Qualitative Model Patterns: a Toolkit for Learning by Modelling

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Abstract

This paper presents a toolkit of model patterns, pieces of model structures that may be reused to create models and represent typical ecological systems behaviour. These patterns are used to support learners to build their own models, in activities aiming at learning by modelling. After analysing a sample of 94 models produced in the DynaLearn project (www.DynaLearn.eu) and identifying 385 occurrences of patterns a classification of six classes of basic patterns, in which only direct influences and proportionalities are involved is proposed. The systems' behaviours captured by these patterns are linear or exponential growth and decay. Some basic patterns can be combined to create more complex patterns and to capture complex behaviours, e.g. two state variables interacting in a direct negative feedback to produce oscillations and cycles. A third group of patterns are based on the refinement of model structures based on basic patterns, by using exogenous quantities, correspondences and conditional knowledge to get specific systems' behaviours. The role of model patterns in a curriculum is further discussed. Finally, an example of how model patterns may be applied to support learners in model building activities is presented.

Introduction

Building a model requires, besides the capacity of abstracting relevant information from the real world, specific skills and a minimum set of modelling guidelines to represent a system and its behaviour. For a learner, such transfer from understanding the real system into a formal representation of its structure, properties, functioning and behaviour may bring enormous barriers.

One of the DynaLearn project goals is to develop means to support learners in expressing and simulating conceptual knowledge. This paper presents a toolkit of model patterns, pieces of model structures that may be reused to create models and to represent typical ecological systems behaviour. This toolkit was developed as part of the pedagogical approach adopted in a curriculum proposed by the DynaLearn project, in the context of learning by modelling activities in DynaLearn workbench (Salles et al. 2012).

In fact, finding patterns in nature is one of the most productive approaches to understanding natural processes and systems. However, defining patterns is not an easy task. According to Pickett et al. (2007), patterns are "repeated events, recurring entities, replicated relationships, or smooth or erratic trajectories observed in time or space" (p.49). Note that in this definition, both the structure and the behaviour of ecological systems are mentioned. When patterns are recognized, they become important elements to anchor theoretical concepts in ecology.

Relevant behaviour patterns in ecological systems include exponential growth (positive and negative or decay), cyclical behaviours (oscillation, overshoot and collapse), S-shaped behaviour and steady state. Underneath these behaviours often there are controlling mechanisms such as feedback loops. These mechanisms refer to the answers of the system's components to changes in their own size (cf. for ex., Odum 1985).

Given that models are abstract representations of physical and natural systems, it is arguably that model patterns, characterized in terms of model structures involving processes and propagation of their effects, may become a powerful tool to transfer real world observations into models. When it comes to systems behaviour, specific behaviour patterns may also be associated to specific model patterns. The model patterns presented in this paper result from the analysis of 94 models produced by project modellers exploring Learning Spaces 4, 5 and 6 in DynaLearn (Bredeweg et al. 2009).

Three classes of model patterns are characterized. Firstly, basic patterns and relevant variations are organized in six groups. Among them, patterns often found in the middle of the model structure, that do not include feedback loops, patterns that include feedback loops and patterns based on inequality reasoning to define the magnitude of rates.

Secondly, some basic patterns are combined to produce more complex model structures that are in turn associated to complex behaviours. Finally, the third class of patterns refers to modelling strategies to obtain simulations showing specific systems' behaviour of interest, implemented by means of restrictions applied to basic patterns. These restrictions include the use of *exogenous quantities*, a facility provided by DynaLearn in which quantities influence the system by exhibiting specific behaviours, but are not influenced by the system (Bredeweg et al. 2007), the use of correspondences, and of conditional knowledge.

After presenting details of the three classes of patterns, the paper presents a discussion about how such model patterns can be used in a curriculum of environmental science. A working example shows how knowledge can be extracted from texts and associated to DynaLearn modelling elements. Such information is further used to guide the selection of adequate model patterns that are finally combined to produce simulation models. Finally, discussion and final remarks are presented.

Dynalearn Curriculum for Environmental Science

It has been widely recognized that modelling activities are so valuable for the acquisition of reasoning and scientific skills that time has come to introduce modelling in secondary school and undergraduate national curricula. DynaLearn project presents a curriculum for environmental science that explores themes and topics relevant for the present (Salles et al. 2009) aiming at the development of learners' systems thinking, a way of thinking that "focusses on the relationships between the parts forming a purposeful whole" (Caulfield and Maj 2001).

A learning by modelling approach (for ex., Borkulo 2009) is the pedagogical strategy adopted by the project, aiming to give the students autonomy, for them to carry on with self-directed learning strategies (Gibbons 2002). In this context, a set of model patterns has the important function of serving as a handle on how to represent domain knowledge in qualitative system dynamics models.

Model patterns are pieces of model structures repeatedly found in different models. Sometimes some of these patterns can be a standalone model. Often, these pieces are combined to produce more complex model structures. From the modelling point of view, model patterns represent one of the most relevant insights for DynaLearn curriculum.

Associated to these model patterns, specific system behaviours were also identified. These building blocks are relevant to organize the learning by modelling process, because there are evidences, coming from evaluation activities (see Mioduser et al., 2012), that mastering these patterns, learners are better off to create their own models.

Model Patterns

Three classes of model patterns are discussed in this section. Initially, basic patterns based on single processes; two processes affecting the same state variable; and networks of causal chains, with no feedback loops, are presented. Next, patterns involving direct and indirect loops are discussed. Basic patterns end with the use of inequality reasoning to define the rates magnitude value. Second, patterns that result of the combination of basic patterns are presented and associated to more complex behaviour. Finally it is shown how the use of exogenous variables, correspondences and conditional knowledge may contribute to create model structures that produce complex systems behaviour.

Basic Patterns with No Feedback Loops

Two basic patterns are presented in this section: (a, b) patterns involving a process, consisting of a rate (R) and a state variable (SV), and possible variations, such as a single rate that affects two or more state variables; (c) two or more processes affecting a single state variable. Figure 1 presents these two types of patterns.

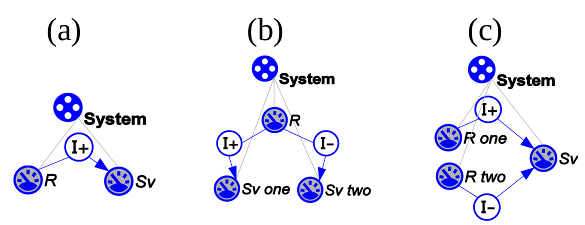


Fig.1. Examples of basic patterns: (a) Single process affecting one state variable; (b) Single process affecting two state variables; (c) Two processes affecting one state variable.

The pattern shown in Figure 1a consists of a single process, having the rate (R) either positively or negatively affecting a State Variable (SV). This is pattern is often found in the middle of the model structure, connected to other patterns (for example, R is influenced by an auxiliary variable, and SV influences another quantity). The quantity space associated to the rate's magnitude is an important aspect. Often it is zp = {zero, plus}. When associated to mzp = {minus, zero, plus} the basic pattern may be used to represent an aggregation of two competing processes. This way, when the magnitude of the rate is positive (m_R = plus) the process with positive influence is predominant and sets the derivative value of the state variable (d_SV); if m_R = minus, the negative influence dominates; and if m_R = zero the two direct influences are in equilibrium.

A productive variation of this basic pattern is shown in Figure 1b: a single process influences two (or more) state variables. This pattern can be used to model the transference of a substance from one place (via I-) to another (via I+). For example, consider the migratory movement of coral reefs between northern locations and the Equator. The model ‘Coral reef distribution’ uses aggregated single rate (Dispersal rate) with quantity space {towards equator, zero, from equator} to represent the competing processes emigration and immigration (Leiba et al. 2011).

Figure 1c presents a pattern consisting of two competing processes (with rates R1 and R2), influencing a state variable. In this case, it does not matter if m_R1 and m_R2 have quantity space zp or mzp, the resultant system behaviour depends only on the relative size of the rates’ magnitudes. Among the possible variations on this basic modelling pattern, it is possible to find models with two concordant influences of the same type (either both I+ or I-), or more than two influences, in different combinations of I+ and I-, affecting the same state variable.

Propagation patterns

Often a linear chain of causality propagates the effects of processes to other parts of the system. Patterns representing propagation of causality are implemented by means of qualitative proportionalities linking a state variable to one or more auxiliary variables or rate. Three possible variations were detected in the sample of models: network of causal influences - *short chain*, with one auxiliary variable; *long chain*, with at least two auxiliary variables; and *branching*. Figure 2 presents examples of these patterns.

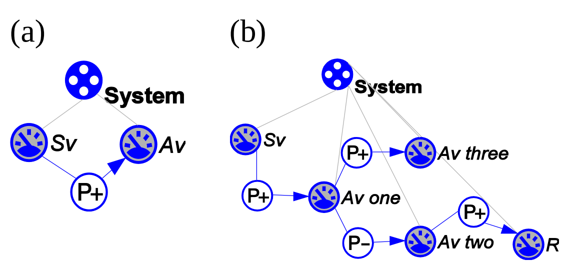


Fig. 2. Examples of bridging basic patterns: (a) Short network chain; (b) Long network chain with branching. The influencing processes are not shown in the figures.

Figure 2a shows the simplest network: an auxiliary variable (AV) is influenced by the state variable (SV) that may be the end of the chain or be connected to a rate. Long networks of causality involve two or more auxiliary variables. A special kind of network is branching, shown in Figure 2b. At a certain point of the chain, the state variable or an auxiliary variable influences two (or more) quantities, so the effects of the initial process propagate to different subsystems. The number of possible variations of these bridging patterns is therefore very high.

Basic Patterns with Feedback Loops

Feedback patterns are based on combinations of positive, negative, direct, and indirect loops. By definition, positive feedback tends to reinforce the effect of the process, and negative feedback, also known as a self-correcting or balancing feedback, tends to reduce the input that has caused it. Both types of feedback may be, in turn, either direct or indirect loops. Direct or simple feedback loops involve at least a rate that influences a state variable and is influenced back by this quantity. In contrast, indirect or complex feedback loops involve at least an auxiliary variable that puts the influence feeding back into the rate that starts the causal chain.

Two classes of model patterns with feedback loops are identified: direct and indirect feedback loops (Figure 3). Any of the basic patterns mentioned above (single process, two or more processes) may be involved in these two types of loops.

Positive direct feedback loops can be created when the effects of a direct influence are combined with a proportionality of the same sign (either negative or positive), that pushes the system in the same direction as the initial input. If however the direct influence and proportionality have opposite signs, a negative feedback loop is created. Figure 3a shows a pattern involving two processes that put competing influences on the same state variable, and this quantity in turn puts positive influences on both rates creating a positive and a negative feedback loops.

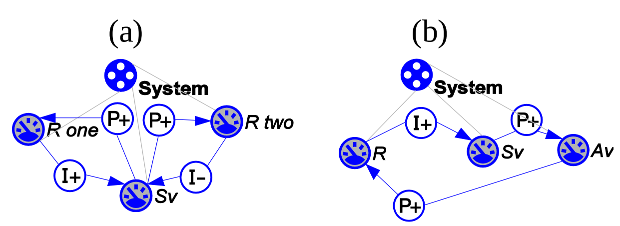


Fig. 3. Basic patterns with feedback loops (a) Double direct (positive and negative) feedback loops; (b) Short indirect positive feedback loop.

In indirect feedback loops, the effects of the initial process(es) are propagated into a network of causal relations, before the feedback mechanism operates, causing a delay on the control mechanism. Short indirect loops are characterized by a state variable influencing an auxiliary variable, which in turn influences the rate (Figure 3b). When two or more auxiliary variables propagate the effects of a process until an auxiliary variable affects the rate, the indirect loop is considered long. As in previous cases, balancing or reinforcing results may be achieved via any type of indirect loops.

Inequality reasoning Patterns

DynaLearn provides a functionality that allows for qualitative arithmetic operations of addition and subtraction involving two (auxiliary) quantities. This feature is useful to promote inequality reasoning. Combined to qualitative proportionalities, the magnitude value of a third quantity (often a rate) can be calculated this way. This mechanism also serves to start changes in the system (in unbalanced situations) and stop such changes (when the system reaches the equilibrium). Figure 4 shows an example of this inequality reasoning based pattern.

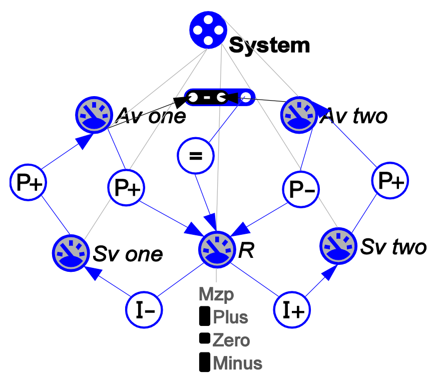


Fig. 4. Basic pattern based in inequality reasoning, with negative feedback loops

This basic pattern can be expressed in a number of variations, being the use of subtraction between auxiliary variables more common among models produced in DynaLearn project. It is also possible to find variations of this pattern with or without feedback loops, which can be either positive or negative.

How Often do These Basic Patterns Appear in *Dynalearn* Models?

DynaLearn has gone through two phases. In the first one, 'simpler' models were produced, and 60 of them were selected to this investigation. 'Advanced' models were produced in the second phase. These models should explore fundamental laws and first principles, and clearly explain the mechanisms that produce behaviour (Noble et al. 2011). A set of 34 'advanced' models were also selected. Criteria for selecting the models were that the models (a) should be implemented in LS4-6; (b) should be 'complete' and 'correct', from the structure point of view. A total of 385 patterns were described, being 243 from the 1st phase, and 142 patterns from the 2nd phase. The distribution of these exemplars among the six classes of basic models is presented in Table 1.

The analysis of the results shows differences in the use of model patterns: comparing simple models (1st phase) and advanced models (2nd phase), it was observed a decrease in less complex model patterns ['single process' (22.2% to 16.2%), 'two or more processes affecting single state variables' (5.3% to 4.9%), and 'direct feedback loops' (20.6% to 12.0%)], and an increase in more complex model patterns ['indirect feedback loops' (3.7% to 8.4%) and 'inequality reasoning' (6.6% to 14.8%)].

These results are in accordance to the authors' expectation: to create advanced models, complex model patterns are used with more frequency and simple model patterns tend to be less used.

Table 1. Number and percentage of each type of model pattern identified in 60 models of the 1st phase and in 34 model of the 2nd phase of the DynaLearn project.

PATTERNS	1st phase (n=243)	1st phase (%)	2nd phase (n=142)	2nd phase (%)	TOTAL 1st + 2nd (n=385)	%
Single process	54	22.2%	23	16.2%	77	20.0%
Two or more processes affecting a single SV	13	5.3%	7	4.9%	20	5.2%
Network causal chain (short)	37	15.2%	30	21.1%	67	17.4%
Network causal chain (long + branching)	64	26.3%	32	22.5%	96	24.9%
Direct feedback	50	20.6%	17	12.0%	67	17.4%
Indirect feedback	9	3.7%	1	8.4%	21	5.4%
Inequality reasoning	16	6.6%	21	14.8%	37	9.6%
TOTALS	243	100.0%	142	100.0%	385	100.0%

Combination of Basic Patterns into Complex Structures

In fact, the basic patterns discussed above produce only simple behaviour such as exponential or linear growth and steady states (represented in qualitative terms as 'increasing, decreasing and stable'). Complex behaviour observed in natural systems, such as oscillations and cycles, can only be produced by more complex model structures. The possibility of combining patterns is a way to overcome this limitation. Some of these combinations are presented in this section.

Salles et al. (2012) present three types complex patterns resulting of combinations between basic patterns: (a) two connected 'single process affecting a state variable' patterns; (b) two connected 'two processes affecting a state variable' patterns; and (c) two connected 'inequality reasoning' patterns. These patterns are described (but not restrict to) in terms of population dynamics, expressing the well-known predator-prey behaviour produced by the Lotka-Volterra equations, often found in ecology textbooks (e.g. Gotelli 1995). Only the first of these patterns is shown in the present paper.

Often population models are based on a 'single (aggregated) process' model pattern in which birth and death rates are replaced by a growth rate, with mzp quantity space (see Figure 1a). When two 'single process' patterns are connected by 'short network chains of causality' patterns (Figure 2a), interactions between two populations can be successfully modelled. For example, Correa (2011) uses this pattern to represent competition between two populations of algae – the *Cyanophyceae* and a functional group that represent other algae species found in the same lake –, and to represent the predator-prey system, involving algae and herbivore populations. The model pattern and a simulation representing the predator-prey behaviour are presented in Figure 5.

Note that the use of the 'short network chain' patterns with opposite signs creates a negative feedback loop, which is responsible for the oscillation behaviour in the two quantities. If the two proportionalities used in the combined pattern have the same sign (a positive feedback loop) both state variables present a simple behaviour (increasing, decreasing or steady).

Double use of 'two processes affecting the same state variable' patterns (Figure 1c) connected by 'network branching' basic patterns (Figure 2b) was the basis for the models showing different types of interactions between species (commensalism, predation, competition, among others) created by Salles et al. (2003). A similar behaviour shown in Figure 5b is also produced in positive-negative interactions such as predation.

A combination of two 'inequality reasoning' based patterns (Figure 4), connected by 'short network chains of causality' patterns (Figure 2a) was used to implement Lotka-Volterra models by Zitek et al. (2011). Again, the system behaviour shown in Figure 5b is produced.

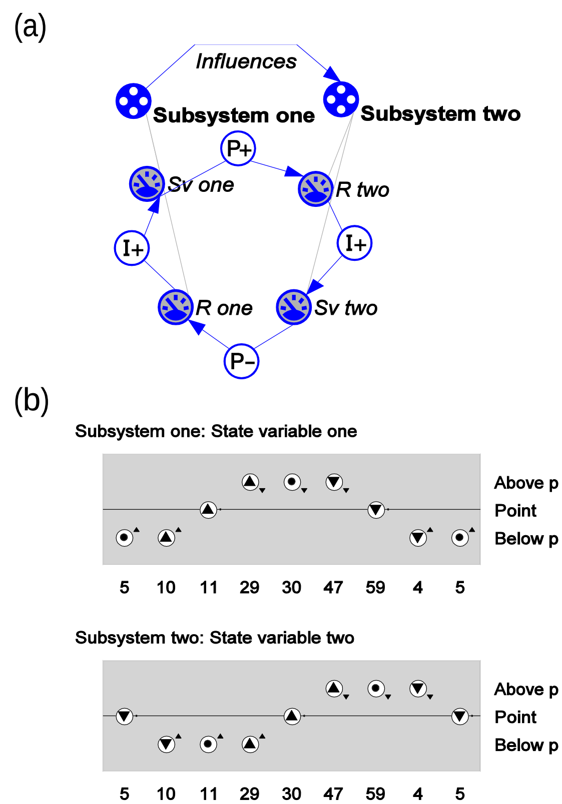


Fig. 5. (a) Two 'single process' patterns with aggregated rates connected by a 'short chain network' pattern; (b) typical behaviour produced by the combined pattern presented above.

Refining Model Pattern Structures to Express Specific Behaviours

Some specific system behaviour patterns of interest can be captured on top of basic patterns, but the use of other modelling elements than direct influences and proportionalities is required. This section reports the use of exogenous quantities, correspondences and conditional knowledge.

Exogenous Behaviour Patterns

While complex system behaviour are associated to complex patterns, as describe so far, DynaLearn offers the possibility of starting a simulation with quantities that exhibit specific built in behaviours, defined outside the system, the so called exogenous behaviours (Bredeweg et al. 2007). In DynaLearn Learning Space 6 (Bredeweg et al.

2010) exogenous behaviours may affect magnitude and / or derivatives of selected quantities. Exogenous behaviour can only be applied in the initial scenario to quantities that are not affected by any other quantity. The magnitude of an exogenous quantity may be affected by the 'generate all values' and 'constant' exogenous behaviours. The derivative of a quantity may be affected by 'increase', 'steady', 'decrease', 'parabola' (positive and negative), 'sinusoidal' and 'random'. These exogenous quantities may transfer their behaviour to other quantities (state variables, rates or auxiliary variables) and, in doing so, they influence whole the system behaviour.

Figure 6 presents one of these exogenous behaviour ('parabola' negative). Examples of applications of other exogenous behaviours can be found in Bredeweg et al. (2007).

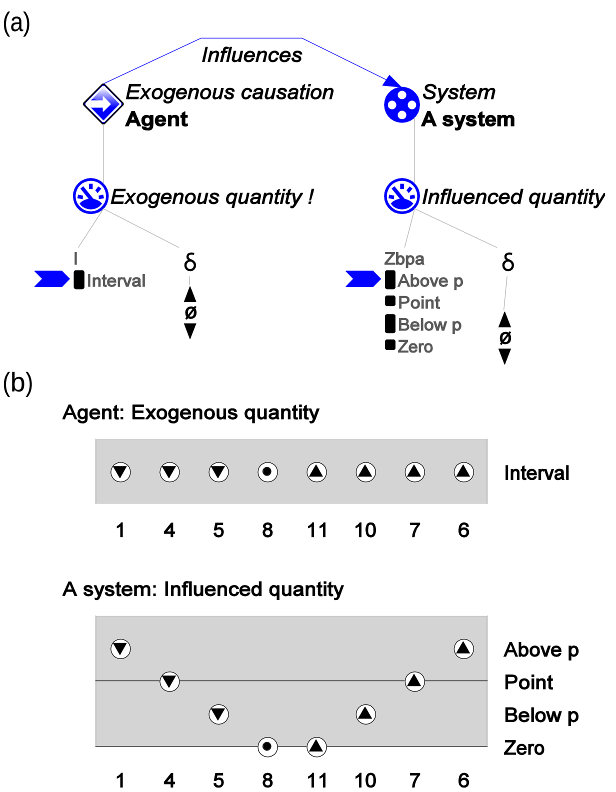


Fig. 6. (a) Initial scenario of a simple model, in which the 'exogenous behaviour' negative parabola is applied to the quantity 'Exogenous quantity'. Its behaviour is shown in (b).

Behaviour Patterns, Correspondences and Conditional Knowledge

Correspondences are directly associated to the behaviour of the system, as the correspondent quantities simultaneously show the same values in all quantity spaces (Q-correspondence) or only some of their possible values correspond (V-correspondence). As such, they are not considered in the present work 'modelling patterns'. However, correspondences are important elements to restrict the behaviour generated by model patterns and, this way, may be used by the modeller to reduce ambiguity and to select specific behaviours wanted in a simulation. Noble et al. (2011) describe a number of interesting applications of correspondences to ecological system behaviours.

To start with a trivial example, the simplest model about population dynamics is based on the pattern 'double direct feedback loop' presented in Figure 3a. If birth rate (R1) and death rate (R2) are not equal to zero when number of individuals (SV) is zero, the simulation has produced a biologically impossible situation: the existence of natality or mortality when the population does not exist. In this case, the use of V-correspondences between the zeros of the quantity space of these three quantities is compulsory. In other words, to capture the correct behaviour of a single population, correspondences have to be included in one of the model patterns.

A more interesting example is given in models aiming to produce the famous (for biologists) 'S-shaped behaviour'. In ecology, the logistic equation has played an important role in implementing the interaction between two laws (exponential growth and limits to growth) to produce a strong sigmoidal pattern showing population trends determined by the influence of resource availability on the abundance of organisms, the 'density dependence' condition (cf. Dodds 2009; Gotelli 1995, among others).

In this context, the variable representing population size has three limit points, where the system behaviour changes: K, the carrying capacity, in which the state variable stabilizes; K/2, the inflection point; and zero, as shown in Figure 7.

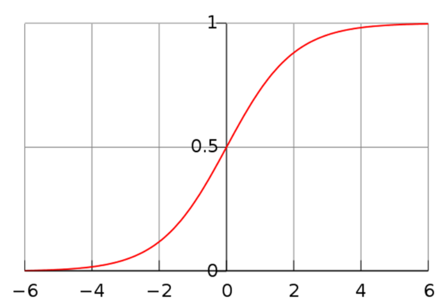


Fig. 7. The logistic curve (from Wikipedia: http://en.wikipedia.org/wiki/File:Logistic-curve.svg)

A model presented in Salles et al. (2012), consisting of eight model fragments, implements the density-dependent population model and captures the S-shaped behaviour. The model is based on the 'inequality reasoning' basic pattern and on extensive use of correspondences and conditional knowledge.

The core of the model is to represent the mechanism that changes two sequential direct feedback loops in order explain the system behaviour (Chung, 1994): a positive feedback during the interval between zero and K/2, equality of birth and death rates at the inflection point (K/2), and a negative feedback in the interval between K/2 and K. Figure 8 shows the two model fragments that capture this knowledge.

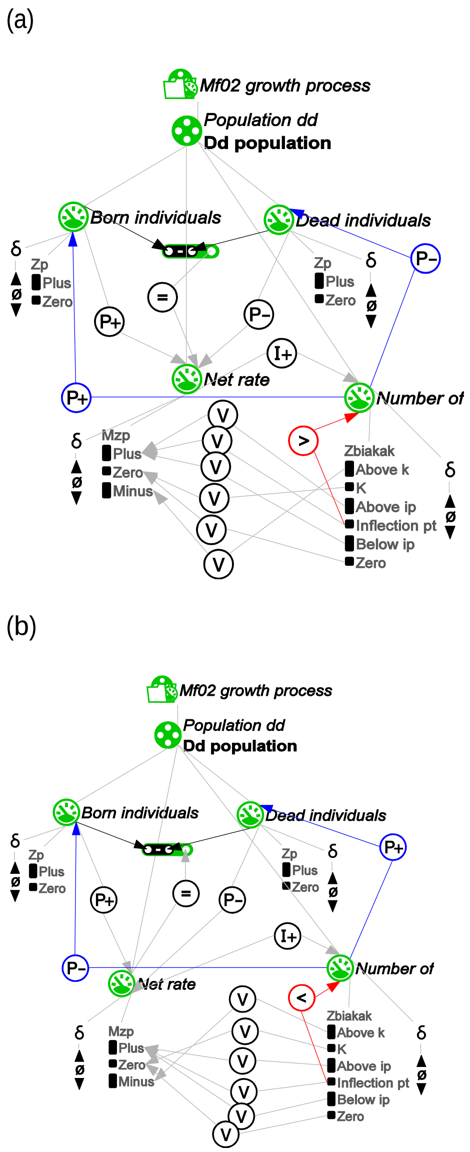


Fig. 8. Two model fragments that capture essential knowledge about the S-shaped curve: (a) Number of individuals smaller than the inflection point; (b) Number of individuals greater than the inflection point.

Model Patterns and Learning by Modelling

Having described the modelling patterns found in models produced in DynaLearn (Table 1), this section presents a discussion on how such pieces of models can be combined to support learners in learning by modelling activities.

Accordingly, this section has the following objectives:

- to introduce notions of model patterns as pieces of complex model structures, via exploring the quantity or system behaviour produced by such a piece of model;
- and to discuss some of the possible variations on each model pattern and combinations among patterns that allow for fruitful sequences in model development.

Examples of how combination of patterns produces models in specific topics of environmental science are presented in Salles et al. (2012).

Single Process Pattern

'Single process' patterns can be used in introductory activities in a curriculum based on learning by modelling to build simple models. This basic pattern and its variations are useful to explore basic knowledge and vocabulary about rates, state variables and quantity spaces, direct influences and propagation of changes. It is important to develop skills to translate from textual references to processes into the modelling language in order to give the learner an overview of how processes are part of everyday life. The system behaviour produced by such models is easy to understand (increase, decrease, stable), although the distinction between linear and exponential growth or decay is not clear in qualitative representations. The three variations of this pattern were found in 20.0% of the analysed patterns, being less common among the advanced models (2nd phase).

Two or More Processes Acting on a Single State Variable

Recognizing the effects of competing processes provides a more realistic view on systems dynamics. The importance of comparing magnitudes and defining the overall behaviour of the system when opposite forces are active induces insights about inequality reasoning – it may be easier for the learner to understand what is not visible and to deduce the reasons for a particular behaviour to happen.

This pattern can be found in the beginning of the causal chain if associated to exogenous variables (otherwise the rates would have no derivative value). Often it appears in the middle or at the end of the causal chain. Alternative implementations include different quantity spaces and, less often, more than two rates affecting the same state variable. Again, even with two rates, the system behaviour produced by the pattern 'two or more process affecting a single state variable' can be linear or exponential growth or decay. This pattern was observed in 5.2% of the patterns sample, and there was a slight decrease of use in the 2nd phase of the project (Table 1).

Network of Causal Influences

This basic pattern completes the introductory set of activities of DynaLearn curriculum related to basic knowledge about modelling elements and vocabulary. It does not include processes, as it is basically related to propagation of the effects of processes represented by another basic pattern. Three variations are possible: short chain, long chain and branching. These are typically connecting patterns, bringing together different patterns. Being a bridging pattern, it can be associated to processes captured in any of the basic patterns in the beginning of the causal chain. Not by chance, these variations account for 42.3% of the total analysed patterns. In the 2nd phase, it was observed a relative increase in the use of the short pattern, and a decrease in the use of long chains, another hint of preference for more complex model patterns in advanced models.

Direct Feedback

Feedback loops are at the heart of systems thinking. These are, therefore, a central topics for any curriculum, in any domain of knowledge. Direct feedback loops involve only the rate(s) and the state variable(s), and can be either positive or negative. Thus, they are ideal to introduce control mechanisms to the learners. More complex arrangements include two direct feedback loops affecting the same state variable. Testing models with different arrangements at length pays off, as the learners should really grasp the functioning of feedback mechanisms to understand systems behaviour. Direct loops were found in 17.4% of the analysed patterns, and a relative decrease in the use of this pattern was observed in the 2nd phase.

Indirect Feedback

In ecological and environmental systems, feedback loops may become very complex, and their effects may appear long after the initial stimulus, due to the huge amount of possible connections between variables. Accordingly model patterns related to indirect feedback loops should play a significant role in models about topics in ecological and environmental science disciplines. In fact, due to a decision that limits the size of the models to be developed in DynaLean project, only 5.4% of the analysed patterns represent indirect feedback loops.

Additionally, an important feature should be stressed for the learners: when managers want intentionally restrict or change the system behaviour, they should focus their attention on feedback loops and their actions on the rates. These are the bases of any system behaviour.

Inequality Reasoning Pattern

Inequality reasoning, associated to indirect feedback loops, provide the possibility of expanding the effects of processes on unbalanced situations to distant parts of the systems, far from where the mechanism of change operates. As a consequence, this kind of feedback may add delays and extra complexity to the system behaviour. These features have potential for including in the curriculum different aspects than those addressed by previous patterns, in which the effects of the processes and feedback loops were direct and the systems represented were relatively simple. This pattern was found in 9.6% of the total sample of model patterns analysed (Table 1). A relative increase in the use of this pattern during the 2nd phase of the project was observed (6.6% to 14.8%).

A Working Example of Using Model Patterns in Model Building

Forrester (2009) points out that a major benefit from the development of system thinking skills is the development of abilities required for translating concepts expressed in natural language into the formal statements required for building computer models. This can be a demanding process, as shown in evaluation activities run in the DynaLearn project (for ex. Mioduser et al. 2012).

Activities exploring texts in natural language to identify entities, quantities and processes were carried on during the evaluation of DynaLearn (for ex., Salles et al. 2010). It is important to associate natural language elements to modelling primitives to develop modelling skills. Processes are associated to verbs, actions; entities, to nouns; properties of the entities are associated to nouns describing collections (as population), amounts and scales (volume, mass, amount, height); quantity values, to grade adjectives (as small, large, high); and so on (see Kuhene, 2003). An example is presented in the following text: 'Evaporation (a process) of water contained in the container (an entity) has caused the volume of liquid water (noun describing amount) to decrease (dynamics) up to small (grade adjective).'

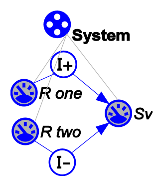
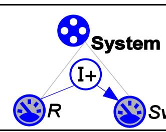
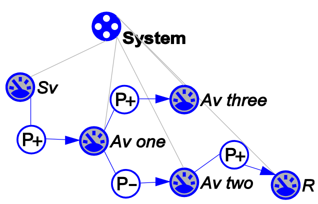
The following educational activity is an adaptation based on a text used in evaluation activities described in Salles et al. (2010). The goal of this exercise is to build a model in Learning Space 4, using direct influences and proportionalities in a single model expression (Salles et al. 2012). Excerpts of this text are presented in Box 1.

The environmental problem of hydrological erosion

> While preparing the ‘National Plan Against Desertification’, focusing on the Brazilian Northeast region, the Ministry of Environment estimates in 1.5 million km2, or 154.9 million hectares, the area under any type of degradation process in the country.
>
> Agência Nacional de Águas. *Programa Produtor de Água*. Brasília: ANA; SUM, 2009. 20p. (in Portuguese)

The starting point of the exercise was the recognition, in the text, of elements that may be included in the model, such as objects (entities), quantities, quantity relations and values, processes and so on. Having the model patterns toolkit available, the activity should move to the selection of pieces of model structures to start with. The following box relates pieces of the text and candidate patterns.

Box 1. Pieces of text and a candidate model pattern to be associated to the text.

“Economic impacts only appear when erosion rates go beyond the tolerance levels, that is, when they are greater than [pedogenesis] the natural soil formation rate.” (…)	
“The high values of erosion rates are due mainly to deforestation in hillsides and river borders,” (…)	
“Erosion impacts go beyond environmental problems. They include risks and losses to the Brazilian energetic matrix, due to the accumulation of sand in dams of big hydropower plants; social impacts caused by rural exodus, economic impacts due to high costs of water treatment for human consumption, and impacts on human health caused by water borne diseases.”	

Having selected the possible model patterns, next step is to build a model by combining them (Figure 9).

A similar operation, but in the opposite direction, could be made in order to move from a model implemented in Learning Space 4 into Learning Space 6 (or a Garp3) model, in which the model has to be divided in model fragments. In these cases, model patterns are the first choice to split the model expression.

Discussion and concluding remarks

The idea of generic and transferable model structures for introducing system dynamics and systems thinking in education has been discussed by system dynamics community (for example, Forrester 1997; Richmond 2001; 1993). Forrester (1997) argues that some *generic structures* can be found repeatedly in different situations, even in entirely different domains of knowledge. For this author, if a particular structure is understood in one setting, it is understood in all settings. This way, generic structures “provide the student with power to move between subjects with the learning on one subject being applied to other subjects. After understanding a collection of basic dynamic structures, a student can quickly draw on one to understand a new situation if its structure has been encountered previously” (Forrester 1997, p. 24).

A similar concept has been independently developed to characterize and identify qualitative model patterns while analysing a set of models produced in DynaLearn (Salles et al. 2012). Both approaches share the notion that pieces of models can be reused, and are valuable tools for learning. Among the differences, the observation that generic structures are actually small system dynamics models, used as stand-alone models or as subsystems of bigger models (Richmond 2001). Qualitative model patterns in turn include micro and partial patterns, as in network chains, that are bridging structures for linking different patterns.

Besides that, qualitative model patterns use only qualitative representations of differential equations and monotonic functions (Forbus, 1984), and may use correspondences and conditional knowledge for overcoming some of these restrictions in order to obtain some behaviours of interest. Of course, different mathematical functions used in generic structures may easily capture behaviours such as exponential growth, damping and precise notions as half-life. Qualitative representations in turn offer explicit accounts for causality, may be used with incomplete knowledge and provide a rich vocabulary and an appropriate language in the educational environment. The S-shaped curve example, with a diagrammatic representation of the system structure explaining the behaviour of density dependent populations in terms of feedback loops illustrates some of the advantages of a qualitative reasoning approach over mathematical models for educational purposes.

Liem et al. (2009), while discussing generic modeling problems and model debugging, identified repetitive model structures – patterns – that modellers encounter as solutions for some modeling problems. These solutions are foreseen as handlers to debug models and to provide modeling advice.

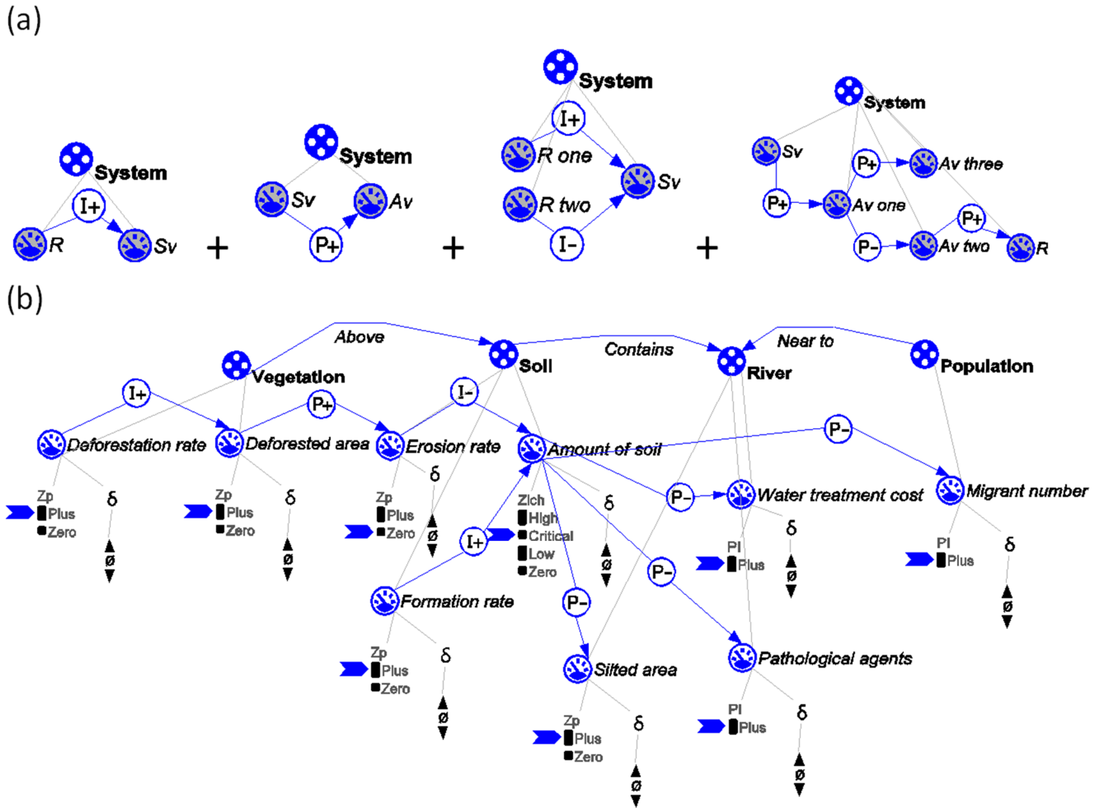


Fig. 9. Knowledge transfer from text into model patterns and then into a model. (a) selection of model patterns; (b) the model expression built.

Although there is some overlap between patterns in Liem et al. (2009) and the work presented here, these authors make no relation between model patterns and system behaviour patterns. Also, while the work presented here sees model patterns as part of a curriculum based on learning by modelling approaches, their focus is on providing better software support to modellers.

However, there are many problems to be solved before a curriculum extensively based on learning by modelling become acceptable for national education systems. Forrester (2009) summarized the central question: "Understanding systems is crucial to improving the organization of schools and to modernizing material that students learn. But how is one to think about systems?" A number of initiatives to bring systems thinking into schools, changing the focus of from a teacher – centred to a learner – centred approach (Forrester 1997) proposing a new curriculum organization (Forrester 1997; Mandinach and Cline 1996) and adopting the following tripod, as put by Mandinach and Cline (1996): system dynamics, as the theoretical perspective; a simulation modelling software and a digital computer.

The model patterns presented in this paper are part of the construction of new curricula and pedagogical approaches. Although their potential is notable, it is necessary to go through evaluations involving students, teachers and institutions where system thinking skills are required.

Ongoing work includes the evaluation of model patterns for organizing courses, and to arrange adequate sequences of topics. As the patterns approach is domain independent, it is also interesting to investigate the application of Dynalearn curriculum in other disciplines. Physiology is a serious candidate, because this domain deals with dynamic systems controlled by a high number of feedback mechanisms.

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