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Learning Domain Knowledge and Systems Thinking using Qualitative Representations in Secondary Education (grade 9-10)

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Abstract

In this paper, we discuss the pedagogical approach of two lessons that are aimed at learning domain knowledge and systems thinking simultaneously using qualitative representations. Next to understanding basic cause-effect relationships, these lessons focus on the notion that systems can move through different states of behavior. An additional focus concerns system boundaries and distinguishing between what is part-of and not part-of a system.

1 Introduction

In this contribution, we present our approach on how qualitative representations can be used effectively as a method to develop secondary learners' systems thinking skills. Systems thinking is an important skill for solving complex problems (pandemics, climate, food supply, nature management, recession, etc.). An important goal of the work presented here is that a pedagogical approach is being developed, aimed at teaching systems thinking, that is directly linked to the current curriculum of secondary education, including in the field of biology, physics, geography and economics.

The project Denker (<https://denker.nu/>) is now in its second year. Together with the various educational partners involved (teachers, teacher educators, researchers), we developed and carried out several teaching activities in the lower years (grade 8-10) of secondary education. The lesson activities focused on various topics such as the greenhouse effect, eutrophication, market mechanisms, poverty cycle and classical mechanics. During these lesson activities (which take approximately 2-3 hours to complete), learners make qualitative representations of various systems, using the DynaLearn software (<https://dynalearn.nl/>), in which learning the subject-specific goals and systems thinking go hand in hand.

Qualitative representations and the accompanying inferences are complex and need to be learned incrementally. Therefore, the DynaLearn software uses multiple levels [Bredeweg *et al.*, 2013] where at each level new features to describe system behavior are available. In this paper, we focus on two lesson activities developed at level 3 for grade 9-10 of secondary education. The domain knowledge covered

in these lessons is *The Neolithic Age* and the *Centre-Periphery Model*. For the design of these lesson activities we assume that learners have already had a lesson at level 2 about another subject.

In the next sections, we discuss our pedagogical approach for these two lessons which are aimed at learning domain knowledge and systems thinking simultaneously.

2 Systems Thinking Goals

System thinking goals for grade 9-10 are derived from the features to describe system behavior that are available at level 3 of the DynaLearn software. Features of level 2 are also briefly discussed here as these are also available in level 3. But see [Spitz *et al.*, 2021b] for lessons created for level 2.

At level 2 learners learn to distinguish entities (physical object or abstract concepts) and quantities (changeable feature of an entity) within a system. Quantities can have causal dependencies (+, -) with other quantities and a direction of change (∂). Learners learn that they have to set initial values that represent a change in the system and that there is a propagation of change by causal dependencies. A system can be in a single state, but ambiguous states can occur when quantities are simultaneously positively and negatively affected.

At level 3 it is recognized that a system can have multiple states. *Quantity spaces* can now be added to the qualitative representation that allow quantities to be in a distinct state represented by a range of possible point and interval values. By adding quantity spaces, the system can go through a sequence of states. Relations between co-occurring qualitative values can be specified by adding *correspondences*. So with regard to system thinking goals, learners have to learn that a system can be in several distinct states and that certain values of quantities may co-occur.

To drive the system through its possible states an external *agent* and an *exogenous influence* needs to be added. An agent is an entity that influences the system without being affected itself. The exogenous influence sets the behavior of the quantity of the agent. From this, learners learn about *system boundaries*, i.e., what is considered part-of and not part-of the system in focus. They also learn how continuous behavior of the exogenous influence propagates its effect through the system as determined by the causal dependencies.

3 Method – Working with teachers

At the beginning of the second project year, teachers of the participating schools received training to familiarize them with the qualitative reasoning concepts available at level 3. After this training, teachers were asked to identify subject matter that matches with this level. Subsequently, a qualitative representation was made in collaboration with experts and the accompanying teaching material for the lesson was developed.

4 The Neolithic Age

An important learning goal for secondary school learners is to understand how human societies have evolved throughout history. The first lesson activity that we describe next focuses on development of human society in the Neolithic Age.

4.1 Subject Matter Learning Goals

Understanding the factors that play a role in the shift from a hunter and gatherer society to an agricultural society is a learning goal throughout many curricula around the world. The main driver of this societal shift is global warming after the last ice age (although alternative hypotheses are part of the scientific discourse). The rise in temperature meant that less water was available in forests and mountains, which reduced the carrying capacity of those areas. At the same time,

the production of crops in river valleys increased. A surplus of food allowed the semi-sedentary society in the river valleys to develop into an agricultural society. The number of hunters and gatherers decreased, partly because of emigration to the river valleys.

The actual way in which this social shift has taken place is of course more chaotic, complex and nuanced. It is however important that learners in grade 9-10 understand the main factors involved and that they can place these in a logical causal chain of events.

4.2 Neolithic Age – The Representation

Figure 1 presents the final qualitative representation of the lesson series about the Neolithic Age. *Temperature* rise due to climate change is the *exogenous* influence that drives the changes of the quantities within the representation. The climates' increasing temperature has a negative effect on the *amount of water* available in the mountains and forests. Decreasing availability of water has a negative effect on the *amount of wild plants* and *animals* thereby decreasing the *carrying capacity* and the *number of hunters* and *gatherers* that can be supported by the system. Decreasing carrying capacity of the mountain and forest areas has a positive effect on *emigration* of the hunters and gatherers. Increasing emigration of hunters and gathers has a negative effect on their number.

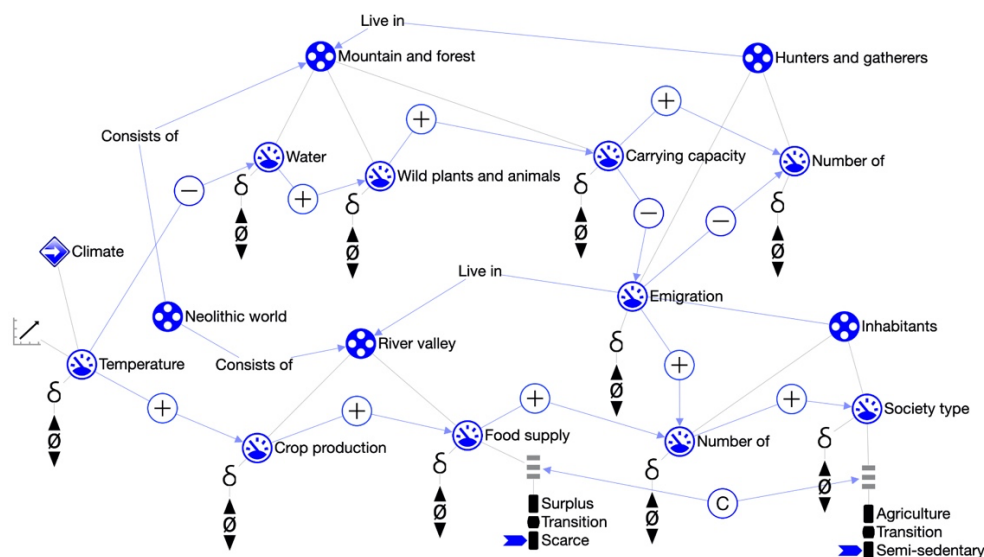


Figure 1. Neolithic Age – Complete representation.

The climates' increasing temperature has a positive effect on the *crop production* in the river valleys. Increasing crop production has a positive effect on *food supply*. At first, food supply is still scarce and the inhabitants of the river valley are still bound to a *semi-sedentary* way of living. As temperature keeps increasing, food supply becomes surplus and the society type changes to *agricultural*. Because the availability of food and the change of society type are linked, there is a correspondence between the quantity spaces. This restricts the qualitative representation to have three states (Figure 2): (1)

food is scarce and inhabitants live in a semi-sedentary way, (2) transition from food being scarce to surplus and society from being semi-sedentary to agricultural, and (3) food is surplus and society is agricultural.



Figure 2. Neolithic Age – State-graph shows society change.

4.3 Pedagogical Approach

The lesson series starts with an instructional video which briefly explains the factors that are involved in the change from a hunters and gatherers society to an agricultural society. The information is meant to give learners an impression of the main mechanisms involved which they can further explore and elaborate by creating the qualitative representation.

The first assignment of the lesson series focuses on the effect of rising temperature on the size of the hunter and gatherer population. learners have to load a template (Figure 3) into the learning space in which the entities and quantities of this part of the system have already been placed. A template can be used for several reasons [Bredeweg et al., 2021]. Firstly, it is a way to save time in class. To this end, it must be considered whether this choice is at the expense of the expected learning gain. Secondly, a template can also be used to simplify the assignment. A learner does not have to place the given elements and their connection himself. Thirdly, by placing the elements in the template you can also give a hint about the direction of the cause and effect chain. For instance, in the template shown in Figure 3 the entities and quantities are placed in a left to right order. This makes it easier for learners to make the causal dependencies between the correct quantities.

In a previous lesson at level 2 [Spitz et al., 2021b], the learners have already become acquainted with entities, quantities and causal dependencies, so this part is repetition with regard to systems thinking learning objectives. The icon used for an external agent is new. At this point in the lesson we do not address the notion of agents and exogenous influence because this information is not yet needed. As a basic pedagogical rule we chose to provide all information to learners just-in-time.

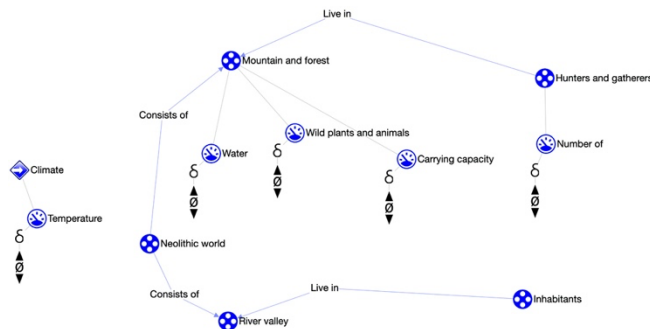


Figure 3. Neolithic Age – Assignment starts with template.

Learners simulate the representation after creating the first part of the system (Figure 4). For this, they specify the direction of change (∂) of temperature to increase. They are asked whether the expected changes in the system correspond with their expectations and they answer two questions: Complete the sentences: ‘If the temperature of the climate *increases*, the availability of water in the mountains and forests *increases/decreases*. This results in an *increase/decrease* of the available wild plants and animals...’. By means of the cloze questions, learners are prompted to translate the qualitative

representation and simulation results into a text-based explanation of the system. This is expected to support them in attaining the subject's learning goals.

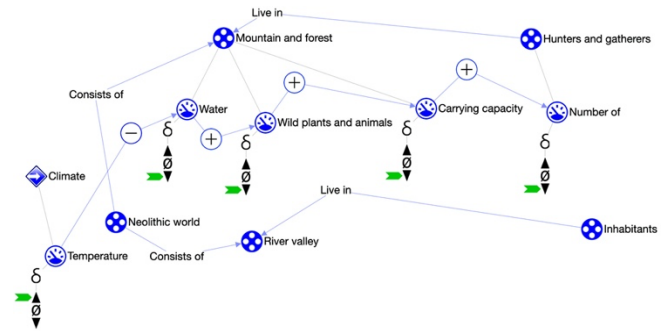


Figure 4. Neolithic Age – Simulation in the first assignment.

In the following assignment, learners create the lower part of the diagram which presents the effect of temperature on crop production, food supply and number of inhabitants of the river valley. Learners have to create the quantities and the causal dependencies. They must consider what type of causal relations there are between the quantities and to which entity each quantity belongs. These are systems thinking learning goals at level 2 and at the same time they work on the specific subject learning goals associated with these quantities.

Learners are also instructed to add the quantity emigration to the representation which connects the upper part (decreasing number of hunters and gatherers) and lower part (increasing habitants of the river valleys). After this, they simulate the representation and make a cloze question about this new part of the representation (Figure 5). The pedagogical approach throughout the lesson activity is to offer an iterative process in which learners constantly receive new information, make part of the representation, simulate and explain results, and translate the qualitative representation and results into a text-based explanation by answering a cloze question.

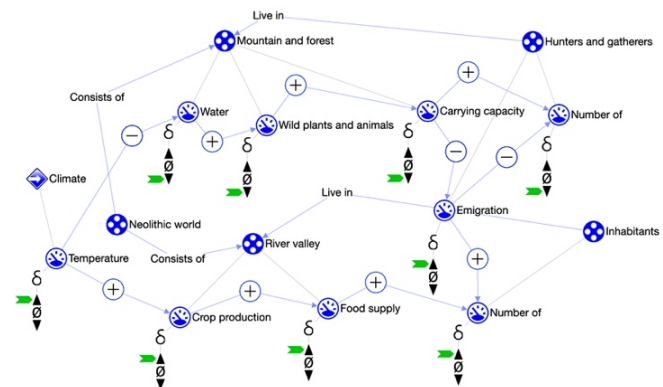


Figure 5. Neolithic Age – Adding migration.

Subsequently, the new concepts around systems thinking at level 3 are introduced. First, the learners watch an instructional video in which the new concepts are briefly explained and how they can be added to the representation. There is also

a text source in the workbook to further explain the difference between points and intervals (key concepts at level 3).

The learners first add a quantity space to food supply with two intervals (scarce and surplus) and a transition point between them. The workbook states which values should be made and in what order they should be.

When learners simulate the new representation, the results show only two consecutive states. The last state in which the food supply is surplus is not reached. This is because the current representation only indicates an initial change for the direction of temperature. Following this result, the notion of external influence emerges and we explain that there is difference between (i) setting an initial change of direction for a quantity and (ii) an extraneous influence that continues to have an effect on the other quantities. In order for the system of the Neolithic age to go through all states, a continuous change of the temperature is required. The learners add the external influence (Figure 1) and then simulate the representation. The results show that there are now 3 states of the system (a sequence as shown in Figure 2): food supply is scarce, transition, and surplus.

In the final assignment, learners create the quantity society type and the corresponding quantity space with two intervals (semi-sedentary and agriculture) and a transition point between these. The workbook states which values to created but the learners now have to decide in which order they should be placed.

The values of the quantity spaces of food supply and society type correspond. To make this clear to learners, we first let them simulate the representation without a correspondence between the quantity spaces. Because the three possible states (values) for both quantities are now independent, results show nine possible states (Figure 6). Learners are asked to explore the nine states and to write down which states do not correspond to the desired outcome. Following this result, the notion of correspondence becomes relevant to the learners. Hence, they add the correspondence and run the final simulation. The lesson activity ends with a cloze question that focusses on the correspondence between the quantity spaces: Complete the sentences: 'At first, food is *scarce/surplus* and the society type is *semi-sedentary/agricultural*. Due to increasing crop production...'. From this, we expect that learners understand that a system can be in multiple states and that values can correspond.

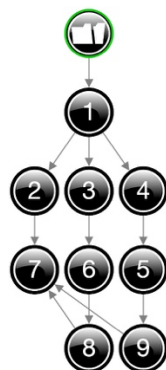


Figure 6. Neolithic Age – State-graph showing ambiguity.

5 Centre-Periphery Representation

The distribution of wealth and the factors involved are a subject that learners must learn in secondary education, for example, in economy or geography class. The *centre-periphery model* is often used to explain poverty and to look for possible solutions.

5.1 Subject Matter Learning Goals

Learners have to learn how the centre-periphery model classifies countries according to the degree of economic development. The countries classified as centre are the most developed. The periphery countries are the least developed. The semi-periphery countries fall in between. Characteristic for centre countries is that the economy is mainly based on services. There is a lot of technological knowledge and capital available and mainly high-quality end products are made. The characteristic of the semi-periphery is that the economy is strongly focused on industrial activity which usually supplies low-quality end products. Characteristic of the periphery is that the economy largely depends on agriculture (or mining and fishery). These countries mainly supply raw materials and (cheap) labor power and lag behind the rest of the world economically.

Learners also have to learn about how internal and external causes can explain a country's lack of economic development. Internal causes can be divided into natural and human causes. Examples of natural causes are: unfavorable climate, mountainous landscape and location. Examples of human causes are: bad governance, corruption and wars.

In the case of external causes, the reason for the low prosperity is sought in the kind of relationship a developing country has with other countries.

There are a number of opportunities for countries to develop economically. For example, a country can invest in the development of export processing zones. These are areas where foreign countries can invest to promote industrial and commercial export on attractive terms. A country can also invest in its infrastructure to support the mobility of labor, goods and capital.

5.2 Centre-Periphery – The Representation

Figure 7 presents the final qualitative representation of the lesson activity about centre-periphery model. Increasing government investments in export zones is the exogenous agent that drives the changes of the quantities within the representation. Natural resources and infrastructure are also added as exogenous influences because these are important concepts for learners to understand the system as a whole.

The final qualitative representation has five possible states (Figure 11). In the first state the country's welfare level is classified as periphery, the workforce distribution is mainly agricultural and the export package consists of unprocessed raw materials. The quantity spaces of export package, workforce distribution and welfare correspond. Increasing investments in export zones have a positive effect on the export package. At first, the export package will shift to low-quality

end products and workforce distribution will be mainly industrial. The GNP/head of the country increases and the welfare state of the country can then be classified as semi-periphery. Finally, the export package will consist of mainly high

quality end products and workforce distribution will be mainly services. The country's welfare level will increase and it can be classified as centre.

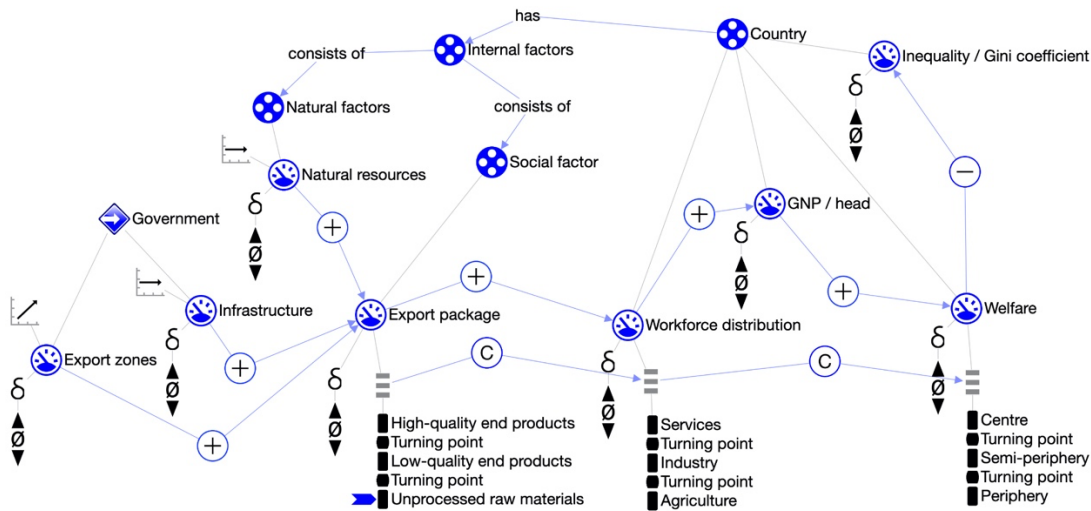


Figure 7. Centre-Periphery – Complete representation.

5.3 Pedagogical Approach

In the first assignment learners start creating the qualitative representation of the centre-periphery model from a template (Figure 8). It is assumed that learners are already familiar with the meaning of the concepts in the template from a previous lesson. Consequently, this assignment mainly focuses on learning the causal dependencies between the given quantities. Causal dependencies between export zones, export package and workforce distribution are already present in the template to further decrease the difficulty of the assignment.

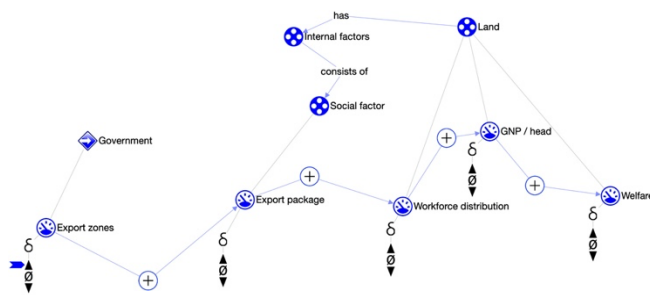


Figure 8. Centre-Periphery – Assignment starts with template.

Learners are asked to add the missing causal dependencies and to start the first simulation (Figure 9). The first assignment ends with a cloze question that prompts learners to interpret the simulation results: Complete the sentences: 'If the investments of the government in export zones *increases*, the export package *increases/decreases*. This results in an *increase/decrease* of the welfare state of the country.' As in the Neolithic Age lesson activity, we expect this to support learners in attaining the subject's learning goals.

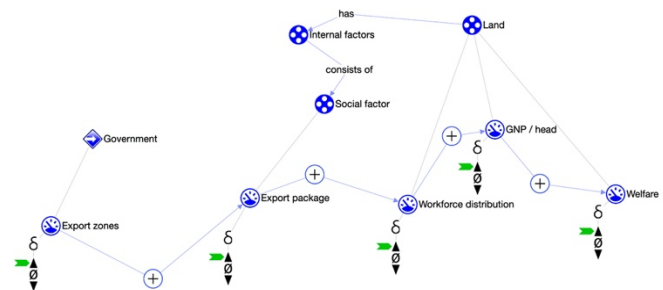


Figure 9. Centre-Periphery – Simulation first assignment.

In the next assignment learners watch the instructional video about the level 3 features and add a quantity space to welfare with three intervals (periphery, semi-periphery and centre) and a transition point between each of these (Figure 10). Some hints are provided about the order of the values but learners have to extract the exact names from theory.

Similar as in the Neolithic Age lesson activity learners have to simulate the representation, which results in reaching only the first turning point as an end state. From this, the need for adding an exogenous influence is explained. Learners are instructed to add an increasing exogenous influence (i.e., increasing investments of the government) to export zones. The simulation results now show that the system moves through five consecutive states (Figure 11).

The next step for the learners is to add a quantity space to workforce distribution with three intervals (agriculture, industry and services) and a transition point between each of these. Again the exact values are not provided, learners have to extract the values from theory. A short instructional video is provided to refresh their memory. Learners are allowed to work together so they can also consult each other if needed.

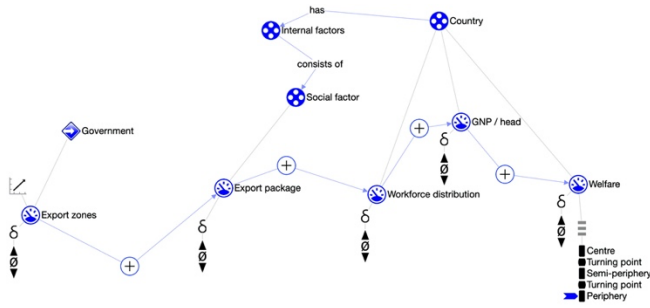


Figure 10. Centre-Periphery – Adding state of welfare.



Figure 11. Centre-Periphery – State-graph shows welfare growth.

At this point in the assignment we introduce the notion of correspondence between quantity spaces. Learners are instructed to first run the simulation without a correspondence between workforce distribution and welfare. With five values per quantity this results in 25 possible states (Figure 12).

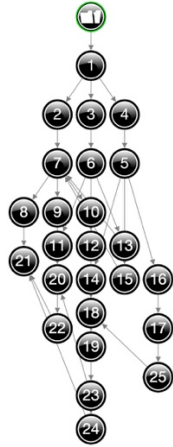


Figure 12. Centre-Periphery – State-graph showing ambiguity.

Learners are asked to explore the state-graph and to find two states that do not meet their expectations considering their knowledge of the system and explain why. From this, the need for creating a correspondence between workforce distribution and welfare is expected to emerge. Next learners create the correspondence and run the simulation resulting in the five expected states.

In the next assignment learners create the quantity space of the export package with 3 intervals (unprocessed raw materials, low-quality end products and high-quality end products) and a transition point between each of these. The values are provided in the workbook, but not their order. Learners are prompted to add the correspondence between export package and workforce distribution and to run the simulation.

In the last two assignments, learners have to further expand the qualitative representation with the exogenous influences on infrastructure and natural resources. There are two reasons

for only adding these exogenous influences in the last assignments. Firstly, it is expected that not all learners complete all assignments during class. The qualitative representation created so far contains the most important subject-related learning goals and all systems thinking skills have been addressed. Secondly, the complexity of the simulation results increases here because some assignments call for experimenting with opposite effects, such as an increase in investment in export zones while natural resources decrease. There is a chance that if these assignments are addressed too early, some of the learners may drop out because they find it too difficult.

7 Conclusion and Discussion

In this contribution, the pedagogical approach of two lessons for learning domain knowledge and systems thinking by creating qualitative representations is discussed. The representations are created at level 3 [Bredeweg *et al.*, 2013].

The pedagogical approach for the lessons have been developed in collaboration with secondary school teachers, teacher educators and experts in the field of qualitative representations and are based on practical and theoretical principles such as going through multiple iterations according to the inquiry cycle [Sins *et al.*, 2005] and creating a need for learning certain concepts so that information can be delivered just-in-time.

The effect of the discussed lesson activities on subject learning and systems thinking skills needs further investigation. Previous studies indicate that learning by making qualitative representations is effective at level 2 [Kragten *et al.*, submitted] and level 3 [Spitz *et al.*, 2021a].

The presented pedagogical approach is subject to change, due to new features that are developed in the software during the project to support the learning and guiding the teachers. For example, in the latest version of the DynaLearn software it is possible to offer learners support through a *help* function that indicates if they make a mistakes in their representation [Bredeweg *et al.*, 2021]. This function makes it necessary not to leave learners free in the naming of the ingredients (entities, quantities, etc.) of the system because otherwise the algorithm will notice too many differences between the learner's representation and the norm. For this, when creating a new ingredient, learners can choose a name from a dropdown box that is generated from the norm representation. Such features have pedagogical implications that require further investigation.

The degree and type of support provided by the teacher also varies. For example, where one teacher quickly gives the right answer to a question about the system to be created, other teachers will focus more on making the learners responsible for finding the answer.

The challenge is not only in finding the right pedagogical approach. It is also important that qualitative representations are made that are in line with the learning content of secondary education. In the project Denker (<https://denker.nu/>), ample time is invested in developing qualitative representations that meet these requirements. This is done together with teachers from secondary education, teacher educators and experts in the field of qualitative reasoning.

Acknowledgments

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