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Learning about Ecological Systems by Constructing Qualitative Models with DynaLearn

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Abstract

A qualitative model of a system is an abstraction that captures ordinal knowledge and predicts the set of qualitatively possible behaviours of the system, given a qualitative description of its structure and initial state. This paper examines an innovative approach to science education using an interactive learning environment that supports learners in expressing and simulating conceptual knowledge by building qualitative models in ecology. The learning environment and tools are being developed as part of the Dynalearn qualitative modeling research project, funded by the European Union's 7th framework programme and carried out by a consortium of eight participant universities. In summing up the results, it is clear that from the perspective of systems thinking, the modeling activity affected students' perception of systems making them able to represent it in a more dynamic and comprehensive way.

Keywords: Qualitative modeling, Qualitative Reasoning, Science Education, Interactive environment, Complex systems

Introduction

Understanding complex systems has become a challenging intellectual endeavor for scientists and science students as well (Jacobson & Wilensky, 2006). The development of systemic approaches since the early years of the previous century opened ways of thinking-about and studying phenomena in the world, unveiling aspects, interrelationships and processes that were overlooked by traditional science.

Laszlo & Krippner (1998) describe this move as a methodological shift from "reduction to components"; systems approach methodologies consist of "reduction to dynamics". They claim that:

"Traditionally, scientists have simplified natural complexity by viewing individual items of observation in isolation from the complex set of relations that connect them with their environment, and ultimately with the rest of the world. They have isolated the object of their investigations, interested mainly in delimited inductive chains that could be readily mapped as linear -and perhaps circular- causality. The heuristic of 'reduction to components' has led to the accumulation of

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vast storehouses of information about specific entities and the interactions among them. It enabled scientists to know how one molecule, cell or organ reacts to a particular kind of energy of stimulant, and how one body reacts to a particular kind of force." …"This type of knowledge proved deficient in one important respect: it did not disclose how complex things behave when exposed to a complex set of influences." …"Another heuristic became necessary, capable of simplifying unmanageably complex phenomena by reduction to dynamics instead of to components." (Laszlo & Krippner, 1998, pp. 54-55).

For science students, the systems approach and its specific concepts (e.g., emergence, self-organization, and non-linearity) represent a serious learning challenge. Portions of this knowledge appear to them epistemologically counterintuitive and/or incongruent with the approaches, assumptions, and practices characterizing the way they learn Science with the curricula prevalent in educational systems.

This paper is part of a larger study conducted with Junior High-School students aiming to assess the contribution of Qualitative Modeling (QM) with "DynaLearn" modeling environment to students' system thinking and understanding of complex ecological systems.

This paper focuses on the contribution of QM with DynaLearn to students' ability:

- To understand and represent complex ecological systems;
- To construct qualitative models of systems; and
- To apply the systemic perspective in different ecological contexts and phenomena.

Theoretical Framework

Understanding complex systems implies understanding that (a) These can be defined generally as a configuration of any given number of interconnected elements, parts or individuals, communicating with each other in non-linear ways; (b) The patterns of interactions form a collective network of relationships that exhibit emergent properties not observable at subsystem or individual parts levels; (c) When new contingencies occur, the network self-organizes in often unpredictable ways, and new properties emerge; and (d) By exchanging information with their environment, complex systems modify their behaviour as regards to it - they are adaptive. Concerning complex systems' processes, understanding the manner in which they communicate, respond to contingencies, self-organize and adapt requires studying the dynamical processes through which they evolve over time (Jacobson & Wilensky, 2006).

Previous research detected many difficulties students face when dealing with complex systems. These studies refer to students' difficulties in lacking the dynamic and cyclic perceptions of the system and the ability to create a meaningful relationship among the system components (Assaraf & Orion, 2005); developing a holistic perception of the system's structure and its multiple-variables configuration of relationships (Jacobson, 2001); in understanding non-linear causal effects resulting from fluctuations in the values of these variables (Plate, 2010); identifying feedback loops and understanding their role in the system's behaviour (Moxnes, 2000); distinguishing among the different levels of a system's behaviour - e.g., specific causal relationships at the components level or emergent behaviours at the system level (Levy & Wilensky, 2008); or in predicting the system's behaviour in varied scenarios - e.g., changing conditions within the system or in its environment (Hmelo-Silver & Pfeffer, 2004). The obvious conclusion from these observations is that there is a need to develop appropriate pedagogical strategies and instruments for supporting students' learning of complex systems.

In recent years, there is strong support for the idea that Learning by Modeling (LbM), namely learning by manipulating and/or constructing models of the systems under study, is a promising pedagogical approach that can support students' learning of complex systems (Bredeweg & Forbus, 2003; Hmelo-Silver, Holton, & Kolodner, 2000; Levy & Wilensky, 2008). Current developments of powerful computer tools allow scientists as well as science students to engage in highly sophisticated modeling processes, to conduct virtual experiments by manipulating a wide range of variable-configurations and scenarios, and to study a system's behaviour in prospective scenarios. Different approaches are taken by researchers as to the nature of the modeling process to be addressed as "natural" to students' intuitions. One of the approaches argues for the value of qualitative modeling (QM) for learning that leans on Qualitative Process Theory (QPT) (Forbus, 1984; Forbus, Carney, Harris, & Sherin, 2001).

Bredeweg, Gómez-Pérez, André, and Salles (2009) suggest that qualitative reasoning "captures human interpretation of reality, and provides a conceptual account that explains why a system has certain behaviour. … The Qualitative Reasoning terms (in fact a symbolic logic-based vocabulary) used in the model, mimic the way humans understand and explain the [system's] observable behaviour." In educational implementations of QM, Qualitative Models are built by learners without the use of numerical or quantitative information. The models represent a conceptual account of the structural and behavioural features of a system under study, and of the network of causal relationships underlying its behaviour.

Bredeweg, Salles, and Nuttle (2007) developed a structured framework for building expert Qualitative Models that presents the key steps in model development that can be linked to the requirements of a LbM approach. The structured framework (Figure 1) comprised six main phases from initial specification, through implementation to documentation, each of which could be considered important when applied to an education context. Whilst these phases can be seen as sequential they actually represent a systematic approach to describing ideas, revisiting them and refining them towards producing a formal qualitative model.

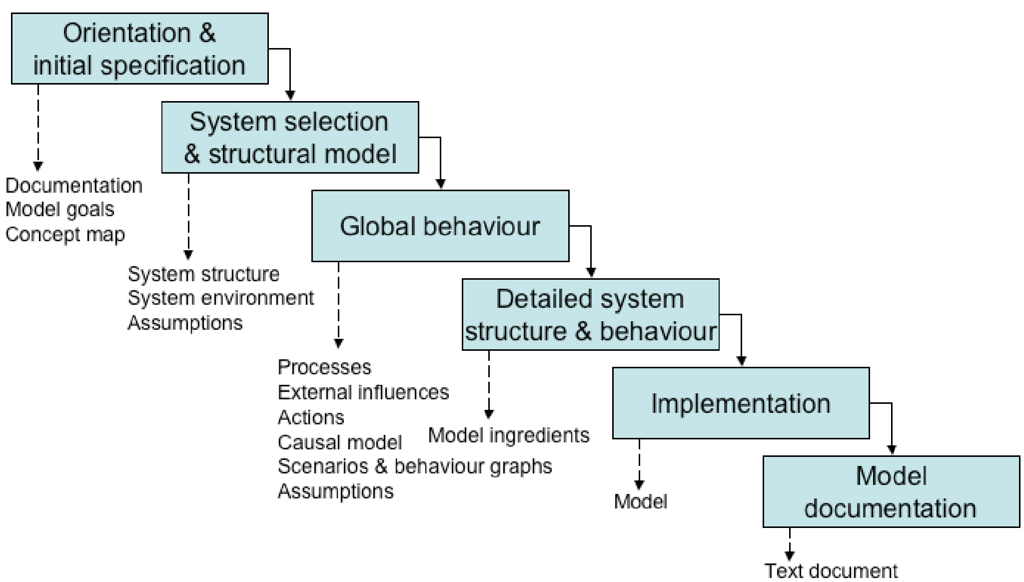

Figure 1: Model building framework and sequence of modeling (Bredeweg et al., 2007)

Of the six stages proposed by Bredeweg et al. (2007) four of them can be seen as the basis for LbM approach: (1) Orientation and initial specification of the model; (2) System selection and global behaviour; (3) Detailed system structure and behaviour; and (4) Implementation (including simulation and testing). Bredeweg et al. (2007) proposed that the first three of these stages could be done outside of the specific modeling software and they would produce important explicit representations of intermediate results. However, for an optimal LbM approach it would be beneficial for the key stage in modeling, the transition from the mental model to the formalised conceptual model, to occur within a single modeling environment that facilitated this modeling transition and provided individualised feedback and support during this process.

This study is centered on the implementation of the Learning by Modeling approach using a QM environment, "DynaLearn". The main components of the DynaLearn Environment are Conceptual Modeling (CM), Semantic Technology (ST), and Virtual Characters (VC). The CM component is used for learners to articulate, analyze, and communicate ideas and, thereby, construct their conceptual knowledge. The VC component is used to generate meaningful feedback of various types and to make the interaction engaging and motivating. The ST component is used to deliver semantically appropriate feedback and to find and match co-learners working on similar ideas supporting collaborative knowledge construction.

For the CM component, conceptual understanding is attained through a progressive modeling process of formulating, analyzing, testing, and revising models. Using qualitative modeling, students move in their modeling process through several stages of representations or Learning Spaces (LS) from specifying and interpreting simple, static models to elaborating on more complex causal and dynamic ones.

Six LS were designed: (LS1) Concept map; (LS2) Basic causal model; (LS3) Basic causal model with state-graph; (LS4) Causal differentiation; (LS5) Conditional knowledge; and (LS6) Generic and reusable knowledge.

Concept mapping requires building a concept map that represents the entities and types of relationships in a given system. Adding "quantities", "derivative values", and "influences", identified as arrows with plus (+) or minus (-) signs, lend causal meaning to the concept maps (LS 1-2 in the modeling process).

The following stages take into consideration the dynamics of the system. During this stage one creates a "quantity space", i.e., an ordered set of magnitudes with all possible qualitative values to enable producing a simulation that defines and expresses all qualitative states of a given system. Here the student is asked to interpret or interpolate on the basis of a given state or earlier states the behaviour of a system. At this stage a time dimension, conditions, and consequences of the model are also considered (LS 3-4-5).

The last stage requires synthetic skills of tailoring together already existing model fragments and scenarios in order to represent a new model aimed at exploring hypothesis or a given explanation of how a system works (LS6).

The knowledge representation (expression) of a system in Dynalearn, its entities and interrelationships among them, and indication of qualitative values are shown in Figure 2 and the results of the simulation are shown in Figure 3 (state graph) and Figure 4 (value history). The System represented in Figure 2 is a typical example from Physics, focusing on issues related to area of thermodynamics. The model describes the heating of an open container with a liquid by a heating source (e.g., stove). The heating source is a part of the system and may exchange heat with other objects when it is hotter than those objects. The heat flow thus depends on the heat difference between the heating source and the container.

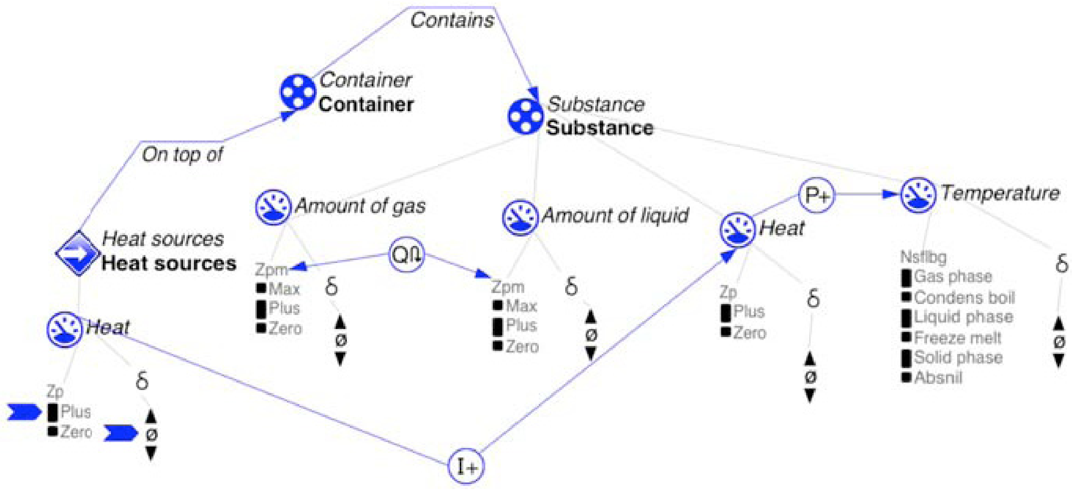

Figure 2: Learning Space (LS) 5 – Conditional knowledge (expression)

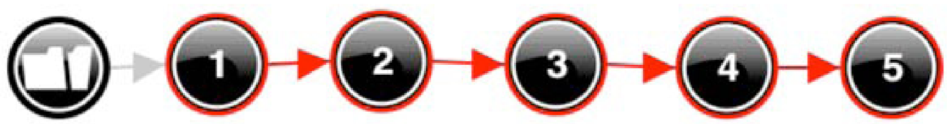

Figure 3: Learning Space (LS) 5 – Conditional knowledge (results, state-graph)

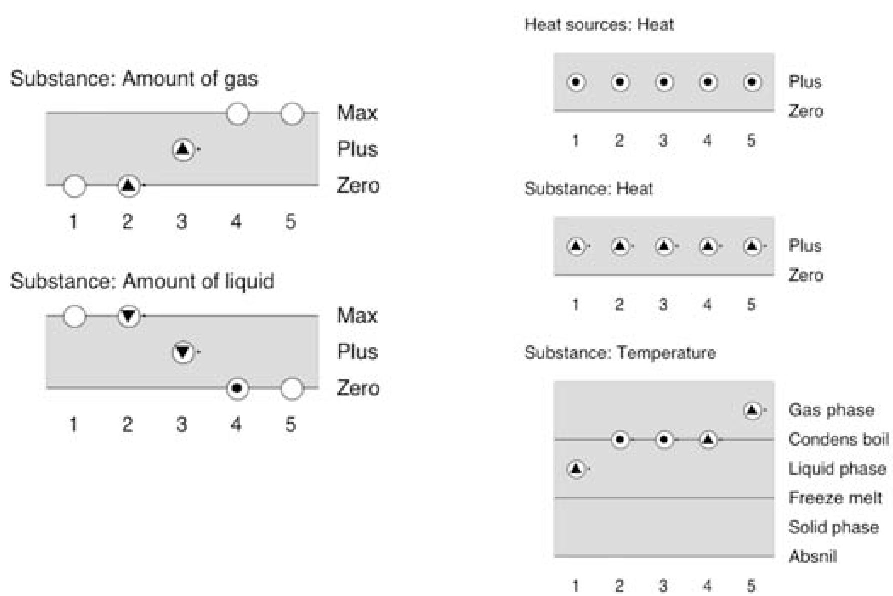

Figure 4: Learning Space (LS) 5 – Conditional knowledge (results, value history)

For the ST component, it has three main functionalities:

1. **Grounding**. It is necessary that terms produced by users (learners and teachers), while constructing expressions using the CM component get grounded in well-formed and established vocabularies. This serves a threefold purpose: (i) it ensures that the terms used and, by extension, the models they belong to are correct both lexically and semantically, (ii) by providing a common vocabulary to the models created by different authors, we ensure that such models are interoperable at a terminological level, and (iii) we provide the means for the vocabulary to be dynamically updated through the terms added by subsequent models.
2. **Ontology-based feedback**. Model quality is established fundamentally through similarities with several resources. In this case, the resources comprise, in increasing order of specificity, external ontological and linguistic resources, models rated with high scores in the DynaLearn community, and models authored by experts.
3. **Recommendation**. Recommending model authors to revise their models using related models and model fragments according to their relevance for the modeler and the properties of the model under development.

For the VC component – the environment supports different character roles (such as expert and learning companion) and different dialogue styles (non-interactive dialogues of character teams and interactive dialogues between a student and one or more virtual characters). Essentially, the characters should provide basic help when the student has a particular question on the use of the software or a model; they engage the student into a quiz and provide an evaluation of a model created by the student in terms of a diagnosis/critic of a comparison. In addition, students may teach their agents and observe their performance in a quiz (dialogue between multiple characters, such as a quiz master and two students). The content is presented by the characters based on input provided by CM and ST or based on pre-authored material contained in the curriculum scripts.

The Study

Participants were 25 High School students in two groups (Experimental = 8, Control = 13) attending a summer course in Marine Biology comprising of short lectures, lab activities, and a field trip. As treatment variable, the experimental-group (DL) completed a set of modeling tasks using DynaLearn, while the control group (C) that did not use DynaLearn did a Web-based inquiry-task.

Research Questions

The study aimed to answer the following questions:

Does Learning by Qualitative Modeling (LbQM) with DynaLearn contribute to junior high-school students':

- Conceptual understanding of a set of key concepts that represent the relevant content-domain (ecological systems)?
- Ability to model a complex system and represent it at different levels of complexity using the qualitative reasoning approach embedded in DynaLearn?
- Capability to apply the knowledge and skills gained for approaching new ecological phenomena?

Data Collection

The data collection was conducted using 3 instruments – each for a different purpose:

1. For assessing conceptual understanding the instrument used was a short open quiz on the main concepts treated in the course, some of which also appear within the scope of the national curriculum. Student responses were coded according to the level of understanding they reflected. The maximum score that could be obtained for the full set of concepts was 60.

2. For assessing the ability to model a complex ecological system and represent it at different levels of complexity, two instruments were used: concept maps and the products of the modeling activity (models and documentation).

Students from both experimental and control groups were provided with a short explanation of ways to draw a concept map acknowledging entities and relationships (nodes and links). No constraints were placed on the way to structure the map, thus, the maps reflected their conceptual understanding of ecological complexity.

The maps were drawn by the experimental group twice: at an early stage, right after the introduction to the activity, and at the end of the activity. While the first map represented intuitive thinking, the second map reflected the impact of all components of the intervention: the field trip, the modeling sessions, discussions, and the interactive scaffolding activities that took place during the intervention.

The control group provided maps only at the end of the activity, thus these maps were regarded as final products that reflected conceptual understanding of ecological complexity.

Students' concept maps and models were analyzed focusing on the following criteria:

- Overall configuration of the system's representation – e.g., hierarchical (H) or Net-type (N).
- Foci - focus on structural static properties (S,s depending on intensity) or on dynamic aspects – processes and causal relationships (P,p depending on intensity).
- Guiding organizing principle: e.g., formal systematic-classification principles (Sys) or ecological-systems' principles (E).
- Type of relationships: e.g., mainly structural related to inclusive relationships (R_1), or referring to causal processes and chains (R_2) or both (R_3).
- Scientific accuracy: on a scale from high (AC_1) to low level of accuracy (AC_3).

The second instrument comprised the models created by the students in Learning Spaces 2, 3 and 4, and the written documentation of the models provided by the students for each model.

The students were asked to report on each of their modeling experiences (including the initial concept map) using a similar questionnaire. The questions posed were:

- What was the phenomenon represented in the model?
- Which entities were chosen to represent the phenomenon? and why?
- Which properties of the entities were chosen to be quantified? And what were the quantities selected?
- Which relationships were essential for representing the phenomenon?
- What insights were gained through the modeling experience?
- Which additional insights were gained from the previous modeling step to the current step?

3. For assessing the capability to apply the knowledge and skills gained for approaching new ecological phenomena, a set of "challenging questions" was administered at the end of the activity to students in both groups. The questions required to use the ecological knowledge gained for providing descriptions, explanations, and predictions about a new marine ecosystem.

Results

Students' conceptual understanding of a set of key ecological system concepts

Average scores of the experimental and control group on the 20 key concepts' quiz in ecology at the beginning and at the end of the course were compared. The results of paired samples t-test of the two groups is presented in Table 1.

Table 1: Group comparison for answers to the concepts quiz

		Pre-Test	Post-Test		
Group	***n***	**Mean (SD)**	**Mean (SD)**	**Paired Pre-Post Differences**	***t* & sig.**
Experimental	8	22.9 (13.0)	32.8 (14.5)	-9.9	-5.3**
Control	13	13.5 (6.9)	22.0 (5.6)	-8.5	-4.7***

** $p < 0.01$
*** $p < 0.001$

Both groups gained significantly and similarly during the summer course intervention. The effect of size in both groups was large (0.8 in the experimental group and 0.65 in the control group). However, the relatively low average scores obtained in both groups indicate that the short intervention that was not specifically targeted toward this type of achievement (i.e., learning generic ecological concepts) was probably not sufficient for attaining their full conceptual understanding.

Students' ability to model and represent complex ecological systems at different levels of complexity using QM approach embedded in DynaLearn

Both concept maps and the models produced were regarded as a representation of complex systems. They were analyzed using the same criteria. Table 2 summarizes pre- and post-scoring of the concept maps of the experimental group and the control group.

Table 2: Scoring of Concept Map Representations in the experimental and control groups

Pre- Post- in Experimental Group		**Post- in Control group**
Pre	**Post**	**Post**
H= 6/10 = 60%	2/7 = 29%	13/13 = 100%
N = 4/10 = 40%	5/7 = 71%	0/13 = 0%
Sys = 4/10 = 40%	1/7 = 14%	4/13 = 31%
E = 6/10 = 60%	6/7 = 86%	7/13 = 54%
R1 = 3/10 = 30%	2/7 = 29%	8/13 = 62%
R2 = 0/10 = 0%	0/7 = 0%	0/13 = 0%
R3 = 6/10 = 60%	5/7 = 71%	5/13 = 38%
Ac1 = 1/10 = 10%	0/7 = 0%	8/13 = 62%
Ac2 = 1/10 = 10%	2/7 = 29%	2/13 = 15%
Ac3 = 8/10 = 80%	5/7 = 71%	3/13 = 23%

Key: H = Hierarchical configuration; N = Net configuration; S = Organizing principle – Systematic; E = Organizing principle – Ecological; R1 = mostly inclusive relationship; R2 = mostly process relationship; R3 = Mixed relationship; Ac1 = Low level of scientific accuracy; Ac2 = Medium level of scientific accuracy; Ac3 = High level of accuracy. The data presented in the table highlight the difference between the experimental group (DL group) and the control group (C group)

A brief account of some results:

- None of the representations in the C group was Net-like
- Less ecosystemic representations in the C group were observed (DL-86% vs. C-54%)
- Most representations in the C group were of structural type (DL-29% vs. C-62%)
- Less representations in the C group combined structural/process relationships (DL-71% vs. C-38%)
- Less scientific accuracy in C group's representations (DL-71% vs. C-23%)
- From the same table we can also observe the changes in the experimental group (Pre – Post):
- Increase (40% → 71%) in Net-type, and decrease (60% → 29%) in hierarchical, types of representations
- Increase (60% → 86%) in the use of ecosystemic organizing principles and decrease (40% → 14%) in using formal-classification organizing principles increase in representing structural relations (10% → 29%) and mixed structural/process relationships (60% → 71%)
- Slight decrease in scientific accuracy (80% → 71%)

An increase in net-type configuration following ecological principles and better representation of causal relationships marks progress toward higher levels of complexity understanding.

From the documentation that followed the models students provided, three themes indicating growth in their ability to construct qualitative models were found: their understanding of the phenomena to be modeled, the type of the relationship in the system they choose to represent, and insights regarding a systemic perspective.

Following is a brief summary of results for the three themes considered, taken from students' written reports on their modeling experiences.

Students' ability to define the phenomenon to be modeled

At first, half of the students phrased their modeling aim as specific questions, e.g., *How much effort the patella (a mussel family) exerts when attaching to the rock in varying intensities of waves.*

At the end of the modeling activities most students (80%) defined a phenomena in more generic and systemic ways, e.g., *the relationship between crabs, barnacles and patella; the effect of jelly-fish on the Israeli marine shore.*

Understanding types of relationships in the system

Along the modeling activities, types of relationships were observed; the patterns in the data collected are summarized in Table 3.

Table 3: Configurations of relationships in students' models and representations

Single/unidirectional	A→B	Wind affects the attachment of the patella (mussel family) to the rock
Single/unidirectional/parallel/independent	A→B B→C	Wind affects the power of the waves The power of the waves affects the attachment of the patella
One-to-many	A → B, C, D	The wind affects the power of the waves, the attachment of the patella and the number of barnacles
Chain of relationships	A→B→C	The wind affects the power of the waves that affects the attachment of the patella
Feedback loops	A↔B	The more predators, the less prey; the less prey, the less predators

Comparing the relationships included in students' early modeling attempts with those from late stages, the following changes were observed:

- Decrease in single/unidirectional relationships (40% → 10%)
- Decrease in parallel/unidirectional relationships (20% → 10%)
- Increase in one-to-many relationships (0% → 10%)
- Increase in chain-relationships (30% → 50%)
- Increase in feedback-loop relationships (0% → 20%)

The inclusion of "chain" and "feedback" type of relationships among entities in most representations and explanations at the end of the course (70%) are clearly indicative that students' perception of the phenomena advanced towards perceiving the complex configuration of relationships among its multiple variables. In addition, it is indicative of students' understanding of the complexity of the system and the type of causal configurations required to explain its behavior.

Insights related to complexity and the worth of modeling for learning

Qualitative analyses of students' documentation reveal their perception of complexity and the contribution of modeling for understanding it. Examples of insights: "The modeling activity enabled predictions"; "The modeling activity enabled the students to understand the dynamics of the system"; "The modeling activity allowed studying many variables and many relationships".

The contribution of QM to student's ability to apply knowledge and skills for approaching new ecological phenomena

In a set of "Challenging questions" that were administered to both groups after the intervention, students had to apply the knowledge gained to provide descriptions, explanations, and predictions concerning a new marine ecosystem. Sample results:

- The average total score of the questions by DL students was much higher than that of the C group (DL-78.3% vs. C-45.8%).
- DL students outperformed C students in understanding different types of relationships in ecosystems (DL-59% vs. C-36%).
- On predicting changes that might occur in a system in response to an interference (external agent, change in conditions), most students in the DL group (60%) succeeded in delineating long chains of events, vs. none in the C group.

Students' ability to tackle a new ecological phenomenon, not studied previously, is higher in DL group.

Conclusions

Along the evaluation activities it became evident that the main learning gain takes place at the conceptual understanding level. Learning by modeling is a scarcely used approach in Science teaching. The teachers lack this kind of knowledge and training, and modeling activities are rarely encountered in the traditional curricula taught in schools.

With the advent of computer technology into the schools' landscape several decades ago, the lecture-like routine has been complemented with the use of simulation software of various degrees of sophistication (Honey & Hilton, 2011). At most, students are allowed to "run" a ready-made model and even manipulate its variables, but this is still far from the idea of affording the building of the model itself.

In recent years educational tools aiming to allow students to model have been developed and implemented in school settings (e.g., Clariana & Strobel, 2007; Jonassen & Strobel, 2006). The main rationale of these tools emphasizes their potential for supporting deep understanding of the structure and processes of the phenomena modeled, and the subsequent exploration of hypotheses and predictions concerning behavior in changing conditions.

Indeed, a main insight obtained in our activities relates to the contribution of the modeling process with DL to students understanding of the structure and behavior of the ecological/marine systems included in the course's curriculum. The need to "translate" data included in the scientific or descriptive texts into representations using DL language, and the actual manipulation of the systems' components and features as building blocks for composing these representations, supported students active (rather than receptive) understanding of the phenomena at hand. Undoubtedly, learning at the content level was an aspect highly benefited by the modeling activities.

Overall, the students acquired rapid mastery of the skills and procedures required for constructing models with DynaLearn. As the modeling sessions advanced, their products reached high levels of complexity. At the end of the course, an increase in the experimental group students' ability to represent a system's structural, functional and behavioral features was observed. This observation was obtained in relation to the group's initial performance, and in comparison with the control group's performance.

At the end of the course, an increase in the students' perceptions and representations of multiple-variables causal relationships, causal chains, and feedback loops was observed. This is indicative of students' evolving understanding of the complexity of a system and of the type of causal configurations provoking its behavior.

Student comments (qualitative account of the group's work) reinforced the conclusions from the data. On this, a representative comment by a student asserted, "*The modeling activity taught me that some changes have long-term and far effects – If you touch one thing, everything can change*"

Knowledge and systemic approach gained during the course supported students' capability to apply these for addressing challenging questions about a system in a new context. The experimental group clearly outperformed the control group in this task.

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References

Assaraf, O., & Orion N. (2005). Development of system thinking skills in the context of earth system education. *Journal of Research in Science Teaching, 42*, 518–560.

Bredeweg, B., & Forbus, K. (2003). Qualitative modeling in education. *AI Magazine, 24*(4).

Bredeweg, B., Gómez-Pérez, A., André, E., & Salles, P. (2009). DynaLearn – Engaging and informed tools for learning conceptual system knowledge. In R. Pirone, R. Azevedo, & G. Biswas (Eds.), *Cognitive and Metacognitive Educational Systems (MCES2009),* pp. 46-51, AAAI Fall Symposium, Arlington, Virginia USA, 5-7 November, Technical report FS-09-02, AAAI Press.

Bredeweg, B., Salles, P., & Nuttle, T. (2007). Using exogenous quantities in qualitative models about environmental sustainability. *AI Communications, 20*(1), 49-58.

Clariana, R., & Strobel, J. (2007). Modeling technologies. In J. Spector, M. Merril, J. vanMerrienboer, and M. Driscoll (Eds.), *Handbook of research on educational communications and technology*. Mahwah, NJ: Erlbaum.

Forbus, K. D. (1984). Qualitative process theory. *Artificial Intelligence, 24*(1–3), 85–168.

Forbus, K. D., Carney, K., Harris, R., & Sherin, B. L. (2001). *A qualitative modeling environment for middle-school students: A progress report.* Paper presented at the Fifteenth International Workshop on Qualitative Reasoning, 17–19 May, San Antonio, Texas.

Hmelo-Silver, C. E., Holton, D. L., & Kolodner, J. L. (2000). Designing to learn about complex systems. *The Journal of the Learning Sciences, 9*, 247–298.

Hmelo-Silver, C. E., & Pfeffer, M. G. (2004). Comparing expert and novice understanding of a complex system from the perspective of structures, behaviors, and functions. *Cognitive Science, 1*, 127–138.

Honey, M., & Hilton, M. (Eds.) (2011). *Learning science through computer games and simulations*. Washington, DC: Academic Press.

Jacobson, M. J. (2001). Problem solving, cognition, and complex systems: Differences between experts and novices. *Complexity, 6*(3), 41–49.

Jacobson, M. J., & Wilensky, U. (2006). Complex systems in education: Scientific and educational importance and implications for the learning sciences. *The Journal of the Learning Sciences, 15*(1), 11–34.

Jonassen, D., & Strobel, J. (2006). Modeling for meaningful learning. In D. Hung, and M. Khine, *Engaged learning with emerging technologies*. Berlin: Springer.

Laszlo, A., & Krippner, S. (1998). Systems theories: Their origins, foundations, and development. In J. S. Jordan (Ed.), *Systems theories and a priori aspects of perception* (pp. 47-74). Amsterdam: Elsevier.

Levy, S. T., & Wilensky, U. (2008). Inventing a "mid-level" to make ends meet: Reasoning through the levels of complexity. *Cognition and Instruction, 26*, 1-47.

Moxnes, E. (2000). Not only the tragedy of the commons: Misperceptions of feedback and policies for sustainable development. *System Dynamics Review, 16*(4), 325–348.

Plate, R., (2010). Assessing individuals' understanding of nonlinear causal structures in complex systems. System *Dynamics Review, 26*(1), 19–33.

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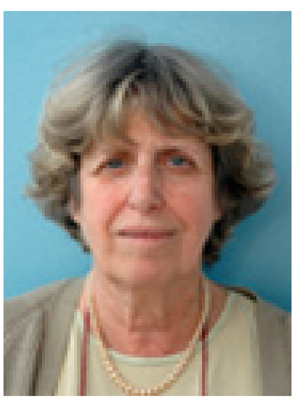

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