Learning Domain Knowledge and Systems Thinking using Qualitative Representations in Secondary Education (grade 8-9)

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Learning Domain Knowledge and Systems Thinking using Qualitative Representations in Secondary Education (grade 8-9)

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Abstract

This contribution presents three lesson activities for lower secondary education that were developed to teach system thinking in concert with subject matter. The pedagogical approach is described, leading to a practical design philosophy for lesson activities using qualitative representations. These representations allow for capturing basic qualitative notions, such as the entities that constitute the system, their changeable features referred to as quantities, and cause-effect relations that propagate changes between these quantities.

1 Introduction

We investigate how qualitative representations can be used as a effective method to develop secondary students' systems thinking skills. Systems thinking is often not given explicit attention secondary school, especially in the lower grades. In this paper, we describe a pedagogical approach for systems thinking in grades 8-9 that is directly linked to the current curriculum in the fields of biology, physics, geography and economics. This way, systems thinking learning goals can be added to the curriculum without extra time investment for the learners. Furthermore, this approach allows learners to encounter systems thinking in many different contexts, hopefully aiding them in better transferring these skills between subjects, something that is notoriously hard to do [Genter *et al*., 2003; Hajian, 2019].

The lesson activities currently developed in the project Denker (https://denker.nu) focus on various topics. They are created as a collaboration between educational partners (teachers, teacher educators and researchers). The main teaching mechanism for these lesson activities is to have students learn by creating qualitative representations of various systems.

The Dynalearn software (https://www.dynalearn.nl) is used for this purpose. Dynalearn offers multiple levels of complexity [Bredeweg *et al*., 2013]; at each level new features to describe system behavior are available. In this paper, we focus on three lesson activities that were developed at level 2, aimed at secondary education, grade 8-9.

Below we discuss the pedagogical approach we developed for these three lessons, aimed at learning domain knowledge and systems thinking simultaneously. We give detailed descriptions of the lesson activities, explaining our pedagogical choices in order to distill a design philosophy for deploying qualitative reasoning in secondary education.

2 Systems Thinking Goals and the Model

At level 2, the main system thinking goal is to have learners acquire an overall understanding of the basic cause-effect relationships governing the behavior of a system [Bredeweg *et al*., 2013]. Notice that, the system thinking goals are in principle the same for each lesson developed within a given level.

A qualitative representation at level 2 in Dynalearn consists of *entities*, which can be linked by their structural relationship (*configurations*), and *quantities*, which are always linked to an entity and represent a measurable quality of that entity (Figure 1). Quantities can be linked by *causal dependencies*, which are either positive (meaning that the change in the source causes a change in the target in the same direction), or negative (a change in the source causes a change in the target in the opposite direction). Each quantity can also be assigned a *direction of change* (decrease, steady or increase).

Once a qualitative representation is built, it can be used to simulate the system. For this, *initial values* need to be assigned to some quantities (i.e., the direction of change at the start). The software then calculates the tendency (direction of change) for all quantities using the known information and the represented dependencies. Next, the user can then click through the different *states* that the system can be in and view the tendencies of the quantities in each state. Not all initial conditions will lead to a unique final state. Some will lead to *ambiguity*, in which case the software shows all possible outcome states. In the case of an *inconsistency*, no outcome states will be generated, because no valid behaviors exist.

In each lesson activity, learners are guided by the workbook to build their model. At various points during the construction they are instructed to run a simulation. This helps learners to understand the model and identify possible mistakes. Thus, building the model can be viewed as a cyclic process of reflection, model building, simulating and reflecting again, etc.

3 Method – Working with teachers

The topics of the lesson activities presented here are *poverty* and *greenhouse gasses* (both developed as part of an interdisciplinary course on globalization, poverty and environment), and *ecology* in a fen lake (developed as part of the biology curriculum).

At the beginning of the school year participating teachers were offered a course on qualitative reasoning using DynaLearn (focusing on level 2). After this course, they were asked to identify topics from the curriculum that leant themselves to this approach. In each case, a topic was chosen to develop into a lesson activity. This was done collaboratively between the teachers and researchers. Over the course of a number of sessions a representation of the subject matter learning goals was developed in DynaLearn, and an accompanying workbook was created. When both were finished to the satisfaction of both teachers and researchers, the lesson activity was adopted as part of the lesson plan by the teachers.

In summary, a lesson activity consists of a workbook and a representation, which takes about 2-3 hours for learners to complete. The workbook provides background information, leads the learners through building and using the representation and contains exercises designed to make the learners reflect on the topic itself as well as the representation. It allows the learners to work independently and at their own pace.

During the lesson activities reported here, a teacher and one of the researchers were available to assist learners. They would do so in the way that is usual in the classroom; providing help when asked for but also when they deemed it helpful to the learning process.

4 Poverty

This lesson was developed for an interdisciplinary course on globalization, poverty and environment. It investigates the relationship between education, health and poverty, both on an individual and on a national level. It fits well into the economics curriculum of grade 8-9.

4.1 Subject Matter Learning Goals

As mentioned above, the main goal of this lesson is to understand the relation between health, education and poverty. Because there is a mutual influence between these quantities, there is a downward spiral effect were being poor has a negative influence on health and education, and having poor health or education has a negative influence on income, leading back to poverty. On the other hand, if this spiral can be turned around it can have a good influence, where good health and education reduce poverty, which then increases health and education further.

4.2 Poverty – The Representation

The final representation for this lesson activity is shown in Figure 1. Most of the key quantities are connected to the entity *people*. In this representation we have chosen for *health* and *education level* as the main drivers of *income*, which in turn determines *poverty*. To get at the negative (or positive) spiral mentioned above we introduced the quantity *poverty at birth*, which influences both *health* and *education level*.

Notice that, in DynaLearn, it is possible to create reinforcing feedback loops at level 2 [Bredeweg et al., 2021], which could have accomplished the same thing by adding negative influences from *poverty* to *health* and *education level*. However, in this case, it was felt more illustrative of the situation to explicitly include *poverty at birth*, both because it makes it clear that just being born into poverty makes it harder to leave it, and because using a feedback loop would introduce too much complexity for this lesson.

The other entity in the model is *country*. Its relation to people is that they *live in* it. *Country* has only one quantity, which is *GDP* (Gross Domestic Product). It is influenced by the *investments* made by people, which in turn is influenced by their *income.* This is of course an oversimplification, but it affords good insight into the main workings of the system. The representation allows us to show, for instance, that if more people in a country are born into poverty, through decreasing health and education level, this will have a negative effect on their income and investments, which will decrease the GDP of the country.

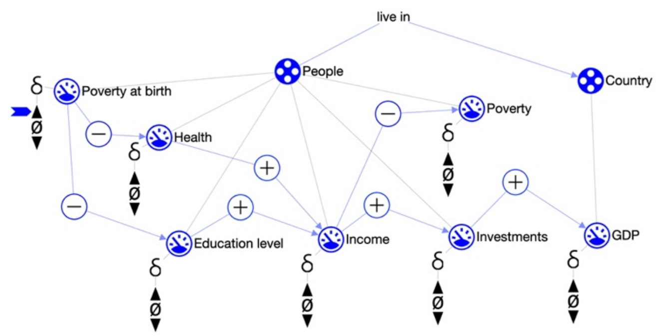

Figure 1. Poverty – Complete representation. *Entities* are *People* and *Country*, whose *relationship* is *live in*. There are seven *quantities*, such as *health* and *income*. They are related by positive (+) and negative (-) *causal* relationships. The direction of change is denoted by the δ. In this case, it is only specified for *poverty at birth*, which is set to increasing.

4.3 Pedagogical Approach

The workbook starts with general information on poverty as part of the Sustainable Development Goals of the UN and a link to a short video about the causes of poverty. Learners are then asked to name causes of poverty, and explain the mechanism by which they cause it. In this way, they are forced to think about causal relationships before starting to build the representation.

Next, there is an introduction to the DynaLearn software, using a short explanation of the main functionality in text and links to short instruction videos. Learners are instructed to create the entity *people*, and subsequently add three quantities to it: *poverty*, *education level*, and *income*. They are then asked to add two causal relationships. Because these quantities all influence one another, the workbook tells the learners in general terms which relationships we are looking for, without stating whether they should be positive or negative.

Another possible approach would be to allow learners to create their own model, with much less direction from the workbook. We have chosen to steer all students toward the same model because it provides focus in the learning process. Moreover, it would otherwise be impossible to use a step by step workbook since the learner-made representations would diverge too much. While it is possible, and even desirable, to have lessons in which the learners are given more freedom, it is more demanding of both students and teachers, so we aim to implement this approach later in the project.

Note that the meaning of positive and negative relationships in the context of qualitative reasoning is not precisely the same as in daily live. For instance, while in daily live one might say that education has a positive influence on poverty (meaning it reduces it, something we see as a positive effect), in a formal representation the relationship is negative (meaning that if education level changes, poverty changes in the opposite direction). In our experience, this can be confusing for learners when they encounter it for the first time. One of the advantages of using an automated system for qualitative reasoning is that students can input the relations the way they think they should be, and then check the results of the simulation. When those do not correspond to their understanding of the system it helps them identify and correct their mistakes. Therefore, to help learners reason with positive and negative influences, they are asked throughout the lesson to complete sentences like these: "IF education *increases*, THEN poverty *increases/decreases*. So, these two quantities have a *positive/negative* relationship." This helps students reason about causal relationships, and also to connect their representation to their understanding of the system itself.

Next, *health* is added to the model, together with its influence on *poverty*, which the learners once again determine on their own. This leads to the model shown in Figure 2.

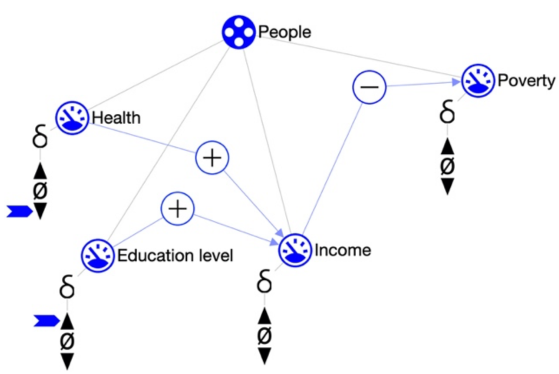

Figure 2. Poverty – First part of the assignment. The specified initial situation (decreasing health and increasing education level) will lead to an ambiguity in the system.

One thing to note is that a significant group of students struggles at first with the distinction between entities and quantities. This categorization is important in systems thinking because learners should be able to separate *things*, which remain the same thing all the time, and their *properties*, which change and in which we are interested. One of the features of the level 2 representation in DynaLearn is that causal relationships can only be added between quantities, not entities, so whenever learners confuse those they will not be able to add causal relationships in the way they would want. In this way, the strictness of the representation serves as feedback for the learners. Our experience is that by the end of a lesson activity, learners are able to make these distinctions.

Part of reason why health was added to the model is that we now have two influences on income, which allows us to introduce ambiguity. To experience this, we ask the learners to specify the initial situation in which health *decreases* and education level *increases* and next to run the simulation. As a result, they will see three possible states in the software (Figure 3). Each of them can be clicked to show how the system reacts to the specified initial situation.

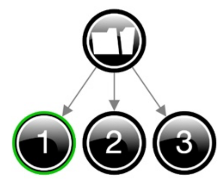

Figure 3. Poverty – State-graph showing ambiguity. Each state can be clicked to show the status of the representation. Here, state 1 is selected. The details of state 1 are shown in Figure 4.

Learners are asked to do so, and explain what happens in each of the three cases. In Figure 4 the outcome of state 1 is shown, in which the influence of decreasing health has a stronger effect than the influence of increasing education level. In state 2 they are balanced, in state 3 it's the opposite. Often, when asked about such systems, students will predict that the effected quantity (here *income*) will remain constant, because the two influences cancel out. They fail to consider the fact that either influence might be stronger than the others. By having learners discover this ambiguity, they may gain this understanding.

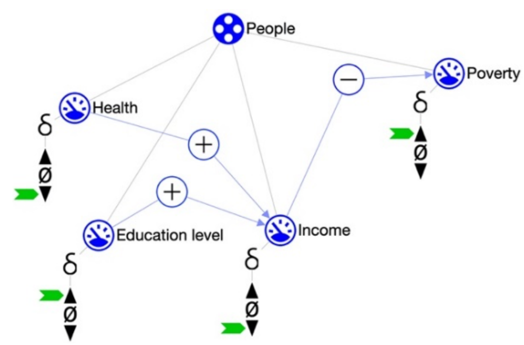

Figure 4. Poverty – Ambiguity (showing state 1 from Figure 3).

The next part of the lesson is aimed at understanding why the poor (often) stay poor. This is accomplished in the model by adding one more quantity to *people*, which is *poverty at birth*. Once again, learners are asked to add the causal relationships between this new quantity and *health* and *education level* and explain whether they are positive or negative. By repeating this question in many different situations, even for those who at first do not understand precisely what is meant by positive and negative causal relationships, it should help them to gain this understanding.

We also want learners to be able to put certain ideas they have about a system into the model. Therefore, we tell them to use the model to show why the poor stay poor, and ask them which initial situation should be specified to do so. The correct answer is of course that *poverty at birth* should be set to increase. We encourage students to experiment. They can set their initial situation and run the simulation; if that simulation does not end up with poverty going up, they know something was wrong with their hypothesis and they can try to figure out why.

The lesson is concluded by adding the entity *country* and quantities *GDP* and *investments*. On a subject matter level, this helps learners understand the relationship between (poverty of) individuals and (poverty of) a country. On a systems thinking level, it introduces a second entity, thereby introducing the idea that quantities really are connected to an entity, and also that entities are structurally related to each other (in this case, people *live in* a country).

5 Greenhouse Gasses

This lesson was also developed for the interdisciplinary course on globalization, poverty and environment, but would fit into the regular geography or biology curriculum as well. It investigates causes and effects of global warming.

5.1 Subject Matter Learning Goals

The main subject matter learning goal of this lesson is to understand the mechanism by which global warming is affecting the planet, both in terms of *cause* (increased CO2 causes rise in temperature) and *effect* (acidification of the ocean and loss of biodiversity are effects of rising temperatures).

The lesson is also meant to help learners understand how rising temperatures lead to lower biodiversity, for instance by increasing acidity of the ocean, which decreases the number of shellfish, which in turn means other fish will have a harder time finding enough to eat. To understand this, a food chain for oceanic life is introduced.

Finally, the effect of incoming solar radiation is investigated; could a decrease in that help mitigate global warming? The conclusion is reached that it could, but that in practice the effect is negligible compared to the increase in temperature due to greenhouse gasses.

5.2 Greenhouse Gasses – The Representation

This representation has four entities (Figure 5). The main one is *planet earth*, two parts of which are also highlighted: the *oceans* and the *atmosphere*. The atmosphere contains *greenhouse gases*. Both planet earth and the atmosphere have *temperature* as a quantity. The main mechanism of global warming is represented by the positive influence of the *amount* of greenhouse gases on temperature of the atmosphere.

To show some of the adverse effects of global warming, we introduced the quantity *biodiversity* to planet earth. There are two ways in which biodiversity is affected. There is a direct negative effect of temperature of the atmosphere on biodiversity, because species cannot adopt fast enough to the change in temperature. There is also an indirect negative effect of the amount of greenhouse gases on biodiversity, going through the quantity *acidification* of the oceans, because the food chain in the ocean is affected by higher temperatures.

Finally, to help us investigate the influence of the sun, there is a positive effect of *incoming solar radiation* on the temperature of planet earth.

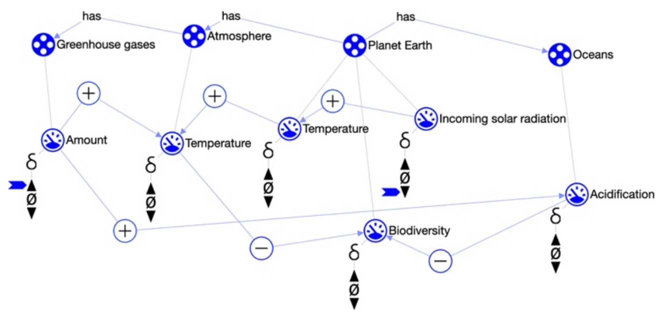

Figure 5. Greenhouse gasses – Complete representation.

Note that this representation is built to help us understand the current situation of global warming. Strictly speaking, the negative influence of temperature on biodiversity implies that decreasing temperatures would increase biodiversity. While this is true currently, it is certainly not true for a large decrease in temperature; biodiversity would go down in an ice-age, for example. We chose to use this model because it would take a much more complicated model to incorporate such effects. That is neither necessary nor desirable; later, in a higher grade it might be worthwhile to come back to this.

5.3 Pedagogical Approach

This lesson starts with a template (Figure 6). The main reason to use a template is to save time and help learners cope with the complexity of the representation. Building this template from scratch would take around 30 minutes of lesson time, which can now be used to work on more advanced learning goals.

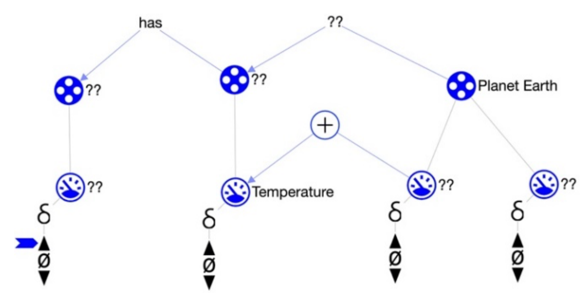

Figure 6. Greenhouse gasses – The starting template for the assignment. Students open the template in the software and build upon it during the lesson.

The first part of the lesson is aimed at understanding the cause of global warming. Learners are given a list of missing names and asked to add them to the template. They are also told two positive relations are missing, and asked to add those as well, using their knowledge of the mechanism behind global warming.

The next step is to check whether the representation works by comparing a simulation with the learners' understanding of the system. The goal is to have learners understand the relation between their representation and reality, and to understand how simulation can help them understand and possibly improve their representation. For this reason, students are first asked to predict what will happen when greenhouse gases increase, decrease, or stay the same, all while keeping incoming solar radiation constant. Next, they use the representation to check their predictions. Figure 7 shows the current representation, with initial situation set to an increasing amount of greenhouse gasses and constant incoming solar radiation. Students are asked to explain any differences between their predication and the simulation, forcing them to reflect on the connection between the model and reality. The result of the simulation is shown in Figure 8.

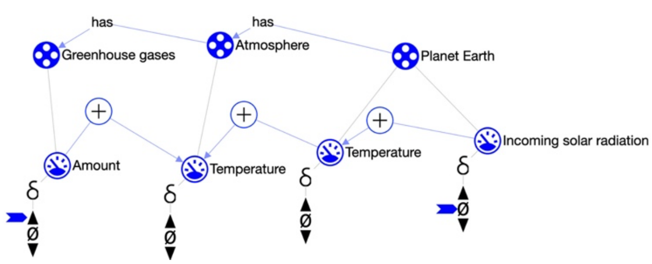

Figure 7. Greenhouse gasses – First part of the assignment. Initial situation is set to constant incoming solar radiation and increasing amount of greenhouse gasses.

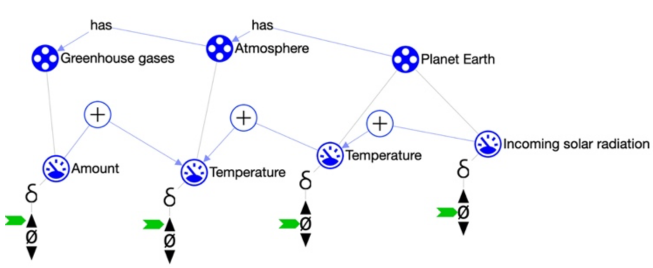

Figure 8. Greenhouse gasses – The result of the simulation set up in Figure 7. Temperature of the atmosphere increases as a result of the initial situation.

The second part of the lesson is aimed at understanding some of the effects of global warming. Learners are given some background information on the food web of oceanic creatures and the influence of rising temperatures on biodiversity. They add biodiversity to the model, connecting it to existing quantities. Throughout the lesson, they are asked to interpret the meaning of these relationships by correcting sentences like: "If the temperature on earth *increases/decreases* rapidly, then biodiversity *increases/decreases* in the short term."

To help them understand that one quantity can be affected in multiple ways, they also add acidification of the oceans to the representation. They are asked to simulate the representation again and compare the result to what happens when they simulate after removing the direct relation between temperature of the atmosphere and biodiversity. The result should be the same since the influence of greenhouse gasses on biodiversity through either route is the same.

Finally, we confront the learners with ambiguity, by asking them to simulate the model with initial settings that work against each other; by *increasing* the amount of greenhouse gasses and *decreasing* the incoming solar radiation. In this case, there are five possible outcome states (Figure 9), because both temperature of the atmosphere and biodiversity can have multiple outcomes. To help learners understand how ambiguity emerges in such a case we ask them to connect each of the five states to an explanation of what is happening in the system.

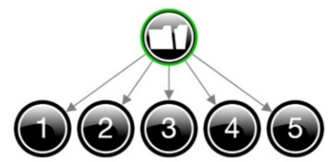

Figure 9. Green gasses – State-graph showing ambiguity.

Of course, it is well known that while a decrease in incoming solar radiation does decrease global warming, its effect in practice will be negligible compared to the increase in greenhouse gasses caused by humans. This is important subject matter knowledge that cannot be learned from the representation because of the ambiguity, so it is explained using a graph of earth temperature and incoming solar radiation from the last 140 years.

6 Fen Lake

This lesson was developed together with biology teachers. The lesson is based on a newspaper article about a Dutch fen lake where a previously collapsed ecosystem was restored by removing a certain type of fish from the lake. The ecosystem previously collapsed at the end of a complex chain of events set of by an excess of fertilizer drifting in from nearby farms. Removing bream form the new ecosystem set off another complex chain of events that was able to reverse the process.

6.1 Subject Matter Learning Goals

This lesson has several main subject matter learning goals. The first is to understand what an ecosystem is and how they are governed by a complex web of cause and effect relationships. The second is to understand how even small changes in an ecosystem can have far reaching consequences. The third is to understand the possibility of two possible ecosystems for a fen lake.

6.2 Fen Lake – The Representation

The representation for the fen lake (Figure 10) is the most complex of the three representations described in this paper.

The main entity is the *fen lake* itself. There is a main chain of entities representing organisms living in the fen lake connected to it, consisting of *nutrients*, *blue-green algae*, *water flies*, *bream*, *pike* and *aquatic plants*. Each of those has a quantity *number* or *amount*, depending on the correct grammar. The entities in this chain are connected by structural relationships according to the food chain, with the exception of aquatic plants, which is where the pike *hunt from*. Bream stir up the mud from the bottom of the lake, which decreases the *clarity* of the water. This is the most visible effect of the ecosystem collapse, which is why it is included in the representation here. A clearwater lake allows sunlight through, which in turn allows aquatic plants to grow, represented here by the positive relation between clarity and number of aquatic plants.

Finally, there is an external influence on the fen lake, which is the use of *fertilizer* in *agriculture*. In level 3 of the DynaLearn software it is possible to explicitly include external influences; agriculture will then be a part of the model. At level 2, the external impact is accomplished by not connecting the entities to the rest of the model.

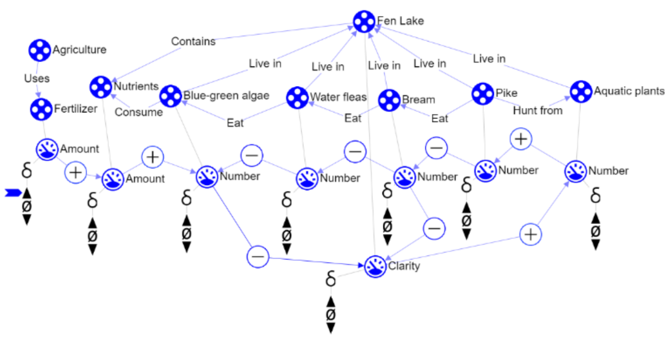

Figure 10. Fen lake – Complete representation.

6.3 Pedagogical Approach

Learners start by reading a small part of the newspaper article describing change in the ecosystem of the fen lake. They reflect on the main causes of cloudy water in the fen lake and then start building the representation. The first add the entities *fen lake* and *blue-green algae*, and then connect some quantities to blue-green algae. It is left up to the learners which quantities they add; this exercise should help them learn about the difference between entity and quantity. They later remove all quantities except for *number*, to work towards the final representation.

Using a description of the ecosystem in the fen lake, students add other entities, each with a quantity *number*. Causal relationships can be somewhat confusing in this representation because the direction of the arrow between predator and prey can be in either direction, as long as the valence of the relationship is changed (predator has a negative influence on prey, or prey has a positive influence on predator). Here, we chose to use negative relationships to have a good mix of both in the final representation. Also, this leads to a more interesting feedback-loop later on, as we will see.

Learners simulate what happens when aquatic plants increase, as shown in Figure 11. As usual, they reflect on the outcome of the situation by comparing it with their expectations.

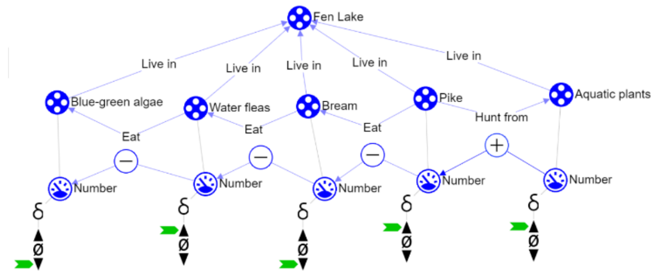

Figure 11. Fen lake – First part of the assignment simulated.

Learners complete the representation by adding the entity *clarity* to fen lake, connecting it to the number of bream, blue-green algae and aquatic plants using the correct causal relationships. As before, they are asked to formulate the meaning of the causal relationships (they just added to the representation) in their workbook. Furthermore, they add the influence of fertilizer from agriculture, and the influence of the amount of fertilizer on amount of nutrients. This allows them to simulate the initial change in the ecosystem by setting the initial situation to be an increasing amount of fertilizer. Next, they reflect upon the outcome of the simulation and the potential differences with their expectation.

When running this simulation, DynaLearn alerts the learner that a positive feedback-loop has been detected by showing an exclamation mark and outlining the correspondences forming the loop in red (Figure 12) [Bredeweg *et al.*, 2021]. This helps explain the sudden collapse of the ecosystem.

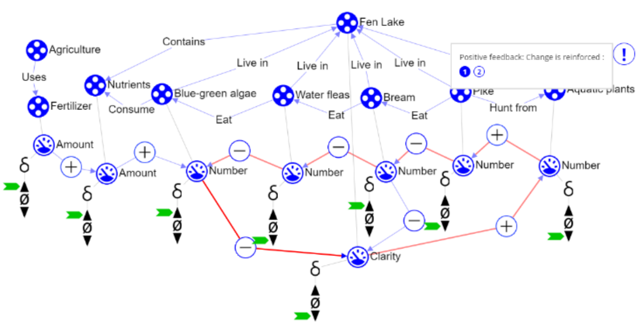

Figure 12. Fen Lake – Two positive feedback loops detected. An exclamation mark alerts the learner, and either feedback-loop can be highlighted in red by clicking on the numbers 1 and 2.

One thing that often confuses learners is the fact that a positive feedback-loop can be formed even by negative influences. By asking them how this can be, and specifically by asking them to count the number of negative influences in each loop, we help them discover that any time a loop contains an even number of negative influences it will lead to positive feedback.

The lesson is finished by the learners using their newly gained knowledge of this system to suggest ways to restore the old ecosystem. For this, they can use the representation to try different solutions and simulate these, thereby reinforcing the connection between the system and the representation.

7 Classroom Evaluation Studies

Each of the lesson activities described in this paper has been used in multiple classrooms, each time in a pre- and posttest type design. These evaluations studies show that these lessons are effective at raising student level in systems thinking as well as the subject matter at hand [Kragten et al., submitted].

8 Conclusion and Discussion

Here we share the main points of our philosophy behind the choices made in creating these lessons on learning systems thinking skills integrated with learning subject matter, using qualitative representations.

Firstly, we use a cyclic approach to create the representation, based on the inquiry cycle for science education [Sins *et al*., 2005]. Learners build, simulate, reflect on the results and build further. This helps learners to better understand their representations, as well as the connection between the representation and the system it describes, while also acquainting them with this way of working which is often used in the professional and scientific contexts. Finally, it forces learners to use simulation often, instead of only once when the representation is finished. This repetition allows them to practice interpreting the results, which is otherwise one of the harder parts of using representations.

Another way to help learners connect their representation to the real-world is to have them go back and forth between short pieces of source material and their representation. When such a connection between representation and system is not actively made, they will remain separate in some of the learners' minds. Learners will not gain a better understanding of the system from the representation nor be able to use their acquired systems thinking skills to reason about the real-world. By actively working on this connection, we avoid this separation.

Thirdly, we try to keep the complexity of the lessons below a certain threshold to keep students from getting overwhelmed. For instance, the representation in the third lesson in this paper is more complicated than the previous two, both because it has more elements and because it contains two feedback-loops. To ensure the lesson does not have too much complexity, we did not include the concept of ambiguity, like we did in the other two lessons. This concept is quite hard to understand and might have been too much for students in this case. The aim is to have learners take multiple lessons on qualitative representations each year starting in grade 8-9, so not all aspects of systems thinking need to be included in each lesson.

Finally, it can be helpful to have learners figure out for themselves which initial situation is needed to show some specified behavior of the system. It is hard to do so without understanding the representation, so this forces learners to reflect, and to make the connection between the representation and system it describes. This technique is used in the first lesson described in this paper, where we ask the students to figure out the initial situation needed to demonstrate why the poor stay poor.

The pedagogical approach described here is not yet complete. There are higher level systems thinking skills not discussed in this paper, as well as possible features of the software that influence pedagogical choices. For instance, in the latest version of the DynaLearn software it is possible to offer students support through a *help* function that indicates if they make a mistake in their model [Bredeweg *et al*., 2021]. Such features have pedagogical implications that require further investigation [Spitz et al., 2021]. A well-developed set of practical design philosophy principles can help create successful lesson activities for systems thinking integrated with subject matter using qualitative representations.

Acknowledgments

We would like to express our gratitude to the teachers who helped develop the teaching activities described in this paper.

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