecology to equilibrium. The system dynamics students were significantly more likely than the engineering students to correctly frame the problem. They were not much better at solving the task, however. It seemed that they had only learnt how to make models and not how to use them for reasoning.

Keywords: engineering education research; modelling; external representations, dynamic systems, qualitative reasoning

Introduction

The literature on modelling tends to focus on the quantitative model that results when the laws of physics have been applied and relevant measurements made. The goal of the modelling process is a model that lends itself to mathematical treatment (e.g., Lesh & Doerr, 2003; Redish & Smith, 2008). The underlying qualitative model appears to be seen as self-evident and/or implicit in the quantitative model. True as this may be, we cannot be certain that it is evident to the students.

When the mathematical model has been manipulated and transformed, and a result calculated, the result has to be given meaning (Bissel & Dillon, 2000; Kehler & Lester, 2003; Redish & Smith, 2008). The students need to understand why a result is as it is. In other words, they have to be able to interpret their results. Furthermore, if they really understand the system under study they would be able to tell changes in the system would affect a result. This demands that the students understand the qualitative structure of the system, i.e., the mechanisms that drive its behaviour.

The aim of this study is to investigate the potential merits of training students in how to *explicitly* model the qualitative, or causal, structure of the systems they study. Do students who receive such training understand the systems they study better than students who do not? It might be the case that students spontaneously model the causal structure when the need arises, or that it is sufficient that the causal structure is implicit in the mathematical models of the systems that the students create. In either case, there would be little to gain from efforts to teach qualitative modelling, or explicit modelling of causal structure. The results from this study suggest, however, that there might be.

Background

Since 2001, the assessments of engineering programs in the United States by the Accreditation Board for Engineering and Technology (ABET), focus on results (what the graduates are able to do) rather than, as earlier, what topics they are taught. There are eleven criteria for student outcomes that are to be met by all engineering programs (General Criteria 3 a-k, the Engineering Criteria 2000). (Accreditation Board for Engineering and Technology [ABET], 2011).

Passow (2007) reports a meta-analysis of ten studies, published 1992 through 2007, of ratings made by alumni, faculty, and practicing engineers on the importance of various competencies to professional practice. She matches competencies reported in these studies to the ABET competencies, to investigate which of the ABET competencies that the respondents considered most important. Alumni, faculty and practicing engineers held fairly similar views on the relative importance of the ABET competencies, and they considered e) problem solving and g) communication skills to be the most important competencies for successful professional practice.

The ABET competencies are fairly broadly stated, which make them difficult to operationalise and assess. Besterfield-Sacre et al. (2000) suggest more detailed definitions of the outcome criteria, based on how the competencies are described in the literature, interviews with engineering faculty and industry practitioners, as well as their collective experience as researchers. Besterfield-Sacre et al. (2000) found that the *problem solving* competency (ABET criterion *3e* consists of several components: problem or opportunity identification, problem statement and system definition, problem formulation and abstraction, information and data collection, model translation, validation, experimental design, solution development or experimentation, interpretation of results, implementation, documentation, feedback and improvement. The components of the *communication* competency (ABET criterion *3g*) were found to be: writing, speaking, graphical presentation, and communication by electronic media (Besterfield-Sacre, et al., 2000). These descriptions of problem solving and communication skills correspond to the abilities mapped onto these ABET competencies by Passow (2007) in her meta-analysis.

The role of qualitative modelling in problem solving

The attributes defined by Besterfield-Sacre et al. (2000) for the problem solving element "problem statements and system definition" include: (a) describes the engineering problem to be solved; (b) visualizes the problem through *sketch or diagram*; (c) outlines problem variables, constraints, resources, and information given to construct a problem statement; and (d) appraises the problem statement for objectivity, completeness, relevance, and validity (Besterfield-Sacre, et al., 2000; Felder & Brent, 2003). This can also be seen as the initial step, or steps, of a modelling process (e.g., Brogan, 1991; Lesh & Doerr, 2003).

Consider a baby door bouncer. The baby is put in a harness that is attached to a door frame with a clamp. The baby is hanging vertically in the harness and a spring inserted between the clamp and the harness allows the baby to bounce up and down. Let us assume that the proper designs of the harness and the clamp are dealt with by other people. Our task is to deal with the bouncing aspect of the baby door bouncer. We have now defined our problem and the system boundary. So, how can we model the relevant parts of the system in a way that will help us solve this problem?

I will start by creating a qualitative model. I use the term qualitative model to refer to any representation that illustrates the principal workings of a system. Qualitative models are used to illustrate the mechanics (or mechanisms) of a system, and may assist reasoning about the system.

Our task is to make sure that the baby doesn’t bump into the floor, but that it still is close enough to the floor to be able to kick off and get the bouncing started. The bouncing should be enjoyable for the kid. Most children would probably not enjoy being shaken about by the spring, but they would also most likely get bored with very slow bouncing.

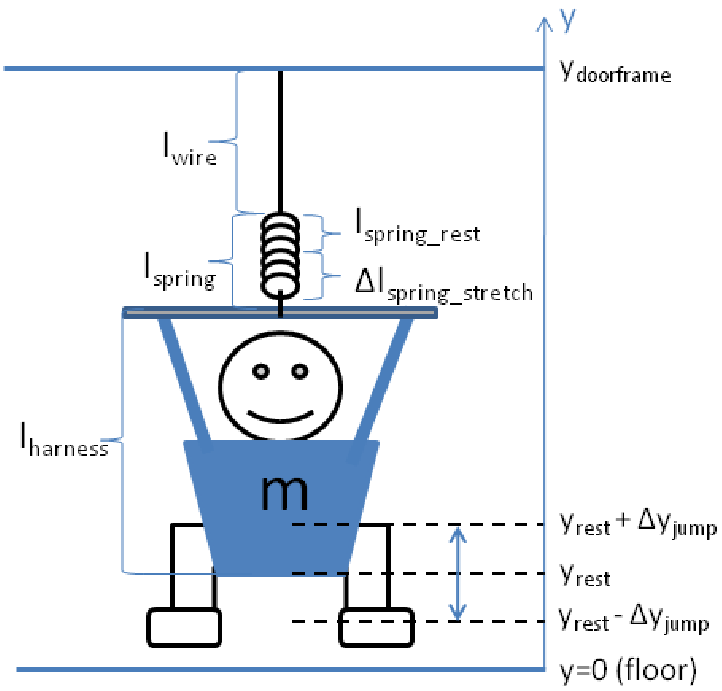

Figure 1. A qualitative model of the baby door bouncer problem.

The sketch in Figure 1 is one example of a qualitative model. It includes only the components of the baby bouncer system that I have deemed relevant to the task. The sketch, or qualitative model, also presents how the components are connected, and may assist reasoning about the causal structure. How do the different components affect the solution of the task?

The traditional textbook problem

In traditional textbook problems, much of the problem statement and system definition is already done. The system boundary is generally defined, and the important system elements identified. The students need not trouble themselves with this part of the engineering process. In the typical engineering classroom (Rugarcia et al., 2000), the professor may refer to (qualitative) models of the system structure when describing how the formulas used to solve problem within the actual domain are derived. The problems the students are assigned can, however, often be solved by simply the copying a procedure demonstrated by the professor in class. The students are then following a recipe rather than analyzing the problem. This relieves the students of the effort to actually reflect on what they are doing. For problems that only require that the students solve a formula for some variable from given values of other variables, the students do not need to reflect much on what the problem is about. They may simply search for a formula or a combination of formulae, which will allow them to calculate the variable asked for, do the math, and check that the answer is given in the correct units. If this is all that is required, it is quite possible to produce the correct answer with very little understanding of what has actually been calculated. This was, at least, my personal experience as an engineering student in the mid-eighties.

A traditional textbook version of the baby bouncer problem would probably to look something like this:

A baby is playing in a baby door bouncer. The baby weighs 10 kg.

a) What spring stiffness is required for an oscillation of 2 Hz?
b) If the resting position of the bouncer with the child in it is 25 cm above the floor, what will the distance from the floor be once the child is removed?

Problem a) is solved by treating the bouncing baby as a one-dimensional simple harmonic oscillation. The differential equation describing such a system is obtained, by applying Newton's second law and Hooke's law.[1] Problem b) is solved by

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[1] The differential equation is $\frac{d^2x}{dt^2} = -\left(\frac{k}{m}\right)x$, where x is the displacement from the equilibrium. The solution is x(t) = Acos(ωt – φ), where A is the amplitude, ω = $\sqrt{\frac{k}{m}}$, and φ is the phase. This means that $k = (2\pi f)^2 m$. The answer to a) is 1.6 kN/m, and the answer to b) is 31.2 cm.

applying Hooke's law and calculating the extension of the spring when it is opposing the gravitational force on the child (and adding 25 cm).

Hooke's law, and how to derive and solve the differential equation describing the simple harmonic oscillation, is likely to be demonstrated by a teacher in class. This means that the problems can be solved by finding the appropriate formulae, remembering the appropriate procedure, and do the math. Questions like "What would happen if a heavier child was put in the harness?" are rarely asked. This would not even be a good question to ask if we wanted to assess the students' ability to reflect upon the system. They could just put in a larger number, redo the calculations, and report the results. A better question to ask would be "What adjustments might be required if a heavier child was to be put in the bouncer?"

In traditional laboratory exercises, as described by Felder and Brent (2003), the students work through a series of fairly rigidly prescribed experiments in which they follow instructions on equipment operation, collect the prescribed data, and perform the prescribed data analyses. The students are rarely asked to make any meaningful interpretation of the results they have reported (Felder & Brent, 2003).

Qualitative models and communication

Engineers need to be able to explain their work, not only to colleagues, but also to other team members when working in multidisciplinary teams, to managers, to clients, as well as to the general public (Rugarcia, Felder, Woods, & Stice, 2000; Martin, Maytham, Case, & Fraser, 2005). This entails presenting identified problems and suggested or implemented solutions in a way that is readily grasped by the intended audience. Regardless of the means of presentation, spoken words or written text, it is the qualitative model that ought to serve as the basis for explanation. The qualitative model contains the system elements central to the problem, and their interactions. Explaining the engineering problem solving requires communicating the qualitative model and how the solution works within this model. If it is possible to present the model graphically, this would most likely facilitate communication. A well-done sketch can explain a lot (Larkin & Simon, 1987).

Student outcomes

Safoutin et al. (2000) identified 13 components of the ABET criterion *3c*: an ability to design a system, component, or process to meet desired needs within realistic constraints (ABET, 2011). The components were: need recognition, problem definition, planning, information gathering, idea generation, modelling, evaluation, feasibility analysis, selection, implementation, documentation, communication, and iteration (Safoutin et al., 2000). There is a substantial overlap with the components of problem solving identified by Besterfield- Sacre et al. (2000), discussed earlier. Safoutin et al. (2000) designed a freshman design course for engineering students based on the identified components of designing ability. After the course both the students and the instructor completed a survey addressing the students' performance on the 13 components. The students assessed their own personal skills, and the instructor reported his (or her) assessment of the students' skills. The means of the students' responses were almost the same for all the components, around 4 (very good) on a five-step Likert-scale from 1 = poor to 5 = excellent. The instructor expressed less confidence in the students' modelling skills (assessed as 2 = fair) and iteration skills (about 2.7) (Safoutin et al., 2000).

According to Felder and Brent (2003), problem-based learning and cooperative learning are two instructional approaches that if combined may address all the ABET Criterion 3 outcomes. This approach to teaching strives to present the students with realistic problems, as similar as possible to the problems the students will encounter as practicing engineers. This means that the students have to do more in the way of stating the problem, defining the system and collect relevant information. When the students do this and work on solving the problem collectively in a group, they will have to explain their reasoning to each other, and argue their favoured solutions (Dym, 2004; Rugarcia et al., 2000; Zawojewski, Difes-Dux & Bowman, 2008).

Structural engineers, studied by Gainsburg (2006, 2007), employ a wide variety of models, ranging from concrete and literal depictions of structures or elements to abstract and fragmented representations of structural behaviour. The engineers meet with two kinds of major challenges in their modelling activity: to understand the phenomenon to be modelled and to keep track of the solution process. The engineers use descriptive models, drawings and sketches, to assist their reasoning about the structural behaviour of the parts of the building, both in their mathematical modelling process and when making sense of the results from performed calculations (Gainsburg, 2006).

The present study

In courses on system dynamics, the students learn to draw simple diagrams to sort out the causal structure of a system. Figure 2 shows what such a diagram would look like for the baby bouncer task. It could be viewed as a way to depict common sense reasoning.

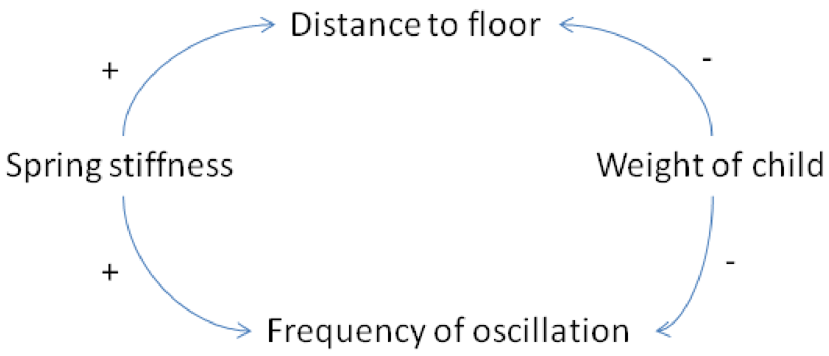

Figure 2. The causal structure of the baby bouncer system.

I assume it to be common knowledge that pulling on a spring by, for example, hanging a child in a harness from it will cause the spring to stretch; the stronger the spring the less stretching, i.e. the child will find itself further from the floor. A plus sign means that there is a positive correlation, and minus signs that it is negative. A strong spring will make the oscillations small and fast, and a weak spring will make the swinging large and slow. So, with common knowledge and common sense reasoning you may reach the conclusion that to solve the task you need to first try find a spring that gives the child a nice oscillation. Try a weaker spring if you want a slower and wider swing and a stronger one if you want a smaller and faster swing. Then adjust the wire so that the child is positioned at an appropriate distance from the floor. This covers the left-hand part of Figure 2. The right-hand part of Figure 2 addresses the question of how the weight of the child affects the system.

This is another kind of qualitative model of the baby bouncer than the one presented in Figure 1. While Figure 1 aids reasoning about the causal structure, Figure 2 explicitly depicts the causal structure, and only that. What kind of qualitative model that is most helpful depends on the problem. It is also possible to use several models to inspect the problem from different angles.

A point I wish to make here is that the task can be solved by qualitative reasoning alone. It requires some *systematic* trial-and-error, however, based on the qualitative model. The qualitative model may be explicitly presented, as in Figure 1 and Figure 2, but it can also be kept internal, i.e. as a mental model.

A qualitative model informs the creation of a quantitative or mathematical model. The qualitative model may be created explicitly, as an intermediate step, or exist only as a mental model and that is implicitly present in the resulting mathematical model.

The present study addresses the question if it is important that students are taught how to create *explicit* models of the *qualitative* structure for their understanding of the systems they study.

The performance of system dynamics students, who receive explicit and extensive training in qualitative modelling, was compared with the performance of regular engineering students, who receive considerably less such training, in a task that tests system understanding.

The task

I needed a task that required attending to the qualitative aspects, i.e. the causal structure, of the system. I also wanted a task that provided opportunity for reflection. If things did not turn out as expected, the participants should be allowed to reflect on the result and have another try (or several as was the actual case). I expected this to encourage qualitative reasoning, if this would not be immediately applied. I also wanted a task that would be possible to solve by qualitative reasoning alone.

The task selected for this study, was to bring is a computer-simulated predator-and-prey system to equilibrium, where the predators are foxes feeding on rabbits, their prey. The task instructions can be found in the Method section.

In one way, the task looks much like a typical word problem, frequently encountered by engineering students. The system boundary, the important variables and their relations are already identified, i.e. the qualitative model is implicit in this system description.

What was expected to be unfamiliar to the engineering students was that the task requires that the provided information is used to control the system, and not only to report the results of some calculations. This means that the participants need to understand how the system works. As mentioned in the Introduction, this is important both to the ability to solve problems in the system in question, and to the ability to communicate with others about it.

As may be inferred, system dynamics students study dynamic systems. Dynamic systems are generally represented mathematically by differential equations. System dynamics students are not taught how to solve differential equations, however. They model the causal structure of the system, and use computer software to run simulations of these models. This requires that quantities are provided, but the computer does the math. This allows system dynamics students to examine, in the computer simulated model, how various changes in the system affects system behaviour.

This means that the rabbits-and-foxes task is also fairly similar to what system dynamics students might encounter, but a typical assignment would have required that they created a model from the information in the task instruction that would enable a computer simulation of the system. In this case, the simulation has already been created for them. They were expected to be familiar with the task of using their understanding of the system's structure to bring the system to a desired state.

Engineering students learn the principles of how to calculate the behaviour of dynamic systems in courses on differential equations. In control theory courses, the students learn how dynamic systems can be steered. They study what properties are required of a controlling device to achieve the desired control of a dynamic system.

For this study I recruited master's degree students in system dynamics and master's degree students in engineering. The engineering students were in their third year of study or later, and who had taken at least one course in control theory. They are required to take courses in differential equations prior to courses in control theory, so they had studied differential equations as well.

Possible approaches to the task

The task does not require modelling in the sense of indentifying the important structures and how they are related in a real-life system. The world to consider is the simulation, no more and no less, and the qualitative model is given implicitly in the task instructions. What the task demands is the extraction of the qualitative model from the information in the task instructions, and productive reasoning based on this model.

There are four possible approaches to the task:

1. The participant creates an explicit qualitative model of the task, and continues by creating a mathematical model.
2. The participant creates an explicit qualitative model of the task, but does not create a mathematical model.
3. The participant creates a mathematical model directly.
4. The participant does not model the problem explicitly at all.

The engineering students could approach the task as a differential equations problem, which would be a purely mathematical approach (3). They could also approach it as a control theoretical problem, and explicitly model the causal structure (2, or 1 if they continue by creating a mathematical model). The system dynamics students were expected to apply a system dynamics approach (2, or 1 if they continue by creating a mathematical model). These approaches are described in more detail below.

The system dynamics students were expected to be more likely to create explicit qualitative models than the engineering students.

If participants who create explicit qualitative models outperform participants who do not create qualitative models, it would suggest that teaching such skills might be worthwhile.

A differential equations approach

This is the approach I expected of the engineering students. Population dynamics and predator-prey interactions tend to be among the examples in courses on differential equations (e.g., Boyce & DiPrima, 1997). They are then modelled mathematically directly, with the qualitative model implicit in the mathematical model, as it is implicit in the four sentences describing the rabbits-and-foxes system above.

There are two populations that may vary over time, a population of rabbits $R(t)$ and a population of foxes $F(t)$. The rate of change for each population is the birth rate minus the death rate. The differential equations that describe the fluctuations in the number of members in the animal populations look like this:

$$\frac{dR(t)}{dt} = 2 \cdot R(t) - 0.04 \cdot R(t) \cdot F(t)$$

$$\frac{dF(t)}{dt} = \frac{0.04 \cdot R(t) \cdot F(t)}{180} - 0.2 \cdot F(t)$$

The information in the four sentences can be directly translated into the differential equations. These are the classic Lotka-Volterra equations (Boyce & DiPrima, 1997; Lotka, 1925; Volterra, 1926). The engineering students may recognize them from their course in differential equations.

For this task, the students do not have to solve the equations, they are only required to find the equilibrium solution, and to perform some qualitative reasoning. Calculating the equilibrium solution is the first step in the process of solving differential equations, so this step ought to be familiar to the engineering students.

When a population is in equilibrium, the number of births is equal to the number of deaths, and the rate of change is zero.

If $\frac{dR(t)}{dt} = 0,$ the rabbits can be eliminated from the equation and the number of foxes when the rabbit population is in equilibrium can be found: $F = \frac{2}{0.04} = 50.$ In turn, if $\frac{dF(t)}{dt} = 0,$ the foxes can be eliminated from the equation and the number of rabbits when the fox population is in equilibrium can be found: $R = \frac{0.2 \cdot 180}{0.04} = 900.$

So, when the system of rabbits and foxes is in equilibrium, there will be 50 foxes and 900 rabbits. Now remains the task to bring it there.

Courses on differential equations generally teach the students how to inspect the qualitative behaviour of dynamic systems (e.g., Boyce & Di Prima, 1997). The students learn to draw so-called direction field diagrams. Figure 3 shows a simple direction field diagram of the rabbits and foxes system. If we return to the differential equations describing the rates of changes in the two animal populations, we can see that if the number of foxes is smaller than 50 the rabbit population will increase, and if the foxes are more than 50 the rabbit population will decrease. Conversely, if the rabbits are more than 900 the fox population will increase, and if the rabbits are fewer than 900 the number of foxes will decrease.

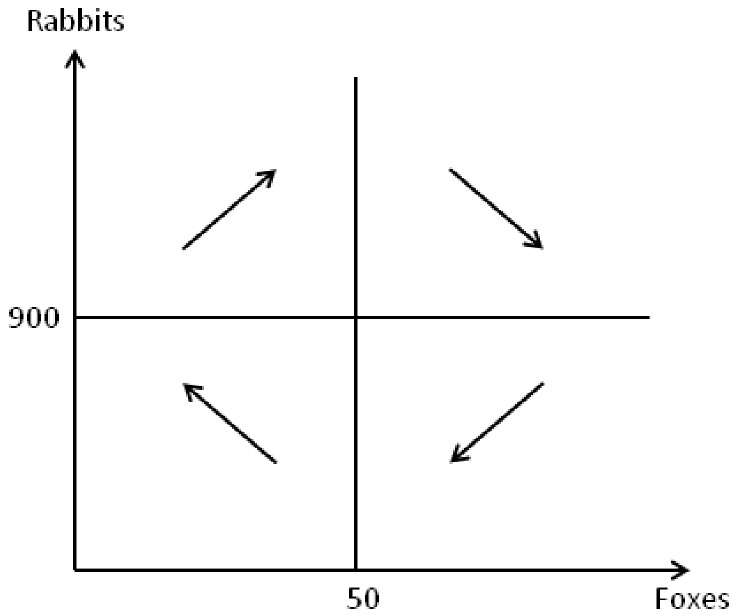

Figure 3. A simple direction field diagram illustrating the qualitative behaviour of the rabbits-and-foxes system.

The students may adjust the fox population to a number larger than 50 if the rabbits are more than 900 and to a number below 50 if the rabbits are fewer than 900, and keep on doing this until the number of rabbits is exactly 900. Then they can set the number of foxes to 50, and the task will be completed.

A control theoretical approach

Control theory is not ideally suited to this task. I include it here because it is how the steering of dynamic systems is approached in engineering programs. It is also interesting to compare it with the system dynamics approach. When introduced to control theory, the students are taught how to model the qualitative structure of systems with block diagrams (Figure 4). The basic block diagram depicts the adjustment of *one* output variable produced by some system. In feedback control, the output is registered by some sensor and compared to the desired output, the reference. The difference (reference - output) is the input to the controller that adjusts the input to the system so that it will bring about the desired adjustment of the output (Franklin, Powell, & Emami-Naeini, 2010).

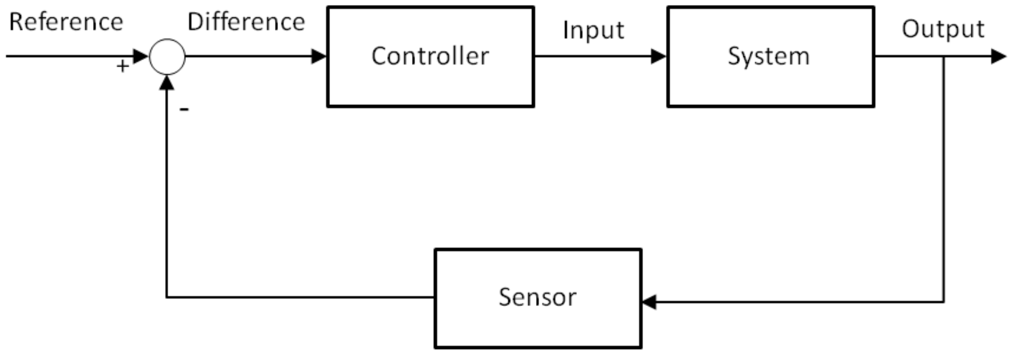

Figure 4. A basic block diagram.

The properties of each of the system's components are described by Laplace transforms. The Laplace transforms of the components can be fused into one expression that describes their combined behaviour, a transfer function that describes the input-output relation of the complete system. The transfer function is used to find the properties required of a controller output (Franklin et al., 2010). This lumping together of the system's components means that control engineering students run the risk of losing sight of the system they are striving to control (Kheir et al., 1996).

A block diagram models a system with one input and one output, while the rabbits and foxes task demands the control of two outputs. The block diagram model can however be used to analyze how the two animal populations may be controlled. It is easiest to first consider one population at a time.

The desired output of the rabbit system is a constant rabbit population. If the equilibrium population that will keep the fox population constant (900) is known, this will be the desired output, the reference. Otherwise the desired output is a constant rabbit population, and hence that the output remains the same. The sensors will be the participants own eyes in this case, and they will control the simulation manually. What the participants is allowed to do is adjust the fox population. This will affect the rabbit population. The rabbits make new rabbits and the foxes eat the rabbits (Figure 5).

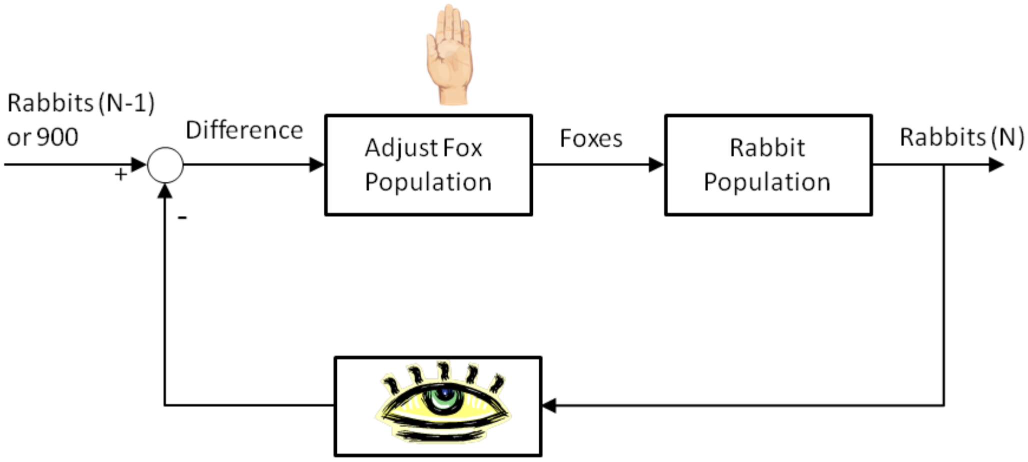

Figure 5. A block diagram of the control of the rabbit population.

The desired output of the fox system is a constant fox population. If the equilibrium population that will keep the rabbit population constant (50) is known, this will be the desired output, the reference. Otherwise the desired output is a constant fox population, and hence that the output remains the same. Still, what the participants can do is to adjust the fox population. The tricky thing is to understand that even if the number of foxes can be set to any number, once the simulation continues it is the number of rabbits that determine the behaviour of the fox population. Foxes die and how many new foxes are born depends on how many rabbits there are for the foxes to eat. So, the adjustment of the fox population will affect the rabbit population, as observed above, and this will, in turn, affect the fox population (Figure 6).

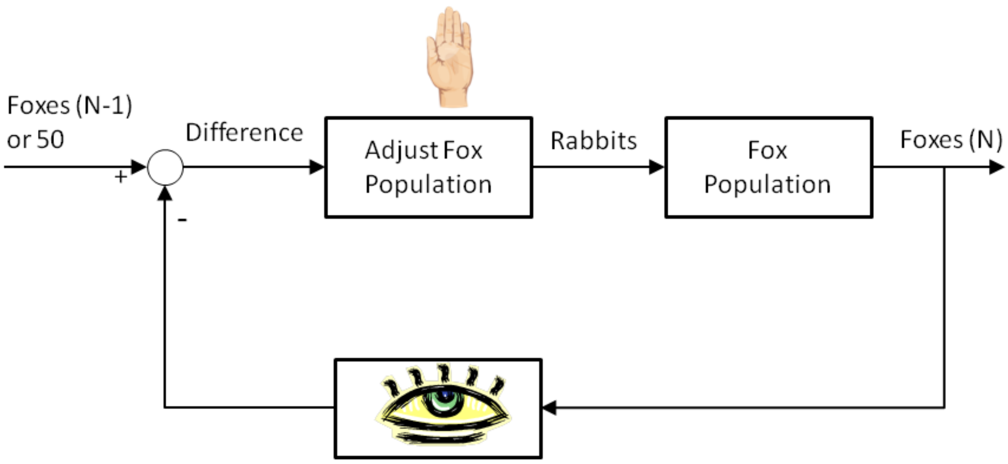

Figure 6. A block diagram of the control of the fox population.

The two block diagrams may be combined as in Figure 7 to illustrate the total system with the two population sub systems, but I would not expect the engineering students to do this. They might, however, use the kind of reasoning illustrated above, and analyze one population system at a time.

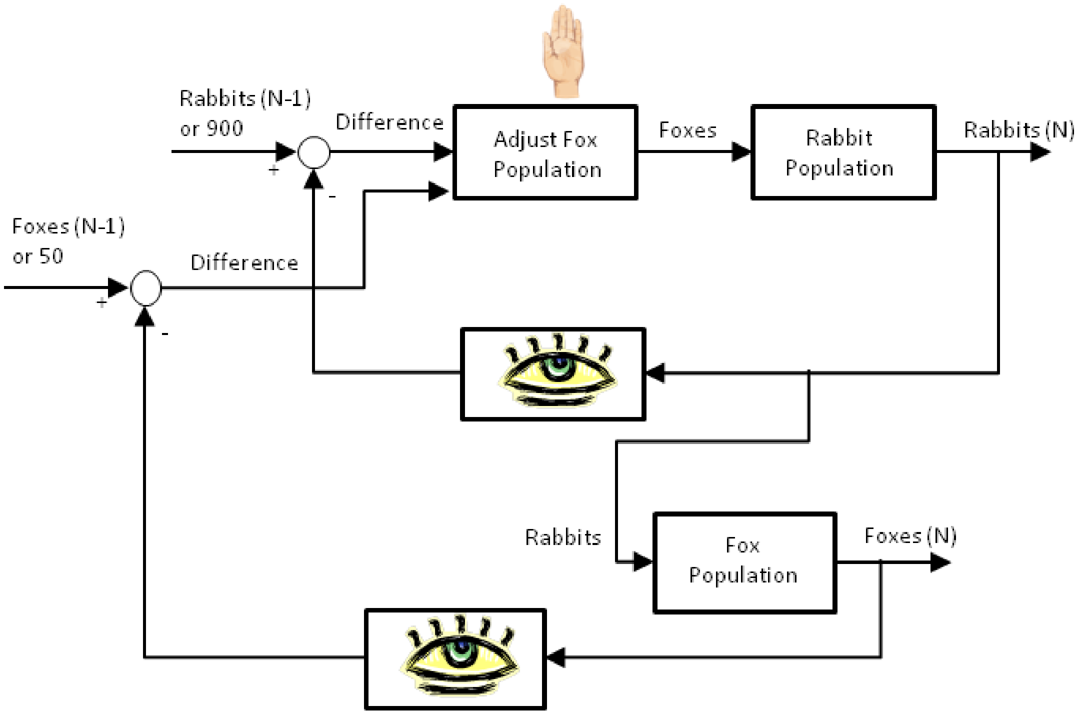

Figure 7. A block diagram of the rabbits-and-foxes task.

A system dynamics approach

The aim of system dynamics is similar to that of control theory, in that it is to control dynamic systems. Control theory focuses primarily on technical systems and automatic controlling devices as the means to control these systems. System dynamics, on the other hand, focuses on how to manipulate variables in the system in order to bring about the desired output. The systems under study are social, economical or ecological rather than technological. The goal is not to construct automatic controllers for these systems, but to find out how to control them "manually", i.e., what decisions to make or policies to implement (e.g., Sterman, 2000).

In system dynamics, the qualitative causal structure of the system is actually modelled. System dynamics modelling rests on a kind of tank metaphor (Forrester, 1961; Sterman, 2000). So-called stocks (or levels) represent resources (the variables, such as water in bathtubs). Flows in and out through pipes attached to the containers (stocks) represent changes in the variables. Valves that regulate the flows in the pipes model the rates of change (the sizes of the flows). Thus, the basic element is a stock with one inflow and one outflow, like a bathtub with water entering through the faucet and leaving though the drain (Figure 8).

Figure 8. The basic building block of system dynamics modelling – a stock with an inflow and an outflow.

The basic stock-flow element is rather similar to a block in the block diagram. In system dynamics the elements representing the different variables are kept separate, however, and are not lumped together as they are in the control theoretical approach. The stock-flow model of the system will therefore depict the qualitative structure of the system, as expressed by this stock-flow, or tank, metaphor. The central variables (the stocks) and their interactions (the flows between them) are all represented in the stock-flow diagram.

System dynamics students also learn to draw causal loop diagrams as an initial step to sort out the causal structure of the system under study, as mentioned earlier. A causal loop diagram of the rabbits and foxes system is presented in Figure 9. The rabbits produce new rabbits, and the newborn rabbits add to the rabbit population. This loop causes the rabbits to increase. The foxes eat the rabbits, and the more rabbits there are to eat the more rabbits will be eaten, and this will cause the rabbit population to decrease. The foxes produce new foxes in proportion to how many rabbits they eat. The more foxes there are to eat the rabbits the more rabbits will be eaten. Finally, the death of foxes causes the fox population to decrease.

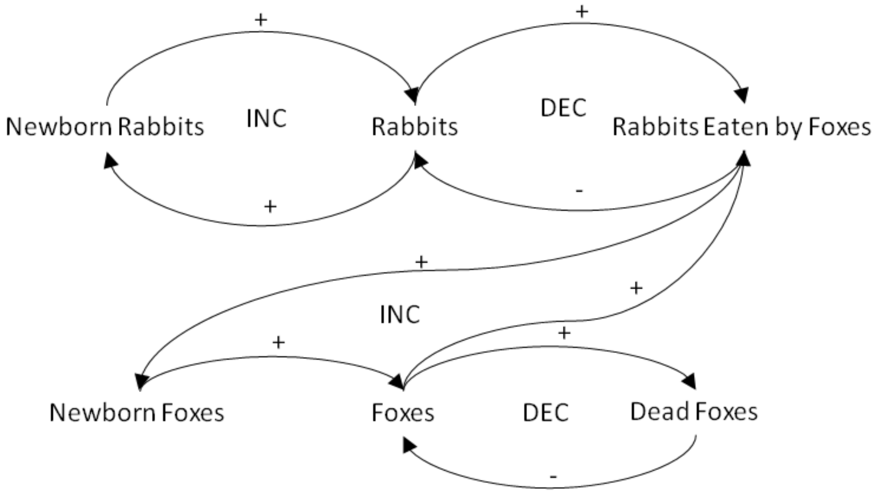

Figure 9. A causal loop diagram of the rabbits-and-foxes system.

This causal structure can also be found in the stock-flow diagram of the rabbits and foxes system. System dynamics students are taught how to identify the qualitative causal structure of the causal loop diagrams in the stock-flow diagrams.

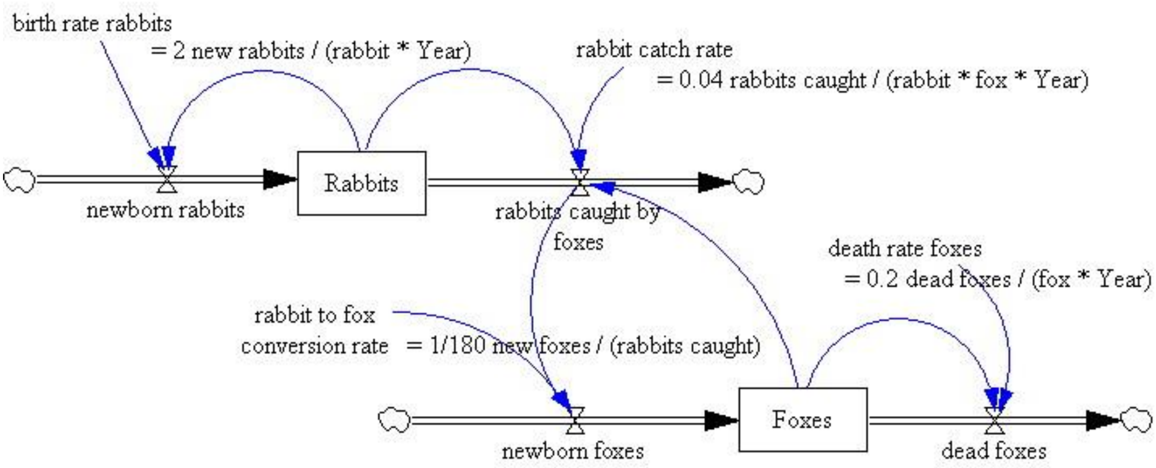

Figure 10. The stock-flow model of the rabbits-and-foxes system.

The central variables, the stocks, are the rabbit population and the fox population. The births and deaths are the inflows and outflows of the two stocks. Arrows are drawn to describe how the stocks and flows are affected by other stocks and flows, for example that the inflow of newborn rabbits depends on the existing number of rabbits. This is what maintains the structure of the causal loop diagram (Figure 10).

The final stock-flow model is a mathematical model of the system insofar that the inflows and outflows of the stocks are described mathematically. These descriptions are connected to the valves regulating the flows in the pipes connected to the container (the stock). Newborn rabbits, for example, will be produced at a rate of two new rabbits per rabbit and year (Figure 10).

The systems studied by system dynamicists may have multiple inputs and multiple outputs. No calculations to find the behaviour of the system are required. Stock-flow diagrams are modelled with computer software, and the software runs simulations of the models. The behaviour of the variables in the simulated system is presented in line graphs, or time graphs, that show how the modelled variables change with time.

System dynamics students are expected to inspect the output and their models and figure out how to adjust variables in the model to bring about the desired output. They may try out their ideas in simulation runs of the model. Their background therefore seems ideally suited to the task presented in this study.

Since inflows and outflows are modelled separately in stock-flow diagrams, this may facilitate the conclusion that in order to maintain constant levels, or rabbit and fox populations, the inflows, or births, should be equal to the outflows, the deaths. I expected the system dynamics students to construct the stock-flow model in Figure 10, and then perform the following calculations:

Newborn rabbits = Rabbits caught by foxes

$$2 \cdot R = 0.04 \cdot R \cdot F \;\rightarrow\; F = \frac{2}{0.04} = 50$$

Newborn foxes = Dead foxes

$$\frac{0.04 \cdot R \cdot F}{180} = 0.2 \cdot F \rightarrow R = \frac{0.2 \cdot 180}{0.04} = 900$$

Now, they have the equilibrium populations, and, as mentioned above, there only remains the rather easy task of bringing the system there. Their understanding of the causal structure should help them with this.

Method

Participants

The engineering students were 22 students at the Royal Institute of Technology in Stockholm, Sweden, seventeen male and five female. Their mean age was 25 years, ranging from 22 to 31 years. They were all in their third year, or later, of their studies for a master's degree in physical or electrical engineering, and all of them had completed at least one course in control theory. These students have experience with dynamic systems from their control theory studies, and they have studied differential equations prior to the control theory courses.

The system dynamics students were 15 students at the University of Bergen in Norway, ten male and five female. Their mean age was 27 years, ranging from 23 to 33 years. Participation in the experiment was part of the course requirements in a course in laboratory experiments and bounded rationality. The course, which is an international course taught in English, is part of a master's degree in system dynamics. A few participants were other system dynamics students who volunteered to participate in the study. All the participants included in the study had taken prior courses in system dynamics modelling, and, hence, had continued their studies in system dynamics beyond the introductory level.

All the participants were rewarded with two cinema tickets.

Task instructions

The participants received the following written instructions: In a lake in the Northern parts of Sweden, there is an island. The island is covered by a mixture of grassland and forest. Initially, there is no animal life on the island. A group of biologists wishes to investigate how the vegetation is affected by grazing animals. Therefore they transport **500 rabbits** to the island and set them free on the island to graze and reproduce. As the biologists do not want the rabbits to become too numerous (rabbits are fertile creatures), **40 foxes** are also transported to the island. All the foxes are equipped with radio transmitters, in order to allow the biologists to locate them and catch them if necessary. Your task is to **establish a balance between the rabbits and the foxes**, i.e., to bring the system to equilibrium. You are allowed to transport foxes to or from the island once every year. Your task is to, eventually, be able keep the rabbit population at a constant level. Your task is **also** to reach a situation where the fox population also remains constant. **The goal** is to achieve a situation where the rabbits and foxes can be left to care for themselves, where both populations remain constant without further intervention. The biologists keep track on the population sizes, and reports them to you. Once every year you may decide on **how many foxes you wish there to be on the island.** Transports will then be arranged according to your wishes. There is always sufficient food for the rabbits, they never stave. If, however, the rabbit population exceeds 5000 rabbits, the island is considered “overrabbited” and the game is over. The game will also be over if the rabbits are extinguished by the foxes. The rabbits only die if they are caught and eaten by the foxes. The rabbits-and-foxes ecology on the island is fully described by the following four sentences:

- A rabbit produces 2 offspring a year.
- A fox eats 4 % of the existing rabbits a year.
- For every 180 rabbits eaten by the foxes, a new fox is born.

- Every year 20 % of the fox population dies.

Task interface

In both the population line graphs (Figure 11), the abscissa represented the years passing in the simulation, running from zero (start) to 30 years (end of trial). In the graph to the left of the screen, the ordinate represented the number of existing rabbits (ranging from 0 to 5000). The graph to the right represented the number of existing foxes (ranging from 0 to 150). The actual population sizes were presented numerically in their respective graphs. Initial population sizes were 500 rabbits and 40 foxes. Population changes were calculated as:

$R_{t+1} = R_t + \Delta R_t$; where $\Delta R_t = (2 * R_t – 0.04 * R_t * F_t) * \Delta t$ for the rabbits, R, and

$F_{t+1} = F_t + \Delta F_t$; where $\Delta F_t = ((0.04 * R_t * F_t) / 180 – 0.20 * F_t) * \Delta t$ for the foxes, F.

The selected time-step, Δt, was one month (1 year / 12). This may be rough and inelegant, but quite sufficient for the purpose of this study. The final results were rounded off. There were no fractions of rabbits or foxes reported.

Close to the fox graph, there was an editing box for changing the actual number of foxes to the number desired. Clicking the step-button close to the editing box made a year pass in the simulation. The years passed month by month, at a rate of about two months per second. The participant had to watch twelve months pass, inviting reflection, before he or she was allowed to make another entry. The number of rabbits born and the number of rabbits eaten by foxes during the year passing, or just passed, were presented separately below the rabbit graph. Similarly, the numbers of foxes born and dying during the preceding or passing year were presented below the fox graph (Figure 11).

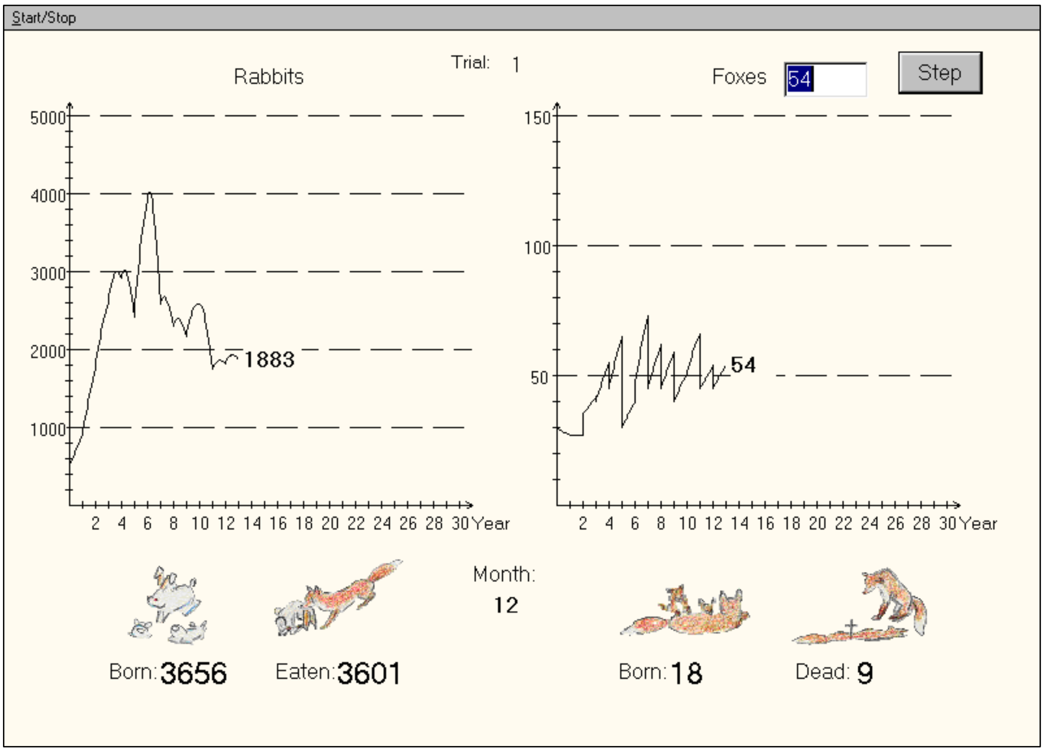

Figure 11. The interface to the rabbits-and-foxes task.

Equilibrium was reached when the fox population remained constant at 50. A rabbit population *close to* 900 is necessary to achieve this. It does not have to be *exactly* 900. That would have been really difficult for the participants to achieve. When the rabbit population was approximately 900 and the fox population remained constant at 50, the rabbit population steadily approached and eventually reached 900, where it remained. (This was a feature included in the programming of the simulation).

Procedure

In the control engineering group, the task was group administered in four sessions with three to eight participants in each session. In the system dynamics group, the task was group administered to all the participants in one session.

All the participants were equipped with writing material, paper and pencil, if they wished to make notes of any kind. These notes were collected afterwards by the experimenter.

The participants were introduced to the interface and received the task instructions in writing, which they were allowed to keep during the whole session. There was no time pressure. The participants decided themselves when to let a new year pass in the simulation. There was no limit on the number of trials. The participants were allowed to continue until they had learned how to accomplish the task. After 45 minutes, they were allowed to decide whether they wanted to give up or to continue. If they decided to go on, they could continue for another 15 minutes. After that they had to stop.

Throughout the experiment, the experimenter remained in the room to answer direct questions only, to decide when the participants had reached the goal. The task was considered completed when the participants had figured out how to reach equilibrium and were able to repeat the performance on request.

In the control engineering group, the participants were asked, after they had completed the test session, to describe, in writing, how they had approached the task.

Analysis

What external models, qualitative and/or mathematical, the participants produced was evident from their notes. In addition to solving the task by calculation, it was possible to solve it by qualitative reasoning based on either an externally produced qualitative model or an internally produced mental model. I had to be able to differentiate the participants who managed this from those who just played with various inputs and just happened to make a lucky guess.

All the inputs the participants made were logged, together with the results from these inputs. A participant was considered to express a qualitative understanding of the system if the following could be observed: The participant did first control the rabbit population by consistently increase the fox population if the rabbit population was increasing, and reduce the fox population when the rabbit population was decreasing. The participant did then continue to search for the correct size of the rabbit population for keeping the fox population constant, by consistently allow the rabbit population to grow if the fox population was decreasing and to reduce the rabbit population if the fox population was growing. It is fairly easy to differentiate such a pattern of inputs from a pattern where the request for foxes is unrelated to the size of the rabbit population, or from one where the participant learns how to control the rabbit population but fails to figure out the next step.

Results

The engineering students

Table 1 summarizes the approaches applied to the task be the engineering students.

Table 1. Approaches Applied by the Engineering Students

Construction of qualitative model (block diagram)	**Mathematical approach (Solution of equilibrium equations)**				**Sum**
	Correct	**Not fully successful attempt**	**Other calculations**	**No calculations made**	
Correct	0	0	0	0	0
Incomplete or incorrect	0	0	0	1	1
None	2	2 (fox ok)	12	5	21
Sum	**2**	**2**	**12**	**6**	**22**

Only one engineering student tried to model the causal structure explicitly. He tried to model the rabbit population with a block diagram, but did not get very far with that, and he did not solve that task.

Sixteen of the twenty-two engineering students approached the task mathematically. Four of them understood that they should search for a solution where births equal deaths in *both* populations. Of those four, only two managed to calculate the numbers of rabbits *and* foxes in equilibrium (and both solved the task), and the remaining two managed to calculate the number of foxes in equilibrium. Of the other twelve who approached the task mathematically, five wrote mathematical expressions for both the rabbit population and the fox population, although incorrect ones.

Six engineering students focused only on balancing births and deaths in the rabbit population, and one on them managed to calculate the number of foxes that keeps the rabbit population constant.

Six of the engineering students performed no calculations, and if they made any notes at all they only recorded the output from the simulation.

None of the engineering students demonstrated any qualitative analysis of the rabbit and foxes system's behaviour, as illustrated by Figure 3, and their inputs to the simulation did not reflect such thinking. One of the participants who got the equations wrong, and who failed at the task, did, however, notice the trend switches occurring for the rabbits when the fox population passes 50 and for the foxes when the rabbits are around 1000, and concluded that the equilibrium population were close to these numbers.

The system dynamics students

Table 2 summarizes the approaches applied to the task be the engineering students.

Table 2. Approaches Applied by the System Dynamics Students

Construction of qualitative model (stock-flow model)	Mathematical approach (Solution of equilibrium equations)			Sum
	Correct	**Not fully successful attempt**	**No calculations made**	
Correct	4	1 (fox ok) + 1	1	7
Incomplete or incorrect	0	1	4	5
None	1	0	2	3
Sum	**5**	**3**	**7**	**15**

Twelve of the fifteen participating system dynamics students tried to make models of the system, i.e., they made stock-flow diagrams of the rabbits-and-foxes system. Seven of them created the correct stock-flow model (Figure 10). Four of them also calculated the equilibrium populations, and three of them solved the task. It is surprising that one participant who both constructed a correct stock-and-flow diagram *and* solved the equilibrium equations, still failed at the task. It is possible that the participant made these notes after the time allowed for the task had elapsed, but before the notes were collected. He may also have made the notes while discussing the solution with a successful friend, forgetting that the notes were to be collected afterwards. Since the task was group administered to all the participants in one single sitting, the experimental control was not perfect. It may, however, also be the case that the participant actually fully grasped the system structure, and equilibrium calculations, without being able to steer the system to the goal, although it seems unlikely. One participant solved the equilibrium equations directly without constructing a stock-flow diagram, and she also solved the task.

Of the remaining three who constructed a correct stock-flow diagram, two made unsuccessful attempts at solving the equilibrium equations. One got the equations right, but was only able to calculate the fox population in equilibrium. The other one understood the principle of the equilibrium equations but failed to get them right. They were both very close. The last of the three, who finally made a correct stock-flow diagram after several attempts, did not try to calculate the equilibrium populations.

Of the seven participants who either made incomplete and/or unsuccessful attempts at modelling or who did not even try to model the system, only one tried to calculate the equilibrium populations. He got pretty far in both his modelling and his calculations, but did not quite make it.

All of the eight system dynamics students who performed calculations understood that they should search for a solution where births equal deaths in *both* populations. None of them represented the problem mathematically in any other way. This is significantly more than the four engineering students, out of 22, who also understood this ($\chi^2 = 5.03$, $p < .05$).

None of the system dynamics students made demonstrated any reasoning about the rabbit and foxes system’s qualitative behaviour, as illustrated by Figure 9. They made no mention of the causal loop structure in their stock-flow diagram, and their inputs to the simulation did not reflect such reasoning.

Achieving equilibrium

As mentioned before, the key to solving the task is to understand that even if the number of foxes can be set to any number, once the simulation continues it is the number of rabbits that determine the behaviour of the fox population. Foxes die and how many new foxes are born depends on how many rabbits there are for the foxes to eat. The rabbit population has to be large enough for the foxes to eat enough rabbits to give birth enough fox puppies to compensate for the foxes that die, but no larger. I only considered the task solved if the participants demonstrated that they understood this. This means that only two of the 22 engineering students (9 %) and four of the15 system dynamics students (27 %) solved the task. Three of the four successful system dynamics students made correct qualitative models, or stock-flow diagrams, which they quantified.

One problem with the chosen task is that since the participants are allowed numerous trials, they may sooner or later chance upon the solution. This is somewhat controlled for by requiring them to repeat the feat. Their prior success has then, however, revealed what the equilibrium populations are, rendering the task more or less solved. Nine of the remaining 20 engineering students (45 %) and four of the 11 remaining system dynamics students (36 %) solved the task by playing with the simulation. If a participant chances upon the solution more or less immediately, this could mean that he or she never even try to approach the task analytically. This was, however, never the case. The participants spent quite a lot of time in the beginning of the session thinking and performing calculations. If and when this failed to produce the solution, they gave up and started to simply play with the simulation.

Discussion

Of the 37 students who participated in this study, 13 participants (12 system dynamics students and one engineering student), approached the task by trying to make an explicit model of the causal structure. Seven of them (all of them system dynamics students) made correct models. An interesting result is that they all modelled the task using the representations they had been taught. The system dynamic students made stock-flow diagrams and the engineering student made a block diagram. In previous studies with the rabbits-and-foxes task, where the participants were university students with no training in modelling, nobody has ever tried to sketch the qualitative structure of the problem (Jensen, 2005; Jensen & Brehmer, 2003). It seems not to be something that people spontaneously do, but rather something they need to be taught how to do.

The only thing the participants used their models for was to support calculation. Nobody solved the task by qualitative reasoning, with or without the support of an externally produced qualitative model.

Besides, the major benefit the participants who made explicit models of the causal structure had from their effort was that it helped them understand the problem. They were significantly more likely to frame the problem correctly than those who did not make such models. They were, however, not significantly more likely to solve the task.

The results suggest that it is not sufficient to be able to *make* a model of the qualitative causal structure of the system. It is necessary to be able to *use* the model to support reasoning as well.

External representations, such as models, may function as reminders of the constraints pertinent to a problem situation (Scaife and Rogers 1996; Zhang 1997). The system dynamics students' familiarity with stock-flow modelling helped them state the problem. They were significantly more likely to identify the problem as finding a way to make births equal deaths in both populations than the engineering students. All of the eight system dynamics students who performed calculations understood that they should search for a solution where births equal deaths in both populations, while this was true of only four of the engineering students.

Qualitative reasoning

There were no signs of qualitative reasoning in the notes or control behaviour of either the engineering students or the system dynamics students. To the extent that the participants considered the causal structure of the system, they did this in search of a mathematical solution. The system dynamics students who actually modelled the causal structure of the system did not use this model to explain and predict the behaviour of the simulation.

Qualitative reasoning does more than inform quantification, however. Qualitative reasoning is also required to figure out how to affect a system in order to bring about desired effects. According to Bissel and Dillon (2000), teachers of mathematics, engineering and technology tend to emphasize the *creation* of models, and pay less attention to model *use*.

System dynamics students are expected to inspect the output from their models and figure out how to adjust variables in the model to bring about the desired output (Forrester, 1961; Sterman, 2000). As mentioned earlier, they try out their ideas in simulation runs of the model. With a simulation, it is possible to simply play with the system and achieve the desired state by trial-and-error. Unless the students are tested thoroughly on their understanding of the system, they may complete their assignments without really understanding the systems they have studied. Kheir et al. (1996) express concern that students who use computer-aided control engineering (CASE) software risk losing contact with and forget about the properties of actual real-life control systems. With CASE software control engineering students can model their systems with the software and the software performs calculations and runs simulations, much as system dynamics software does.

It would be interesting to know how system dynamics students would fare at the task, if the system description was purely qualitative. If the written description only described the causal relations, without revealing the actual parameter values, what would system dynamics students do? Would they be able to make productive use of the qualitative stock-flow model, if this were the only system dynamics approach possible? Or, would they make the models and then fail to figure out how the models could help actually them, or what?

Bobrow (1985) argues the need for means to model the qualitative causal structure of systems, in order to enable an understanding the causal processes which underlie the system's behaviour. In the words of Bissell & Dillon (2000), part of being an engineer is to be able to tell stories about, to give causal account of, what is going on in technical systems.

Meta-representational competence

Meta-representational competence (MRC) is the capability to construct and use external representations (such as models). One component of MRC is the ability to invent and design new representations (diSessa & Sherin, 2000). The engineering students did not demonstrate such ability, and the system dynamics students did not have to. We do not know how they would perform if they were presented with a problem that could not be represented in a stock-flow diagram.

Another component of MRC is the understanding of the function of representations (diSessa & Sherin, 2000). What are representations for? How can they be used? It appears as if neither the system dynamics students nor the engineering students understood how to make the best use of models. Schools, in general, offer their pupils little training in building and using models, even in science classes (Greca &Moreira, 2002). The pupils are taught ready-made models as facts, but have a rather weak grasp of what a model really is and how it can be used (Schwartz & White, 2005). Alarmingly, this appears to be true of even a fair number of science teachers (Van Driel & Verloop, 1999).

Conclusion

The results from this study suggest that modelling the system structure helped the system dynamic students state the problem, and what solution to search for. Creating the explicit model was thus beneficial. It was only used to as basis for further mathematical treatment of the problem, however. It seemed never to support qualitative reasoning to figure out how to bring about the desired state. It appears that in addition to learning how to model system structure, students need training in how to *use* these models to understand how the system works. Otherwise they will be hard put to explain a suggested solution to anybody, themselves included. Students would probably benefit from being assigned tasks that truly assess their understanding of the workings of the systems under study. This could be done even within the more traditional teaching approaches, and would therefore not be too difficult to implement. It is likely to make the students both better problem solvers and better communicators, and, consequently, better engineers according to the ABET criteria (ABET, 2011).

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