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Abstract

This deliverable represents the background, and justification, of the advanced topics and models prepared by partners at The University of Hull for Task 6.4 of DynaLearn. The deliverable presents nine advanced models in learning spaces LS5 or LS6 across four main topics. These models advance and integrate some of the models and topics presented in D6.2.2. For each advanced topic and model the curricula background, key modelling objectives, modelling decisions and outcomes are presented. For each model the efficacy of the representation is discussed in terms of both the modelling and educational objectives.

Internal review

- Michael Wißner, The University of Augsburg (UAU).
- Petya Borisova, Bulgarian Academy of Sciences (IBER).

Acknowledgements

The authors wish to thank the WP6 partners for their feedback and internal review of the advanced topics and models presented here. Thanks must also go to the partners at UAU and IBER for their comments and review of this deliverable. Special thanks must go to Floris Linnebank (UVA) for his technical support and ideas regarding the construction of some of the models.

Document History

Version	Modification(s)	Date	Author(s)
01	Draft	2011-09-28	Richard Noble & Ian Cowx
02	Final following integration of comments from internal reviewers	2011-09-30	Richard Noble & Ian Cowx

Contents

1. Introduction

1.1. Background

The DynaLearn project is developing a software learning environment that integrates three well established, but as yet independent, technologies to create an individualised and engaging cognitive tool for acquiring conceptual knowledge in environmental science. The software integrates a diagrammatic approach to constructing qualitative conceptual models, ontology mapping and semantic technology to ground model building terms and compare models, and virtual character technology to provide individualised feedback and enhance motivation of learners. In addition to the software development the project is also developing a curriculum in environmental science based around the learning by modelling approach which is the cornerstone concept for the DynaLearn pedagogical approach.

Development of the learning by modelling curriculum requires the creation of a resource base of models that cover important concepts identified in the themes and topics relevant to environment science education. The relevant themes and topics were identified in project deliverable D6.1 (Salles *et al.,* 2009). In addition to providing a resource base for an environmental science curriculum the topics and models (and modelling activity) presented here serve three purposes:

- Explore and test the capabilities of the new modelling software and the new learning spaces (LS);
- Provide a resource of models to help develop and test the semantic and virtual character technologies;
- Provide a resource on which lesson plans and evaluation activities can be developed.

Following the development of a repository of basic topics and models for the curricula in Task 2.2 (D6.2.2, Noble, 2010), Task 6.4 (T6.4), Advanced topics and models (M22 - 30), is defined in the Description of Work as follows:

A refined set of curriculum topics and related models will be timely provided by FUB, TAU, UH, CLGE, and BOKU for the evaluation study in WP7, so that WP7 beneficiaries have material to prepare the second lessons and evaluation activities. Topics and models will be customized in accordance to each beneficiary's expertise and interest.

This deliverable presents the topics and models developed by The University of Hull as advanced topics and models within this context.

1.2. Goals for advanced models

Following the review of the basic topics and models presented as part of the results of Deliverable D6.3 (Noble *et al.*, 2011), advanced topics and models were defined as being independent units of advanced system oriented knowledge that could be re-used in different curricula on environmental science. Deliverable D6.3 identified that advanced models should be focussed around the most important patterns and processes within curricula topics. Furthermore, the advanced models should be insightful and situated at an appropriate level of complexity to capture insightful explanations of phenomena, taking best advantage of the available features of each learning space in DynaLearn.

The features identified for “advanced models” in D6.3 included:

- “advanced” means more complex models, that provide insightful explanation for more complex domain phenomena;
- “advanced” model “complexity” comes from two sources;
    - by representing more complex phenomena = integration of basic laws and first principles to address a more complex problem;
    - including more elements on the model, refining concepts = requires complex LS 2-4 models, and LS5 and LS6 models;
- describe mechanisms that explain how things work and integrate;
- develop formal explanations for the system behaviour of advanced topics;
- advanced models should be optimised to exploit the software capabilities.

D6.3 indentified that advanced models should be clearly and suitable framed within a domain topic and have an appropriate curricula context. In that context, in addition to the criteria listed above, the models and topics addressed here were all chosen due to their characteristic systems behaviour that presented both challenges and opportunities for advanced qualitative conceptual modelling. That is, one of the key criteria for selecting which of the basic topics and models to advance in Task 6.4, was the extent to which identifiable and characteristic behaviours were a key curricula element of the concept, rather than topics that had less well defined systems behaviour that could be considered.

The advanced models developed here are formulated around these criteria for advanced models, and around the good modelling practice defined in D6.3 (Noble *et al.*, 2011). The elements for good modelling practice were identified as:

- A parsimonious approach should be applied to the definition of quantity spaces, where the spaces are only expanded where there is a need to show explicitly distinct qualitative states or there is a clear need to visualise behaviour within a simulation value history.
- A clear distinction between the structural and the behavioural aspects of a system and, as such a clear distinction between entities and quantities.
- A model should have a clear modelling goal in the sense that it should explain a particular mechanism that is aimed to be conveyed to students.

2. Topics and models addressed in this deliverable

2.1. Links to DynaLearn curricula and basic models

The DynaLearn deliverable D6.1 (Salles *et al.,* 2009) identified and described a series of topics in Environmental Science that cover the seven main themes identified in the project description of work (Table 2.1). These topics and themes are considered to be a comprehensive curriculum for concepts in environmental science. Fourteen of these topics were assigned to UH and had basic models developed for them in Task 6.2 (D6.2.2, Noble, 2010) (Table 2.1).

Table 2.1 Summary of themes and topics assigned to UH from the D6.1 curricula in Environmental Sciences and the topics and models developed as basic models in UH D6.2.2. Topics highlighted in bold are those successfully developed as advanced models and topics and reported in Task 6.4.

Theme	Topic	Sub-topic	LS01	LS02	LS03	LS04	LS05	LS06
ESR	*Nutrient availability and cycling*	*Carbon cycle*		✓				
		Nitrogen cycle				✓		
		Phosphorous cycle				✓		
		Nutrient cycles	✓					
	Adaptation to environmental stress	**Homeostasis**	✓			✓		✓
TLW	*Evolution*	*Evolution*	✓	✓	✓			
	Decomposition	*Decomposition*	✓	✓	✓	✓		
HP	*Reduce, reuse, recycle*		✓			✓		
	Human Development Index (HDI)		✓	✓				
LWU	*Agro-ecology systems*		✓	✓				
	Fishery	**Fishery**	✓	✓			✓	✓
		Intra-specific population regulation						✓
	Photosynthesis	**Photosynthesis**	✓	✓	✓	✓		✓
	Aerobic respiration	**Cellular Respiration**	✓	✓		✓		✓
P	**Diffusion and osmosis**	**Diffusion and Osmosis**	✓	✓	✓	✓		✓
	River rehabilitation		✓	✓				
GC	*Greenhouse gases*	*Green house gasses and climate change*	✓	✓	✓	✓		
	Climate change							

Earth Systems and Resources (ESR), The Living World (TLW), Human Population (HP), Land and Water Use (LWU), Pollution (P), and Global Changes (GC)

The review of models and topics in D6.3 (Noble *et al.*, 2011) highlighted the key goals for development of advanced models, with one of the key ones being that the models address topics with identifiable and clear behaviours. As such five key topics were identified from Table 2.1 (highlighted in bold) as having clear potential to be developed into advanced models. For the advanced models presented here this represented systems with well defined behaviours that could be simulated. In this context advanced topics were chosen as those with advanced behaviours that could only be expressed in the advanced learning spaces of DynaLearn (LS5 and LS6). These topics were also chosen as having high relevance to current A Level curricula and local curricula at The University of Hull, in particular the Fishery topic.

2.2. Educational context of modelling content and goals

To frame the models within an education setting the current curricula requirements of the selected topics were considered. By defining the educational level at which the models would be used, the appropriate level of content and concepts was identified. For the purposes of the basic topics considered in D6.2.2 the current A-Level curricula for Biology, Geography and Environmental Science in the UK were considered as the appropriate level to focus the topics and models delivered here (AQA, 2007a, b; CCEA, 2008; Edexcel, 2008). Therefore, the content and goals for the advanced models were mostly defined using literature and texts associated with A-Level guides (Pickering, 2009) and text books aimed at this level. In addition to these guides, general text books aimed at under-graduate level were also used to generate the additional background material required to frame the models at a more advanced level. The fishery topic, together with the application of the photosynthesis and respiration topics to a limnological setting was chosen for development of advanced models given their relevance to the Aquatic Ecology and Fisheries curricula of the undergraduate courses of The University of Hull. Therefore, local curricula and module information were also used to help frame and develop the models for these topics.

The topics selected for development as advanced models also reflected the need for models for use in evaluation studies that matched the curricula requirements and student interests in local settings. As such the fisheries topic became a key focus for advanced models, reflecting both its links to undergraduate modules delivered the Hull International Fisheries Institute and also the links to current A-Level curricula taught in local schools.

2.3. Model presentation and documentation

The models presented here are grouped by topic. Within each section the background knowledge and key curricula goals relevant for the topic at the appropriate educational level are presented. For each topic and advanced model the links to the basic models prepared in D6.2.2 (Noble, 2010) are presented. For each model the rationale, assumptions and goals are briefly summarised and the model structure is presented. Focus is given to the key behaviours that the model is trying to replicate and the educational material on which it is based. In most contexts this is related to sections of specific text books, diagrams or specific experiments a student may undertake. For each model an example scenario and simulation or the range of possible scenarios/simulations is described. For each specific scenario the causes and conditions for the resulting behaviour are given in terms of exogenous controls, (in)equalities, ambiguity or inbuilt controls (either within model fragments or within the DynaLearn simulation settings). For each model a summary of key features and discussion points are presented in terms of its efficacy (in terms of modelling success or constraints), the modelling features used and the potential educational value. These individual discussion points from each model are collated and discussed in Section 7.

3. Photosynthesis & Respiration

3.1. Topic and model metadata

Topic	Diurnal fluctuations in oxygen concentrations in lakes (Photosynthesis & Respiration)		
Author	R Noble	**Version(s)**	DL 0.9.4
Advanced Models	Daily lake oxygen concentration LS6		
Links to basic models (D6.2.2)	Photosynthesis basic LS2.hgp Photosynthesis and respiration LS4.hgp Respiration basic LS2.hgp		
Target users	A Level/Undergraduate		

3.2. Topic rationale

3.2.1. Curricula background

As justified in D6.2.2 (Noble, 2010) the processes of photosynthesis and respiration are fundamental concepts to the study of biology and environmental science. In addition to the molecular, biochemical and physiological aspects to photosynthesis and respiration they can also be viewed at a number of different scales (from molecular and cellular to organism and ecosystem) as they are fundamental processes involved in carbon and energy transfer between different components of ecosystems. In addition to the role they play in the carbon cycle both processes can also be seen as fundamental processes that can alter/regulate environmental conditions. In addition to the role of photosynthesis and respiration in affecting the carbon dioxide concentrations in the atmosphere, and the resultant consequences for climate change, they also play a significant role in regulating the oxygen concentration in freshwater environments (Wetzel, 2001). The daily fluctuations in the rate of photosynthesis of algae and aquatic macrophytes, in relation to daily cycles in light intensity, means that there can be marked diurnal oscillations in the oxygen concentration of freshwater systems (Figure 3.1). This is primarily due to the production of oxygen from photosynthesis during the day exceeding the consumption by respiration of aquatic biota. Oxygen levels fall at night as it is consumed by the respiration of aquatic biota, the rate of which is independent of light intensity. The intensity of these diurnal oscillations can be affected by the trophic status of the system (essentially the extent to which respiration of highly abundant algae and bacteria in eutrophic systems strips oxygen from the water during the night) and also by the physical nature of the waterbody, including how well oxygen can diffuse from the atmosphere into the water through surface mixing. These oxygen concentration oscillations can have knock on effects to sensitive aquatic biota if overnight oxygen depletion reduces the oxygen concentration below levels which are critical to their survival.

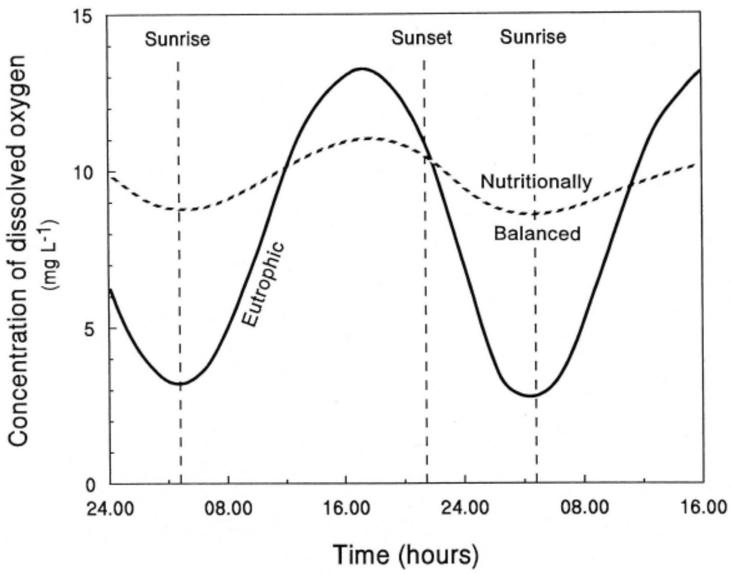


Figure 3.1 Diurnal cycle of dissolved oxygen concentration in waterbodies of differing nutrient status (reproduced from Wetzel, 2001 after Walling & Webb, 1994; using data from Gower, 1980).

3.2.2. Key themes

The fundamental themes for the role of photosynthesis and respiration in regulating oxygen concentration in freshwater environments are:

- The light-dependence of the rate of photosynthesis.
- The balance between oxygen consumption by respiration and oxygen production by photosynthesis as the driver of the diurnal oscillations in oxygen concentration.
- The link between trophic status and the intensity of the oxygen concentration oscillations.
- The possibility of overnight oxygen concentration sags falling below the critical oxygen concentrations for sensitive species such as fish, and causing oxygen stress or mortalities.

3.3. Diurnal fluctuations in Oxygen concentrations of lakes

3.3.1. Concepts and goals

The main goal of the model addressing diurnal fluctuations in the oxygen concentration of lakes was to be able to mimic the oscillatory behavioural pattern shown in Figure 3.1. Essentially this required that the model was able to reproduce the pattern in a simulation and was also driven by an appropriate mechanism that fully explained the oscillations as being regulated by the light-dependency of photosynthesis. They other key objective for the model was that it could act as a foundation model on which models addressing the themes of eutrophication and oxygen depletion fish kills could be built.

Therefore, the model aimed to have a structure that could apply generic knowledge concerning photosynthesis and respiration in aquatic systems to more specific systems and scenarios which include a number of different species and animal groups (e.g. bacteria, algae, macrophytes and fish).

3.3.2. Model design

Given that the model was required to exhibit a complex oscillatory behaviour, and aimed to be able to apply generic knowledge to a number of specific situations and scenarios, the model was created utilising the entity hierarchy, inheritance and compositional approach of LS6.

The ability to apply generic and specific knowledge in the model was achieved using the entity hierarchy shown below where numerous sub-types of *Biota* entities were defined (Figure 3.2). This enabled model fragments to be created describing knowledge about respiration that applied to all forms of biota and fragments about photosynthesis that only applied to *Autotrophs*. The hierarchy structure also allowed the model to be developed such that the generic background behaviour would be the same if the scenario considered *Fish* and *Macrophytes* or whether it considered *Bacteria* and *Algae*.

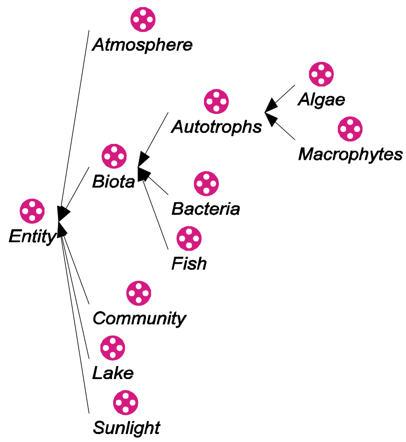


Figure 3.2 The entity hierarchy used in the model representing diurnal fluctuations of oxygen concentration in freshwater lakes. The use of hierarchy for the different types of biota allows general expressions to be made about biota respiration but more specific expressions about autotrophic plants and their photosynthesis.

The compositional modelling approach was used for the model, also attempting to employ an approach where static fragments were created for each of the individual core entities in the model (e.g. *Atmosphere*, *Autotrophs*, *Lake* etc., Figure 3.3). These fragments of core knowledge describing the quantities associated with each entity were then re-used in the more complicated static fragments and process fragments that developed system structure and behaviour.

The model is driven by three process fragments representing respiration by any form of biota, photosynthesis by any type of autotroph and surface diffusion from atmospheric oxygen (Figure 3.3). However, the oscillatory behaviour in the relative (in)equality between photosynthetic oxygen production and oxygen consumption is controlled by the interplay of an exogenous sinusoidal behaviour of light intensity, an expanded quantity spaces to represent different periods of day and a suite of model fragments that specify the (in)equality of respiration and photosynthesis at different times of day.

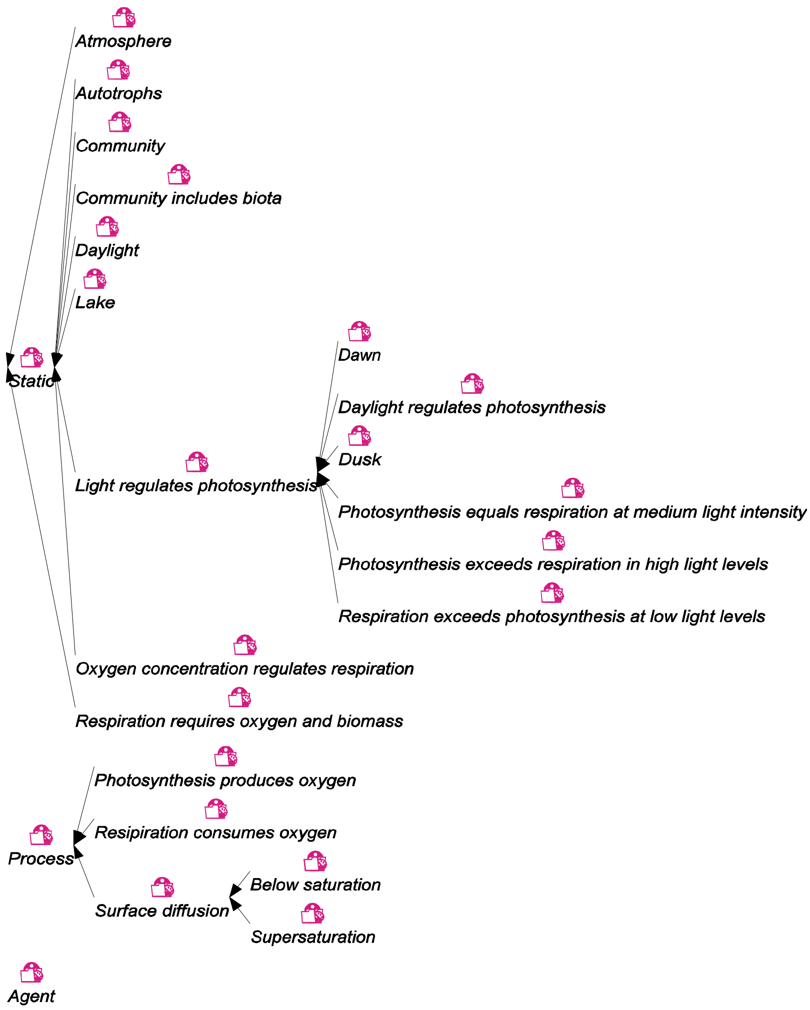


Figure 3.3 The model fragments used in the model representing diurnal fluctuations of oxygen concentration in freshwater lakes. The static fragments represent the decomposition of knowledge into basic elements that are the re-used for process fragments and for the static fragments containing conditional knowledge regulating the cyclical behaviour.

Most of the quantities and quantity spaces used in the model follow a minimalist approach in that they are either {Plus} (a simple interval) or {Zero, Plus}, a quantity space consisting of a zero point and a positive interval (used to represent rates). However, two of the quantities had expanded quantity spaces which were designed to both give a distinctive visual pattern to value histories of behaviour paths and to allow representation of different phases in the behaviour in relation to the diurnal cycle. The quantity space for *Light intensity* was expanded to represent times of day, such that a particular time of day (e.g. morning or afternoon) could be inferred by inspecting both the magnitude and the derivative of the QS. The *Light intensity* QS was defined as {Zero, Night, Dawn/Dusk, Low, Medium, High, Midday}, and was designed to be controlled by an exogenous influence in a simulation such that it oscillates through the QS from zero to midday and back again. Given this a light intensity that is above the dawn/dusk threshold point and has a negative derivative can be seen as being afternoon with the sun setting. In addition to enabling the representation of diurnal cycles in light intensity the quantity space also used two point values, {Medium} and {Midday}, to represent firstly the light intensity at which the *Photosynthetic rate* started to exceed the *Respiration rate* (Figure 3.4 for example of conditional model fragment), and secondly the point at which the *Photosynthetic rate* was at its highest.

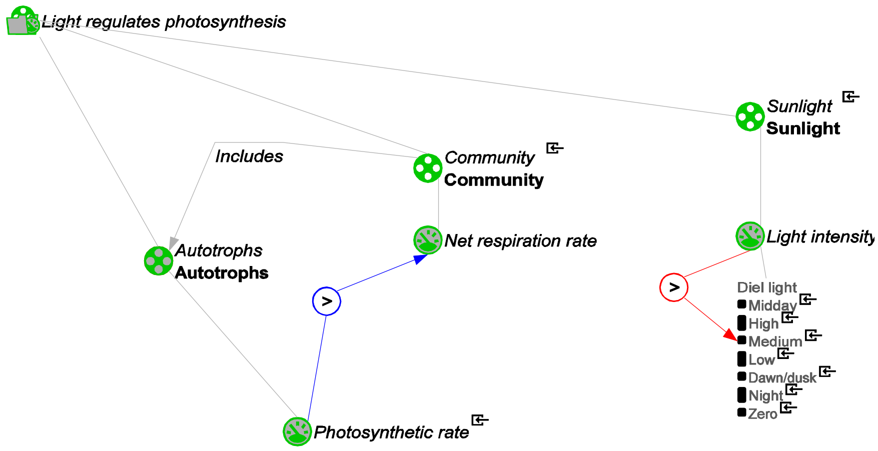


Figure 3.4 An example model fragment from the suite of conditional expressions that regulate the cyclical behaviour of the system in terms of the relative effects of respiration and photosynthesis on oxygen concentration. This fragment states that when *Light intensity* is greater than the value {Medium} (a non-specific threshold) then *Photosynthetic rate* is greater than the *Net respiration rate*.

In the model fragments shown in Figure 3.3 the suite of model fragments formed from "Light regulates photosynthesis" and the six child fragments (inheriting the information presented in the main parent fragment) control the value and behaviour of *Photosynthetic rate* in relation to the magnitude and derivative of *Light intensity*.

Table 3.1 Summary of the seven model fragments that control derivative behaviour and relative (in)equalities in the diurnal fluctuations in oxygen concentration model.

	Name	Function
1	Light regulates photosynthesis (Parent)	Introduces equality statements between *Photosynthetic rate* and *Light intensity* – essentially there is zero photosynthesis when light levels are equal to or below {Dawn/Dusk}
2	Dawn (Child)	Conditional statement – If *Light intensity* is equal to {Dawn/dusk} and increasing Then *Photosynthetic rate* is increasing (note *Photosynthetic rate* is defined as zero under these conditions in the parent model fragment).
3	Daylight regulates photosynthesis (Child)	Conditional statement – If *Light intensity* is > {Dawn/dusk} Then there is a positive proportionality from *Light intensity* to *Photosynthetic rate*
4	Dusk	Conditional statement – If *Light intensity* is equal to {Dawn/dusk} and decreasing Then *Photosynthetic rate* is steady (note *Photosynthetic rate* is defined as zero under these conditions in the parent model fragment).
5	Photosynthesis equals respiration at medium light intensity (Child)	Conditional statement – If *Light intensity* is equal to {Medium} Then *Photosynthetic rate* is equal to *Respiration rate*
6	Photosynthesis exceeds respiration at high light levels (Child)	Conditional statement – If *Light intensity* is > {Medium} Then *Photosynthetic rate* is > *Respiration rate*
7	Respiration exceeds photosynthesis at low light levels (Child)	Conditional statement – If *Light intensity* is < {Medium} Then *Photosynthetic rate* is < *Respiration rate*

All the model fragments shown in Figure 3.3 integrate together to form the full causal model which is represented below (Figure 3.5).

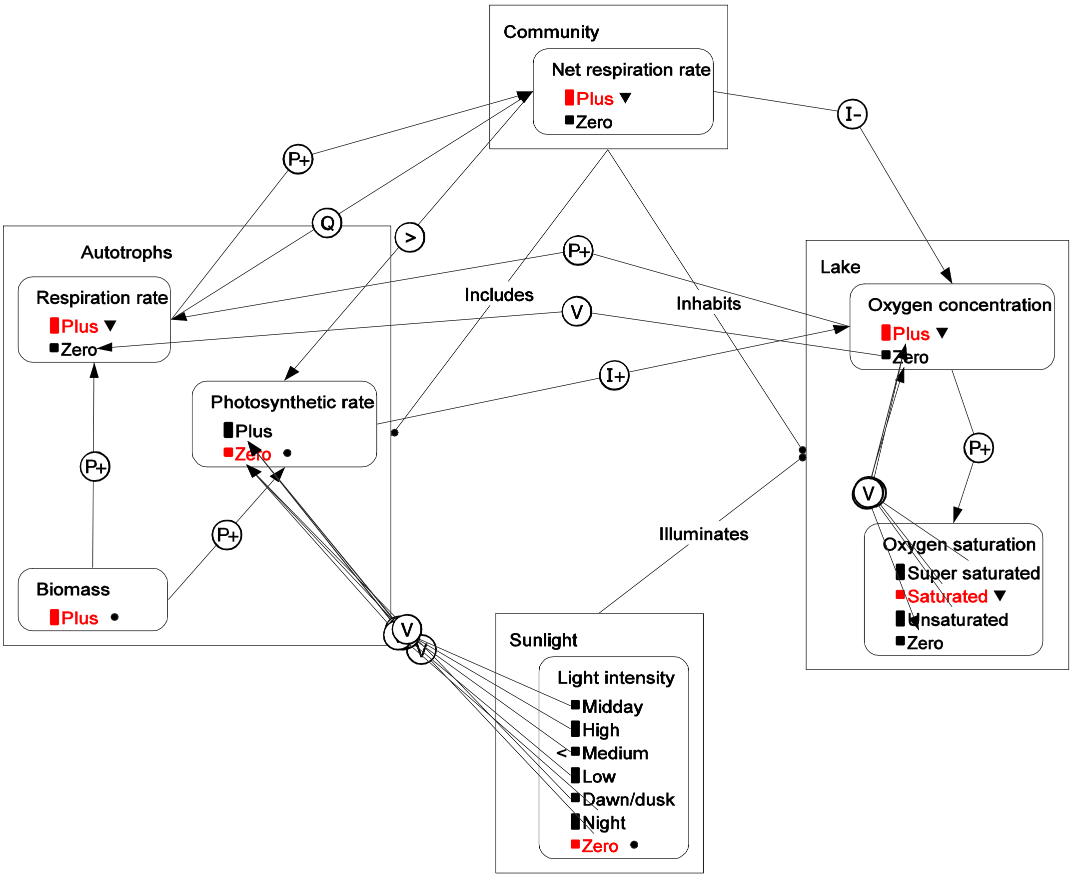


Figure 3.5 Full causal model indicating how all the individual model fragments integrate in a scenario/simulation to reproduce the behaviour of diurnal oscillations of oxygen concentration in a lake.

3.3.3. Scenarios, simulation and behaviour

The model described above was designed to be a foundation for more complex scenarios and simulations that required the diurnal oscillations in oxygen concentration as a backbone to their behaviour. The diurnal oscillation behaviour was generated using the simple scenario below considering only an aquatic community consisting only of autotrophs (Figure 3.6). In this scenario the system is started with the lake being saturated with oxygen and it being midnight (zero light intensity). The simulation is initiated using an exogenous sinusoidal control over *Light intensity*.

Table 3.2 Summary of the starting conditions generating the behaviour for a scenario for the diurnal oxygen concentration fluctuation model.

Type	Details
Exogenous control	Sinusoidal exogenous influence on Light intensity Biomass of Autotrophs is set as steady using an exogenous control
(In)equality	None
Ambiguity	None
Simulation settings	Fastest path heuristic applied (see figures 3.7 and 3.8)

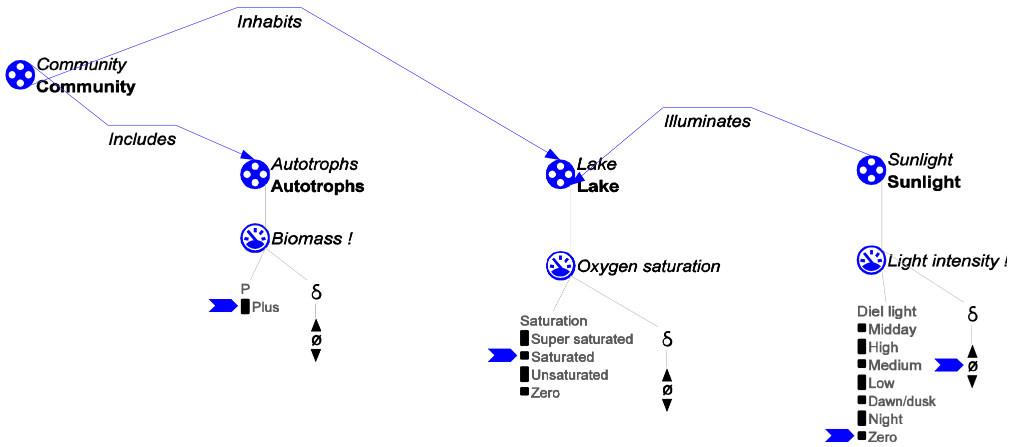


Figure 3.6 A basic scenario designed to represent and simulate diurnal fluctuations in oxygen concentrations in lakes as a function of the regulation of photosynthesis by sun light.

The simple scenario above generates a number of cyclical behaviour paths as shown in Figure 3.7. These cyclical paths are of different lengths and are fundamentally differentiated by the extent to which the oxygen concentration and saturation fluctuates in any one oscillation of *Light intensity*. This is similar to the pattern represented in typical text book figures (as shown in Figure 3.1). However, the different amounts of fluctuation are a result of the open-ended and qualitative nature of the model. In this context a single period of fluctuation could result in a daily fluctuation where the saturation remains constantly within the unsaturated interval, or constantly within the supersaturated, or fluctuates between unsaturated and supersaturated. The multiple loops are generated because it is not possible to quantitatively specify how much oxygen is generated or depleted during any one period where photosynthesis exceeds or is less than respiration. However, by using the fastest path heuristic simulation setting a single cyclical behaviour is observed (Figure 3.8). The example behaviour path shown in Figure 3.8, where the fastest path heuristic is applied and its associated value history (Figure 3.9) shows an oscillation where the oxygen saturation fluctuates between unsaturated and supersaturated.

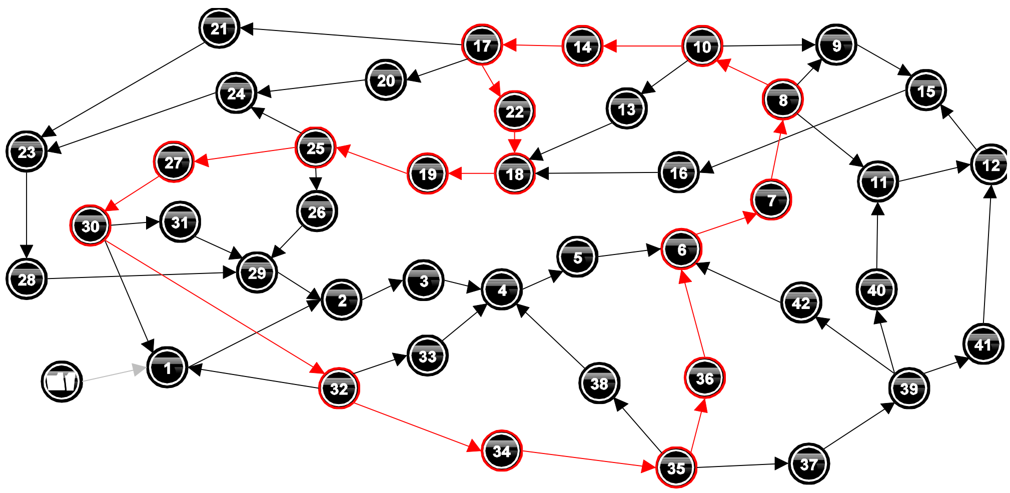


Figure 3.7 The behaviour graph for a basic scenario (Figure 3.6) designed to represent and simulate diurnal fluctuations in oxygen concentrations in lakes as a function of the regulation of photosynthesis by sun light. In this simulation a number of cyclical oscillations can be observed, a result of the different possible oscillations available within the whole quantity space for *Oxygen saturation*.

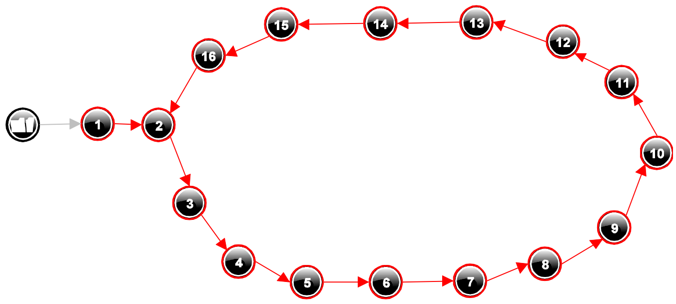


Figure 3.8 The behaviour graph for a basic scenario (Figure 3.6) designed to represent and simulate diurnal fluctuations in oxygen concentrations in lakes as a function of the regulation of photosynthesis by sun light. In this simulation the fastest path heuristic setting was active.

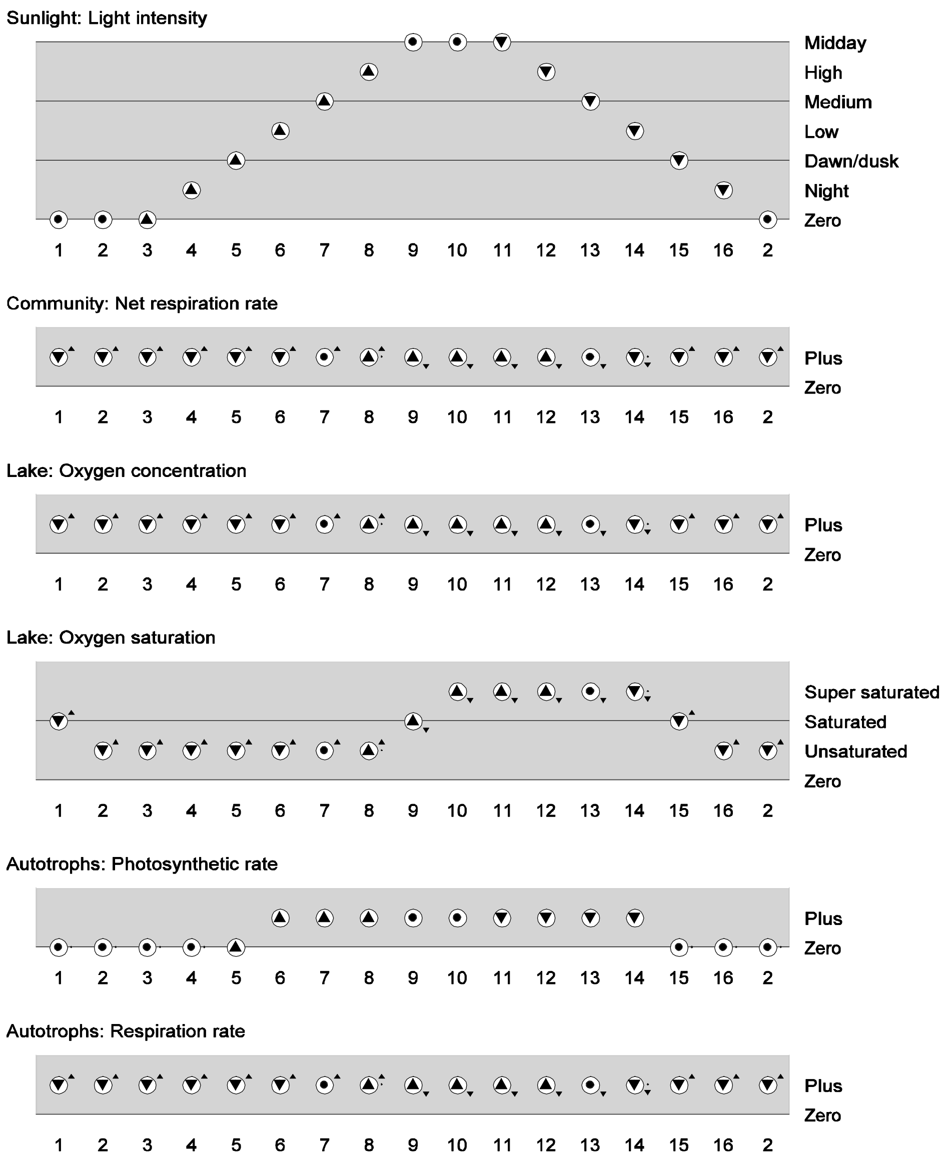


Figure 3.9 An example value history for the behaviour path (Figure 3.8) for the basic scenario (Figure 3.6) designed to represent and simulate diurnal fluctuations in oxygen concentrations in lakes as a function of the regulation of photosynthesis by sun light.

3.3.4. Summary and features for discussion

- The model was clearly focussed on a specific behaviour rather than merely a system.
- The model made a clear use of the entity hierarchy to enable the construction of model fragments and scenarios addressing both generic and specific knowledge about the behaviour and the systems it could be observed in.
- The compositional approach used, where a static fragment was built for each individual basic unit (entity) in the model, enabled the more complicated fragments of knowledge to be constructed by reusing previously defined fragments and also for the model to be more easily examined than one built from a single complex model expression.
- A large proportion of the static fragments built were actually used to define the expected behaviour (particularly derivative behaviour) rather than to construct the system structure. These “behaviour” fragments re-used the fragments that described the system structure.
- There was a parsimonious approach to defining quantity spaces to minimise complexity in a simulation except for specific quantities where an expanded QS was used to clearly differentiate key phases, states and transitions in behaviour in the model (e.g. *Light intensity*).
- The control over derivative behaviours was determined using conditional value assignments for both the magnitude and derivatives of the quantities concerned.
- Exogenous sinusoidal behaviour of *Light intensity* was used, in conjunction with its expanded QS, to generate the desired diurnal oscillation. In this case both the magnitude and the derivative of the quantity combined to describe the state of the simulation in terms of the time of day.
- The fastest path heuristic simulation preference was used to simplify the simulation behaviour path, extracting the key behaviour pattern from all those possible due the possible magnitudes of *Oxygen saturation*. This pattern of behaviour replicated that in the stimuli textbook diagram.
- Whilst without the fastest path a number of oscillatory paths are possible, conceptually relating to the different magnitudes of fluctuation shown in the stimuli textbook diagram in relation to eutrophication it is very difficult to control which of those paths would be produced in a qualitative model.

4. Osmosis & Diffusion

4.1. Topic and model metadata

Topic	Osmosis & Diffusion		
Author	R Noble	**Version(s)**	DL 0.9.4
Advanced Models	Cellular osmosis and diffusion LS6		
Links to basic models (D6.2.2)	Diffusion one sided LS2.hgp Osmosis one sided LS2.hgp Cellular diffusion and osmosis LS4.hgp		
Target users	A Level		

4.2. Topic rationale

4.2.1. Curricula background

Cellular diffusion and osmosis are key drivers in cellular processes and cell regulation. Diffusion is the movement of solute molecules or ions down a concentration gradient from a region of high concentration to a region of low concentration. Osmosis is the special case of the diffusion of water, in the case of water the molecules move down a water potential gradient (a measure of the free kinetic energy of water in the system). In all systems with a semi-permeable membrane, molecules with unrestricted movement will be constantly flowing across the membrane. The rate at which molecules move across the membrane is dependent on the rate at which molecules collide with the membrane (with solute and solvent molecules constantly moving at random in the solution). Areas with higher concentration will have a higher collision rate with the membrane than areas with low concentration, hence resulting in a difference between the rate of inflow and outflow of molecules in the cell (Withers, 1992; Pickering, 2009). Osmosis and diffusion are fundamental concepts that are essential for understanding more advanced concepts in biology and environmental science such as osmoregulation and homeostasis.

4.2.2. Key themes

- Movement of molecules across a membrane, down a concentration gradient.
- Osmosis as the diffusion of water.
- Osmosis/diffusion as the net balance of inflows and outflows.
- Equilibrium characterised by equal inflow and outflow NOT by no flow.
- Concepts of osmotic and cell pressure (turgor)

- Diffusability of different types of molecules and alternative means of movement across membranes (facilitated diffusion, active transport etc.).

4.3. Cellular osmosis and diffusion

4.3.1. Concepts and goals

The main aim of the advanced diffusion and osmosis model was to decompose the basic model created in LS4 (D6.2.2 Noble, 2010) into its constituent elements of basic knowledge to:

a. Present a simplification of the representation, given that the LS4 model had a very cluttered model expression.

b. Enable elements of generic knowledge to be applied to specific situations and scenarios.

c. Enable the introduction of concepts relating to cell turgor and active transport where applicable to a scenario.

d. Build a foundation for the application of representation of osmosis and diffusion to other advanced concepts such as homeostasis and osmoregulation.

4.3.2. Model design

The osmosis and diffusion model from D6.2.2 (Noble, 2010) was deconstructed from a large and confusing model expression into a compositional model in LS6. The model made full use of the inheritance function of the entity hierarchy enabling generic model fragments to be made with generic knowledge concerning membranes, solutions, solutes and solvents which could then be applied to specific fragments or scenarios that considered specific types of solutions or solutes (Figure 4.1).

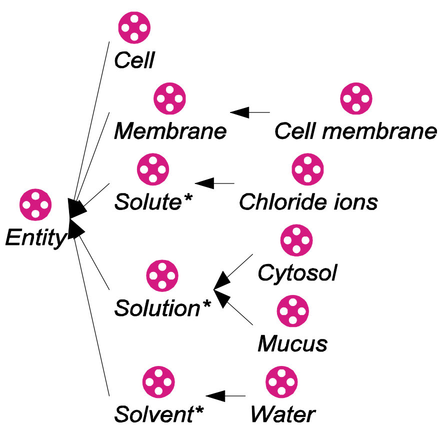


Figure 4.1 Entity hierarchy used in the advanced LS6 model concerning cellular osmosis and diffusion. The use of hierarchy and sub-types of entities allows the derivation of generic and specific knowledge and the re-use of model fragments capturing generic knowledge in specific scenarios.

The compositional approach used initially defined a series of static model fragments that represented each individual element in the model, so that each entity concerned had a model fragment representing it together with its respective quantities. These basic model fragments were then reused and integrated into more detailed fragments showing how the different entities related to each other in terms of configuration and structure and behaviour (in the process fragments). For example, the *Solution* model fragment re-used the *Solvent* and *Solute* fragments and the separated solutions fragment re-used the *Solution* fragment twice (Figure 4.2).

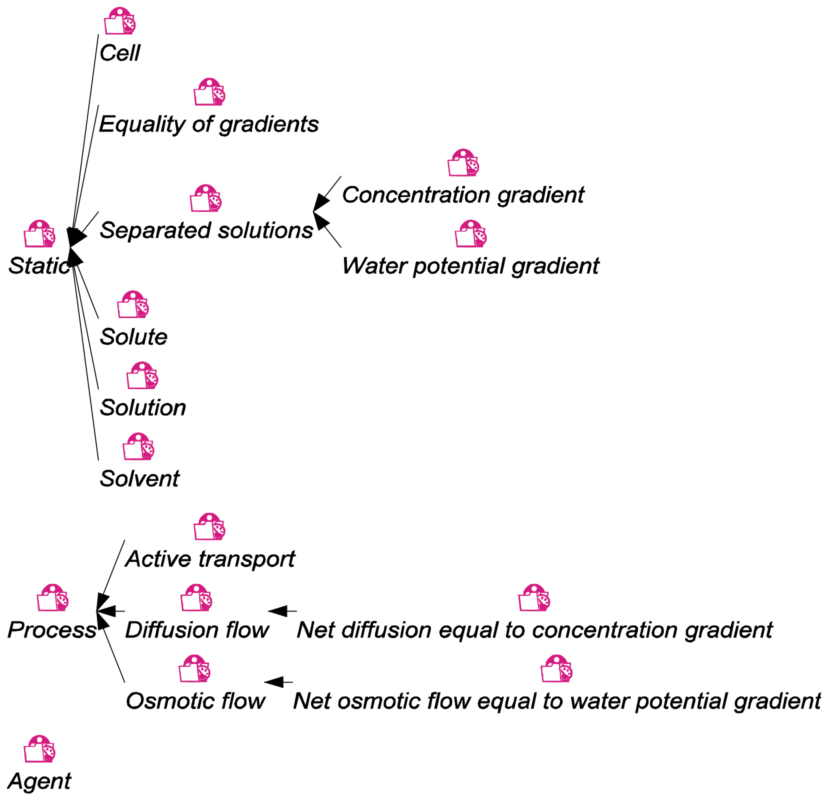


Figure 4.2 The model fragments used in the model representing cellular osmosis and diffusion. The static fragments represent the decomposition of knowledge into basic elements that are the re-used for process fragments and for the static fragments containing conditional knowledge regulating equilibrium behaviour.

One of the fundamental representational decisions in the model was to have both osmosis and diffusion represented as a pair of competing flows (rates) of molecules flowing across a membrane. For example, this would mean diffusible molecules are both entering and leaving a cell at the same time and that the net diffusion rate was the difference between these two rates. This was achieved by using configurations and a membrane entity to separate the concept of an internal and an external solution (Figure 4.3, a fragment which reuses the Separated solutions model fragment). The model then has a pair of diffusion rates implemented; *Diffusion in* and *Diffusion out*. Both the rates act to move molecules of solute across the membrane, but in opposite directions using direct influences.

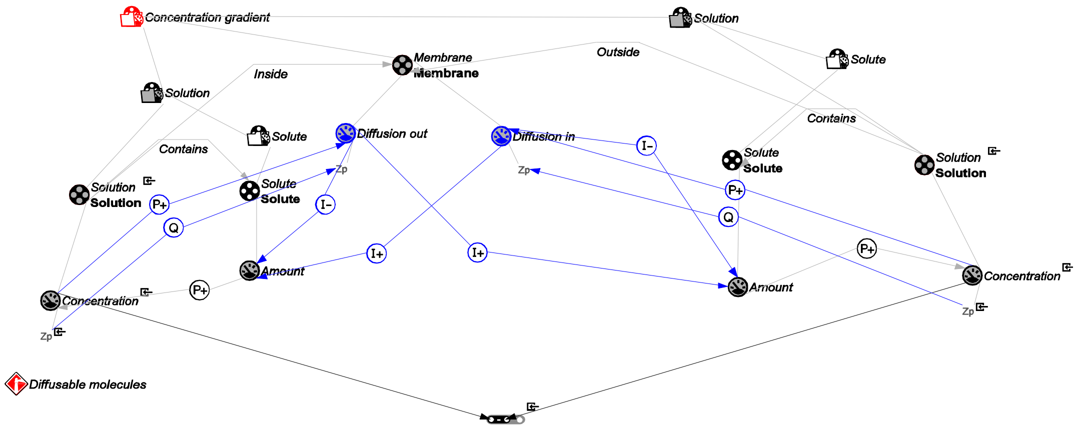


Figure 4.3 An example process model fragment representing diffusion as the balance of both an inflow of diffusible molecules and an outflow. In this expression both flows have opposite direct influences in the amount of solute in the internal and external solutions.

The model implements two pairs of calculi (one pair each for osmosis and diffusion), firstly to calculate the concentration gradient (or water potential gradient in the case of osmosis) as the difference between the concentrations of the two solutions (Figure 4.4) and secondly to specify that the difference between the *Diffusion in* flow and the *Diffusion out* flow (the net diffusion) is also equal to the *Concentration gradient*. In other words the magnitude of the net diffusion rate is directly related to the magnitude of the concentration gradient across the membrane.

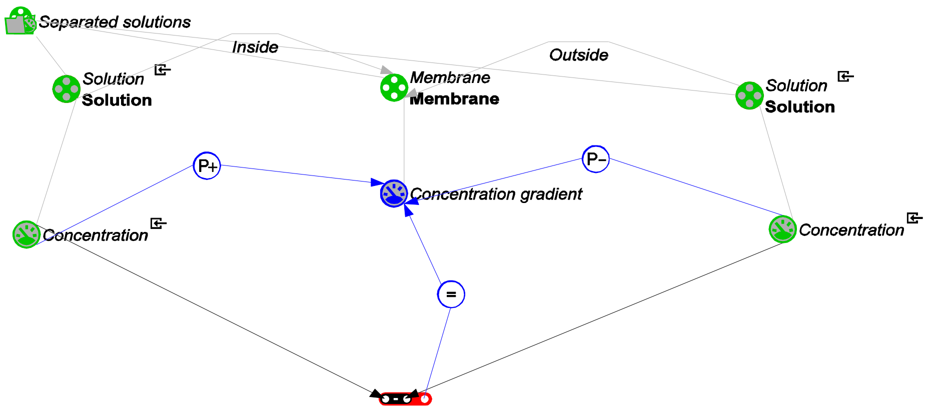


Figure 4.4 An example process model fragment representing a concentration gradient as being a quantity related to the membrane separating two solutions. The gradient is represented as the result of a calculus between the concentrations of the two solutions.

The osmosis and diffusion model uses minimalist quantity spaces with most quantities restricted to {Zero Plus} or {Plus} since the concepts to be conveyed are generally to do with (in)equality between flows and between concentrations. However, an unusual QS is used for *Water potential* to represent a curricula concept. This quantity has a {Zero Minus} QS to show that *Water Potential* is usually defined as a negative number (where pure water has a water potential of zero), such that the more negative the value for water potential the more concentrated the solution is (Pickering 2009). As such there is an inverse value correspondence between the QS of *Concentration* and of *Water potential*.

The model fragments listed above combine within scenarios and simulations to give the full causal model shown in Figure 4.5 where the behaviour is driven by the (in)equality between the concentrations of the two separated solutions. In the example listed below only osmosis is represented as the "*Diffusible molecules*" assumption has not been applied which is required to activate the Diffusion flow model fragment (Figure 4.3).

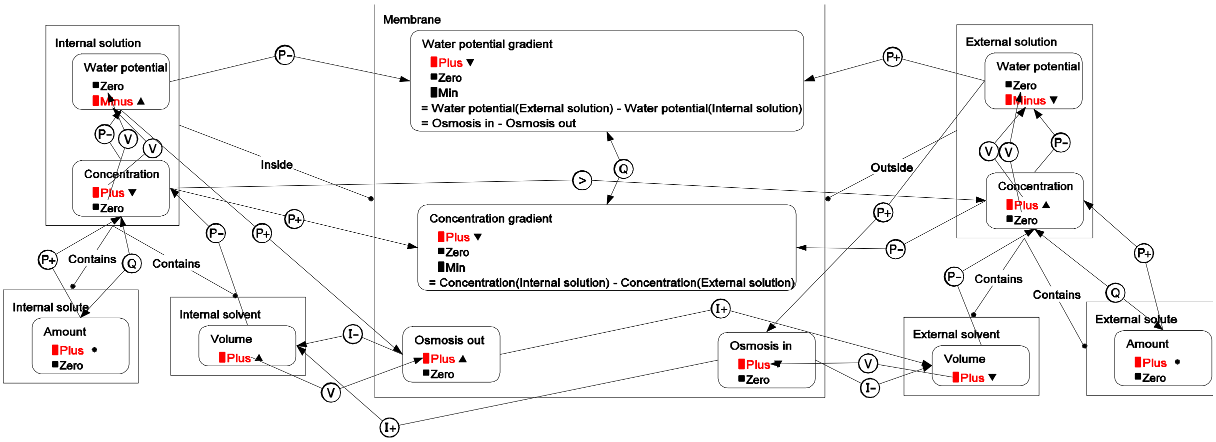


Figure 4.5 Full causal model indicating how all the individual model fragments integrate in a scenario/simulation to reproduce the equilibrium behaviour of cellular osmosis.

4.3.3. Scenarios, simulation and behaviour

The basic scenario for separated solutions that only considers osmotic movement of water between two solutions of different concentrations generates a very simple behaviour (as shown by the LS4 model in D6.2.2, Noble, 2010). The initial state is one of inequality in concentration which then changes to a state of equilibrium. The simulation results are not reproduced here as they match those presented in D6.2.2.

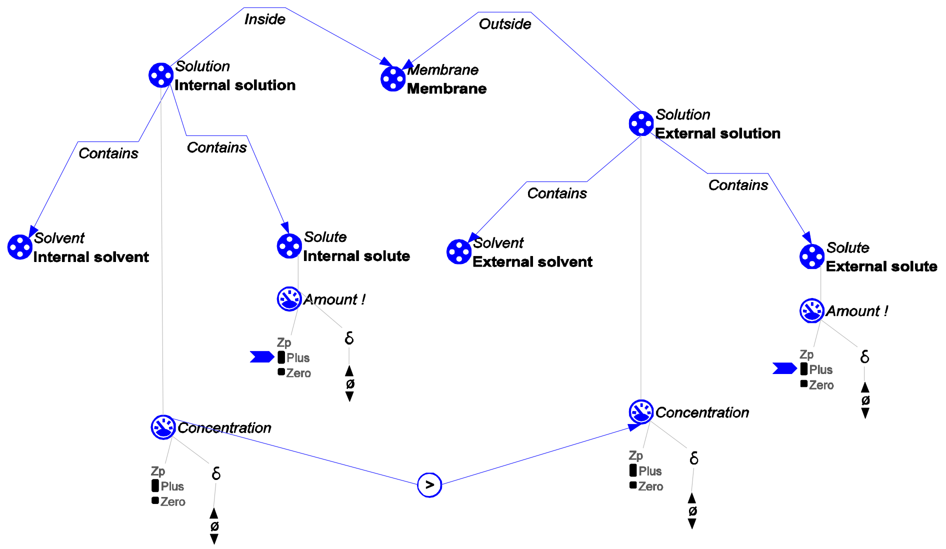


Figure 4.6 A basic scenario designed to represent and simulate osmosis and diffusion as an equilibrium system.

Table 4.1 Summary of the starting conditions generating the behaviour for a scenario for the osmosis and diffusion model.

Type	Details
Exogenous control	Amount of Internal and External solute set to steady (Diffusion not considered)
(In)equality	Concentration of internal solution > Concentration of external solution
Ambiguity	NONE – assumption label not specified for Diffusible molecules
Simulation settings	Default settings

4.3.4. Summary and features for discussion

- The deconstructed compositional view used makes the model much easier to inspect and interpret than the single model expression used in LS4 from D6.2.2 (Noble, 2010).
- The use of the entity hierarchy enables the model to have expressions and scenarios built concerning both generic and specific knowledge about osmotic and diffusion systems.
- There was a parsimonious approach used to defining quantity spaces to minimise complexity in the simulation and also because the key states in the system relied on (in)equalities in quantities rather than their actual magnitudes. Only one QS is unusual, water potential having a {zero, minus} quantity space, to replicate specific domain knowledge concerning how this is usually expressed in standard scientific notation and units.
- The model employs pairs of competing rates (inflow and outflow) for both osmosis and diffusion to replicate the appropriate system and curricula notions of what diffusion and osmosis are and for what it means to be at equilibrium.

5. Fishery & Maximum Sustainable Yield (MSY)

5.1. Topic and model metadata

Topic	Fishery		
Author	R Noble	**Version(s)**	DL 0.9.4
Advanced Models	Intraspecific population regulation LS6 Intraspecific compensation experiment LS5 Fishery Yield LS5 Fishery MSY LS6		
Links to basic models (D6.2.2)	Fishery LS4.hgp Fishery LS6.hgp (adapted from a model developed by F. Linnebank & G. Dante)		
Target users	A Level/Undergraduate		

5.2. Topic rationale

5.2.1. Curricula background

Fisheries are used as a topic in A-Level Biology and Environmental Science to explore the themes related to sustainable use of natural resources. The fishery theme contains many concepts related to population dynamics, resource exploitation and human impact on the environment. Environmental Studies curricula (AQA, 2007) indicate that whilst studying students should gain an understanding of:

- Why an understanding of population dynamics is important in monitoring species' survival, breeding success and in assessing the Maximum Sustainable Yields (MSY) of exploited species.
- How reproduction, mortality and migration control population size.
- How density-dependent factors control population size.
- Carrying capacity.
- The relationship between biomass, recruitment, growth, mortality and capture.
- The concept of MSY and the difficulties in calculating it. Where MSY is the maximum harvest that will not reduce the ability of the population to replace losses.

Fisheries can be managed through a number of input and output controls. One of the most used methods is determination of allowable catches through the application of stock recruitment and population dynamics models. Maximum sustainable yield is a fishery management concept that has underpinned the development of much of the current fisheries management strategies. Maximum sustainable yield theory relies on the concept of sigmoid population growth, where the potential growth and recruitment in a stock occurs at about 30-50% of the maximum possible stock size in the absence of exploitation. This theory would suggest that catches could be maintained at this point where the highest potential for recovery could sustain high catches. Despite the widespread use of MSY in the past there are a number of limitations in its applicability to many fish stocks, especially where their life histories and stock-recruitment relationships are not well known (King, 1995; Begon, Townsend & Harper, 2006).

Therefore, understanding of the fishery topic requires integration of knowledge regarding a basic understanding of population dynamics, density-dependent population regulation, fishery yield dynamics and the sustainability of natural resources. As such it makes a good model system to explore the integration of basic models into advanced models, representing a possible progression of ideas or curricula items. Furthermore, density-dependent sigmoid population growth and yield/catch-effort responses to exploitation represent more complex, non-linear behaviours which represent good challenges to qualitative conceptual modelling in general. This makes the fishery topic a very good model system for advanced modelling within DynaLearn.

5.2.2. Key themes

The fishery topic contains three key themes that need to be represented:

1. Density-dependent population regulation, carrying capacity and completion (Sections 5.3 and 5.4).
2. Yield and catch-effort models in fisheries (Section 5.5).
3. Maximum sustainable yield of exploited fish stocks and over fishing (Section 5.6).

These three key themes are addressed by four advanced models utilising LS5 and LS6. The models capture fundamental knowledge and assumptions about population dynamics and fisheries dynamics that underpin the MSY concept and the basis for management of fish stocks.

5.3. Intra-specific population regulation and density dependence

5.3.1. Concepts and goals

One of the key concepts behind the maximum sustainable yield model is that fish populations can be seen to grow following a sigmoid, rather than an exponential, growth curve. This sigmoid growth curve is caused by density-dependent growth patterns and the effect of competition on the birth and death rates in a population. The patterns of the effects of intraspecific competition on birth and death rates are presented in Figure 5.1 (from Begon, Townsend & Harper, 2006). These idealised patterns bear three main patterns that need to be represented in a conceptual model:

- Birth rate (total numbers born per unit time) may decline with increasing density (Figure 5.1 a, c, d)
- Death rate (total number of deaths per unit time) may increase with increasing density (Figure 5.1 a, b, d)

- Populations stabilise at a density known as the "carrying capacity *K*" where the birth rate equals the death rate (Figure 5.1).

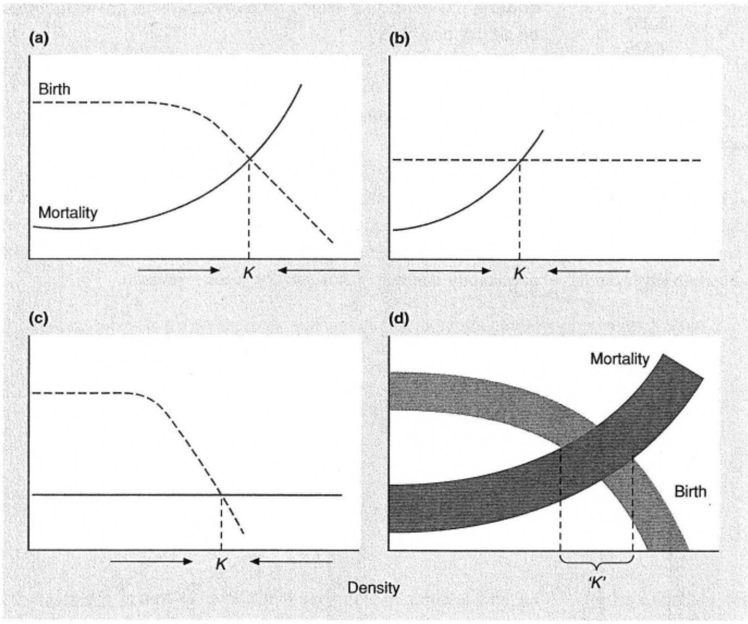


Figure 5.1 Basic schematics of potential relationships between density and birth and mortality (a, b & c). The density at which the lines for birth rate and mortality rate cross is the carrying capacity (*K*). Below this point the population increases in size whilst above this density the population declines. Schematic "d" represents a more realistic situation where *K* is not fixed but represents a dynamic range of possible values (reproduced from Begon, Townsend & Harper, 2006).

The typical model representing intraspecific population growth assumes both density-dependent birth and density-dependent death. As such there is a parabola pattern of net recruitment (birth – death) that defines population growth. Therefore, density-dependent populations grow fastest at intermediate densities and growth slows as the population reaches carrying capacity (Figure 5.2).

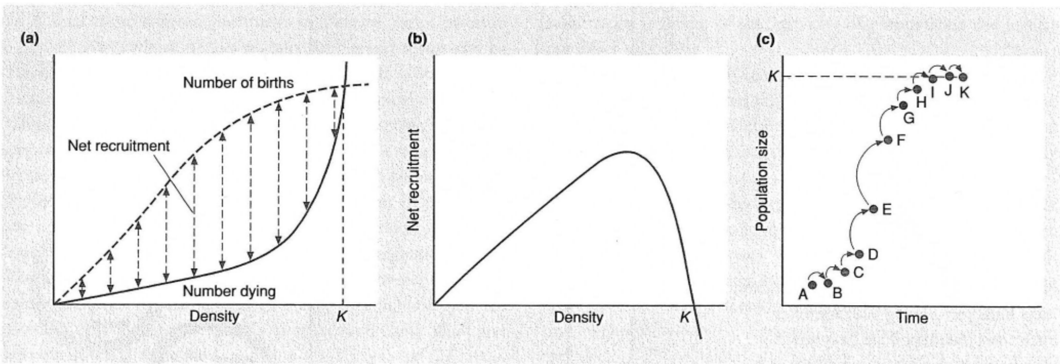


Figure 5.2 Schematic diagrams representing the nature of net recruitment in intraspecific completion. (a) the density-dependent effects on birth and deaths (b) the relationship between net recruitment (births-deaths) and density and the sigmoid growth curve of a density-dependent population approaching carrying capacity (reproduced from Begon, Townsend & Harper, 2006).

The aim of the model developed here was to reproduce the sigmoid growth pattern and represent its cause through density-dependent mortality and birth, together with the concepts of net recruitment (essential for developing the ideas of surplus yield in a fishery topic) and the concept of carrying capacity. One of the key modelling challenges for this was to reproduce a sigmoid curve which essentially meant representing second order behaviour for changes in population size, not just the rate at which it was changing but also the way in which that rate was changing with density.

5.3.2. Model design

The model is formed around the birth and death processes and the static concepts of a population and a resource (habitat, food base etc.). Fragments were defined for these key concepts and these fragments were then reused to define other concepts and to regulate the behaviours (Figure 5.3). *Birth* and *Mortality* processes were represented as rates having direct influences on the population size, representing the total numbers being born or dying in a specified time period. This follows typical qualitative model representation of birth and death.

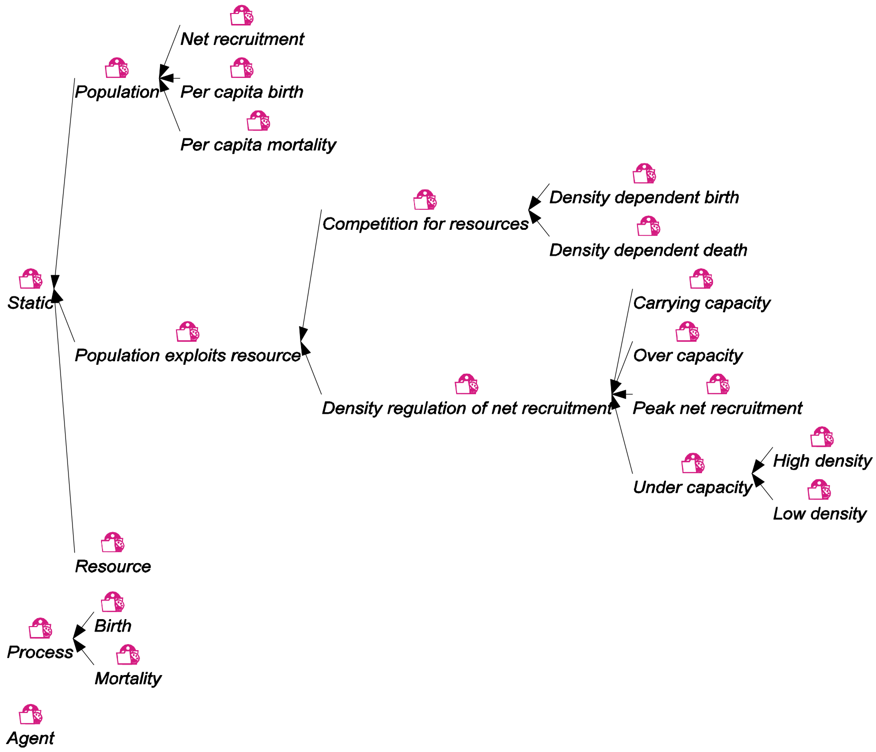


Figure 5.3 The model fragments used to build a compositional model on intra-specific density-dependent population growth. The model is regulated by only two processes (birth and death), although the behaviour is mediated by a suite of static fragments defining the relative size and behaviour of mortality and birth rates depending on the density of the population. This density-dependence is mediated through the concepts of per-capita mortality and per-capita birth rates.

In contrast to classical qualitative models of birth and death the density-dependent effect on mortality was represented as the effect of density and competition altering the per capita birth or mortality rates. These per capita rates represent the probability of an individual dying or the potential reproductive success of an individual in a population. When density dependence is active the per capita rate has an effect on the actual birth and death rate through a positive proportionality (Figure 5.4). Therefore, using mortality as an example, when density dependence is active the actual mortality rate (the numbers dying per unit time) is affected by both the population size and by the per capita rate. This gives the effect that when density independent the mortality rate increases proportionally with increasing density whereas when density dependent the per capita rate increases and the mortality rate increases more than proportionally with the population size.

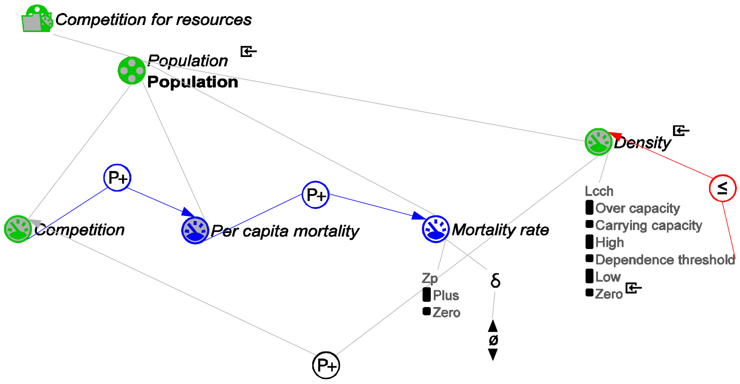


Figure 5.4 An example of a static model fragment representing density-dependent mortality. In this fragment when the density is greater than a dependence threshold (a non-specific threshold representing the point at which density dependence starts to occur) then the resultant competition acts on the per capita mortality which itself affects the actual mortality rate.

Beyond the basic static fragments that make up the main components of the system a suite of static fragments are required to regulate and control the outcome of the simulations (Figure 5.3 e.g. Density regulation of net recruitment). These fragments control the relative magnitude and behaviour of the *Birth rate* and *Mortality rate* through specifying the behaviour of the *Net recruitment rate* quantity in relation to *Density* (where *Net recruitment rate* is specified as a calculus between Birth rate and *Mortality rate*). Each of the child fragments of "Density regulation of net recruitment" use conditional knowledge statements to specify a condition based on the magnitude of *Density* and then make consequence statements for the magnitude of *Net recruitment rate* (effectively whether birth is <, > or = to mortality) and a correspondence between the derivative of *Density* and *Net recruitment*. Therefore, the derivative of *Density* controls the derivative of *Net recruitment rate*. This effectively specifies second order derivative information for how *Birth rate* and *Mortality rate* are changing relative to each other e.g. which rate is changing faster than the other. These fragments combine together into the full causal model shown in Figure 5.5. The regulation of the derivative of *Net recruitment rate* from the derivative of *Density* can be seen at the top of the figure.

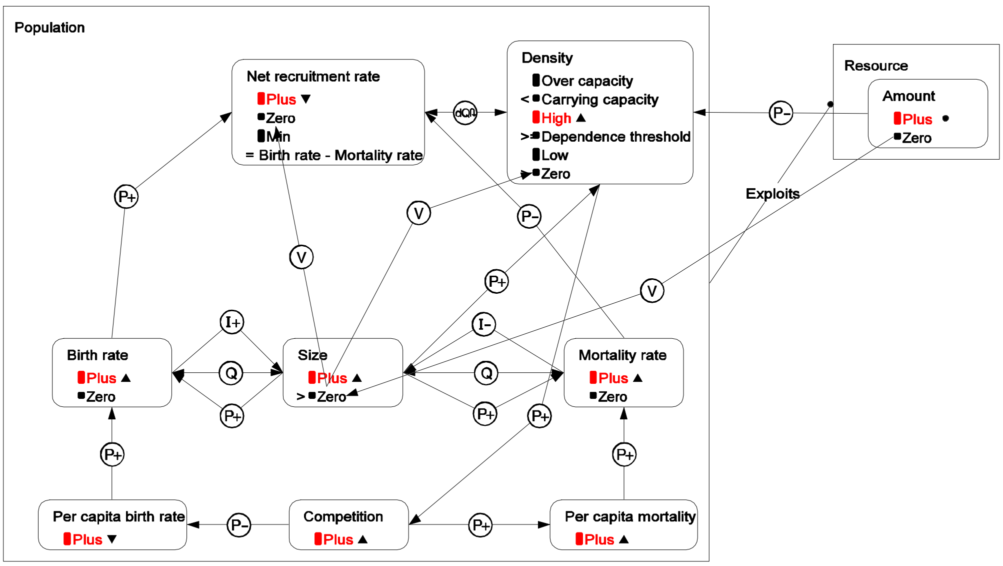


Figure 5.5 Full causal model of intra-specific density-dependent population growth for a scenario of a population growing until it matches the carrying capacity which is set by the abundance of a non-specific resource (habitat, food availability etc.)

5.3.3. Scenarios, simulation and behaviour

The scenario developed for the intraspecific population regulation model shows the behaviour of a population to grow and stabilise at the carrying capacity of the system. In this scenario a population exists at a low density, which is less than the carrying capacity (Figure 5.6). The simulation runs without an exogenous change as in this state the model identifies that *Birth rate* is greater than *Mortality rate* (a positive *Net recruitment rate*).

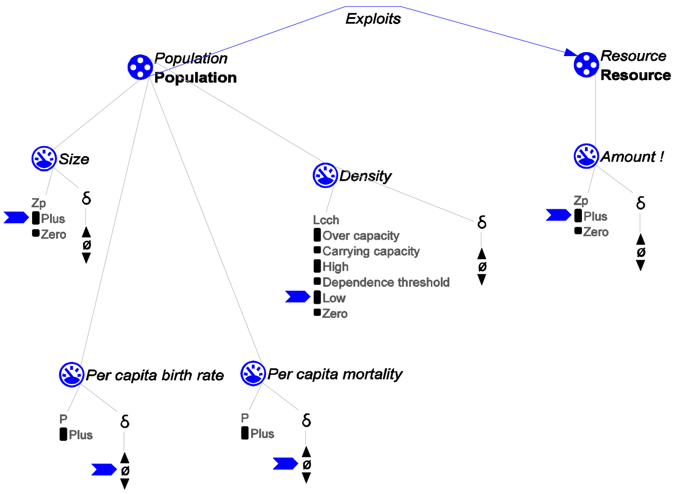


Figure 5.6 An example scenario for a simulation representing sigmoid population growth regulated by density-dependent birth and mortality.

Table 5.1 Summary of the starting conditions generating the behaviour for a scenario for the density-dependent population regulation model.

Type	Details
Exogenous control	*Resource Amount* exogenous steady *Density* initially low
(In)equality	Inequality between *Mortality rate* and *Birth rate* defined in model fragments causes population to grow
Ambiguity	None
Simulation settings	Apply quantity space constraints on extreme value (active) Remove inactive quantities after transition (active)

The simulation and behaviour path of this scenario shows the population size increase from low until it stabilises at the carrying capacity of the system (Figure 5.7). This behaviour path shows all the features of a sigmoid growth curve (albeit distributed across the behaviour of a number of quantities). The sigmoid nature of the behaviour can be inferred from inspection and interpretation of the behaviour of the *Density* and the *Net recruitment rate*, where net recruitment can be specifically viewed as the rate at which the population size is changing. As such the magnitude of net recruitment presents first order information for how *Population size* is changing and the derivative of *Net recruitment rate* presents second order information for the growth (Figure 5.7). In this case the sigmoid curve is inferred from the initial increase in net recruitment followed by a maximum net recruitment and then a decline in the net recruitment until the population stabilises in carrying capacity when there is zero net recruitment.

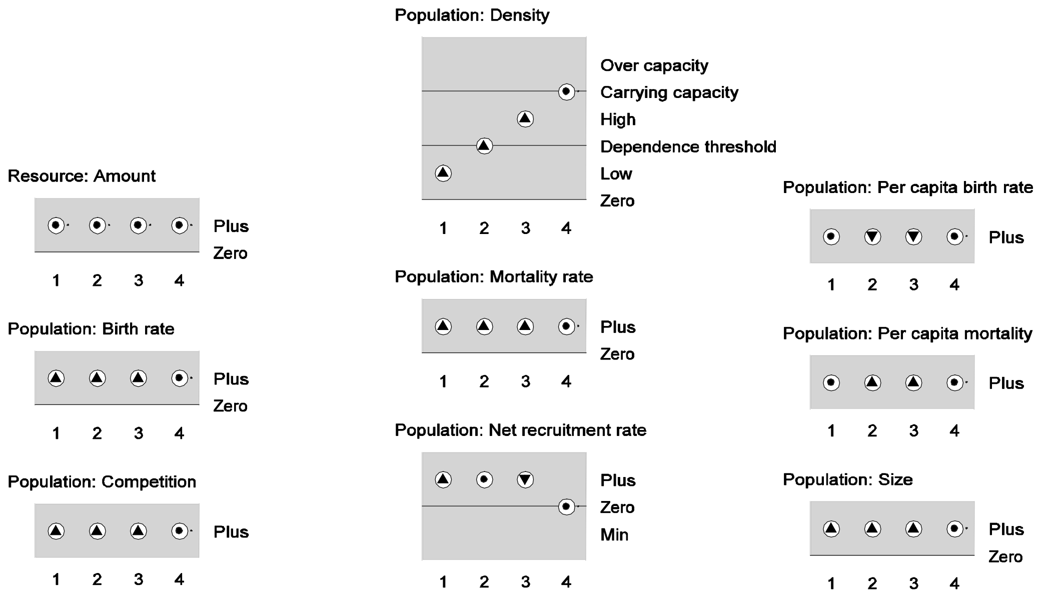


Figure 5.7 The value history for the simulation of the simple scenario of sigmoid population growth. In this simulation the population size and density grow from a low density and then stabilise at the system carrying capacity. The behaviour has an initial phase where *Birth rate* is increasing faster than *Mortality rate* followed by a phase where density-dependent mechanisms equilibrate the two rates such that at carrying capacity the size of the population has stabilised because birth and death are equal.

5.3.4. Summary and features for discussion

- A large proportion of the static fragments used in the model are designed to control behaviour rather than define structure or causal relationships.
- The majority of control over derivative behaviour is achieved using derivative correspondences rather than conditional value assignments (as used for the lake oxygen concentration model).
- The model contains two different concepts for mortality and birth (actual rate and per capita rate); this is a significant advancement in representing population dynamics in QR models.
- The model uses a couple of changes to the simulation settings to visually “clean up” simulations and removes inactive quantities from the value history.
- The model and scenario produces a behaviour pattern that has all the characteristics of a sigmoid density-dependent growth curve. However, the sigmoid pattern is not immediately obvious from inspection of the value history for the *Population size*. It can only be inferred by interpretation of the value history of a number of additional quantities.

5.4. Density dependence, compensation and over-compensation

5.4.1. Concepts and goals

Density-dependent mortality and competition can be seen to result in three key patterns of population regulation (Figure 5.8, Begon, Townsend & Harper, 2006; after Bellows, 1981). These patterns depend upon the intensity and type of the competition, the species involved and the system they are in. These patterns relate to the extent to which density-dependent mortality compensates for increasing recruitment. Three key phases or patterns for density dependence can be identified:

1. Density independence – the numbers dying increase proportionately to increases in density whilst the mortality rate (expressed as the per capita mortality rate, the probability of an individual dying) does not increase with increasing density (Figure 5.8 zone 1).
2. Under compensation – mortality rate increases with density such that the numbers dying increases more than proportionately with density (Figure 5.8 zone 2).
3. Over compensation – the increasing mortality rate overcompensates for the increases in density such that the more individuals that are initially present the fewer individuals survive. This generally occurs as a result of intense competition and can theoretically lead to situations where there are no survivors because densities and competition are so high that no individual can obtain the resources needed to survive (Figure 5.8 zone 3).

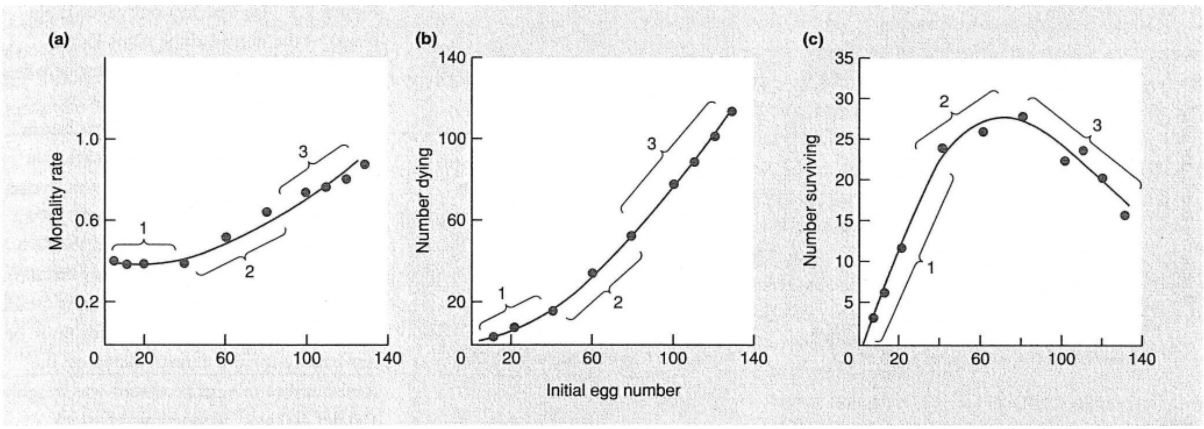


Figure 5.8 "Density-dependent mortality in the flour beetle *Tribolium confusum*: (a) as it affects mortality rate, (b) as it affects the numbers dying, and (c) as it affects the number surviving. In region 1 mortality is density independent; in region 2 there is under-compensating density-dependent mortality; in region 3 there is over compensating density-dependent mortality" (Figure and caption reproduced from Begon, Townsend & Harper, 2006; after Bellows, 1981).

Compensation in density dependence can also lead to exactly compensating density dependence. This is a situation that can be seen for survival and mortality in juvenile trout (Figure 5.9 from Begon, Townsend & Harper, 2006; after Le Cren, 1973). In this example at lower densities density dependence is under compensating but beyond a certain density the numbers surviving approaches a constant level irrespective of the initial density. Therefore, in this system density dependence is never overcompensating. This pattern of compensation links to the concept of carrying capacity and the ecological law of constant final yield (Begon, Townsend & Harper, 2006).

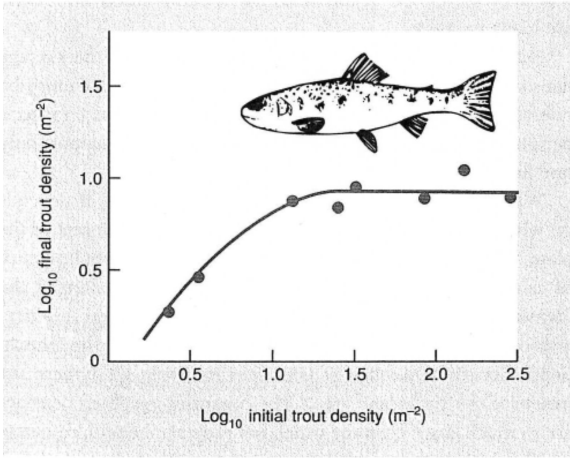


Figure 5.9 An example of exactly compensating density dependence in a trout population (reproduced from Begon, Townsend & Harper, 2006; after Le Cren, 1973).

The aim of the model developed here is to represent the three patterns of compensation described above. Conceptually the model was designed to consider an experiment that a scientist may undertake to measure the relationship between numbers of animals surviving as a function of manipulating the number of animals starting the experiment and their density.

5.4.2. Model design

This model was designed to act like a hypothesis or experimental statement that might mimic an experiment or growth trial that a student might undertake in association with learning about intraspecific competition and yield (particularly crop yield). Therefore, the model was aimed to address a question of the style “what happens to numbers surviving if the numbers starting increases”? As such this has a quality about it that mimics the style of reasoning available in LS2 and LS3 where derivative relationships are the only causes of change (if x increases then y increases/decreases). However, LS2 and LS3 could not be used for this representation given that density dependence and density independent behaviours require the use of conditional knowledge. Therefore, the model was developed in the style of LS3, using only proportionality relationships, but in LS5 where conditional statements could be made and exogenous behaviour could be applied (Figure 5.10).

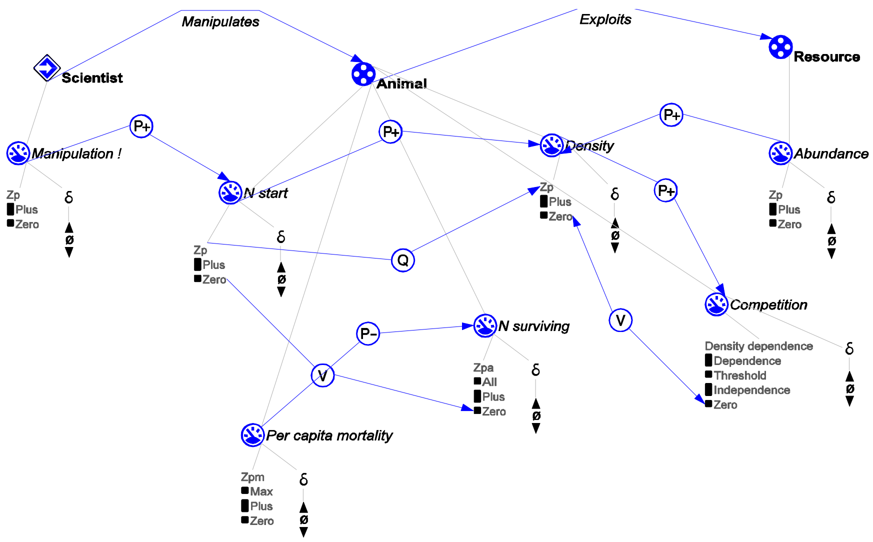


Figure 5.10 Model expression for the “Intraspecific compensation experiment LS5” model. This model is conceptually based around the ideas of an LS3 model, where all change occurs as a consequence of proportionalities rather than direct influences, with the use of the LS5 conditional knowledge approach to allow for changes in behaviour (under, exact or over compensation).

5.4.3. Scenarios, simulation and behaviour

The scenario used mimics the pattern shown in the text book diagram for the density dependent mortality in the flour beetle (Figure 5.8). As such the initial value for the number starting was zero and this then increased due to the manipulation of a *Scientist* agent. To enable the simulation to generate the three end states desired (under, exact and over compensation) the settings of the simulation preferences had to be changed with the second order derivative reasoning settings deactivated. Whilst second order derivative information is essential for working with direct influences (I’s) they are not required for reasoning with proportionalities. However, with these settings active the unknown second order derivatives are assumed to be zero whereas this simulation requires that they are left ambiguous such that these three possible behaviours can emerge.

Table 5.2 Summary of the starting conditions generating the behaviour for a scenario for the density-dependent compensation model.

Type	Details
Exogenous control	Scientist Manipulation exogenous increase
(In)equality	None
Ambiguity	None
Simulation settings	Calculate 2nd order derivatives (deactivated) Generate derivative terminations (based on 2nd order derivatives) (deactivated) Apply 2nd order derivative continuity constraints (deactivated)

This scenario for the model generates three behaviour paths (Figure 5.11) that represent the three possible compensation behaviours described in section 5.4.1. The path to state [5] represents under-compensation where the numbers surviving increases with increasing number of animal starting. The two key compensation behaviours are show by path [1, 2, 3, 7] (exact compensation, Figure 5.12 A) and by path [1, 2, 3, 6, 8] (over compensation, Figure 5.12 B). Exact compensation can be identified by the number of animals surviving stabilising despite continued increase in the number of animals starting. Over compensation can be seen by the behaviour path exhibiting a positive symmetrical parabola in the numbers surviving (Figure 5.12 B).

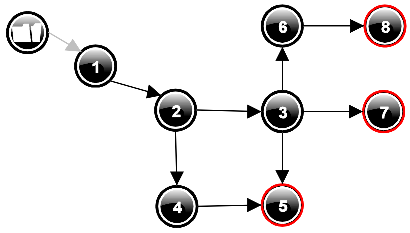


Figure 5.11 The behaviour graph for the "intraspecific compensation experiment LS5" model indicating three possible end states relating to [5] under-compensating density dependence; [7] exactly compensation density dependence; and [8] over compensating density-dependent mortality.

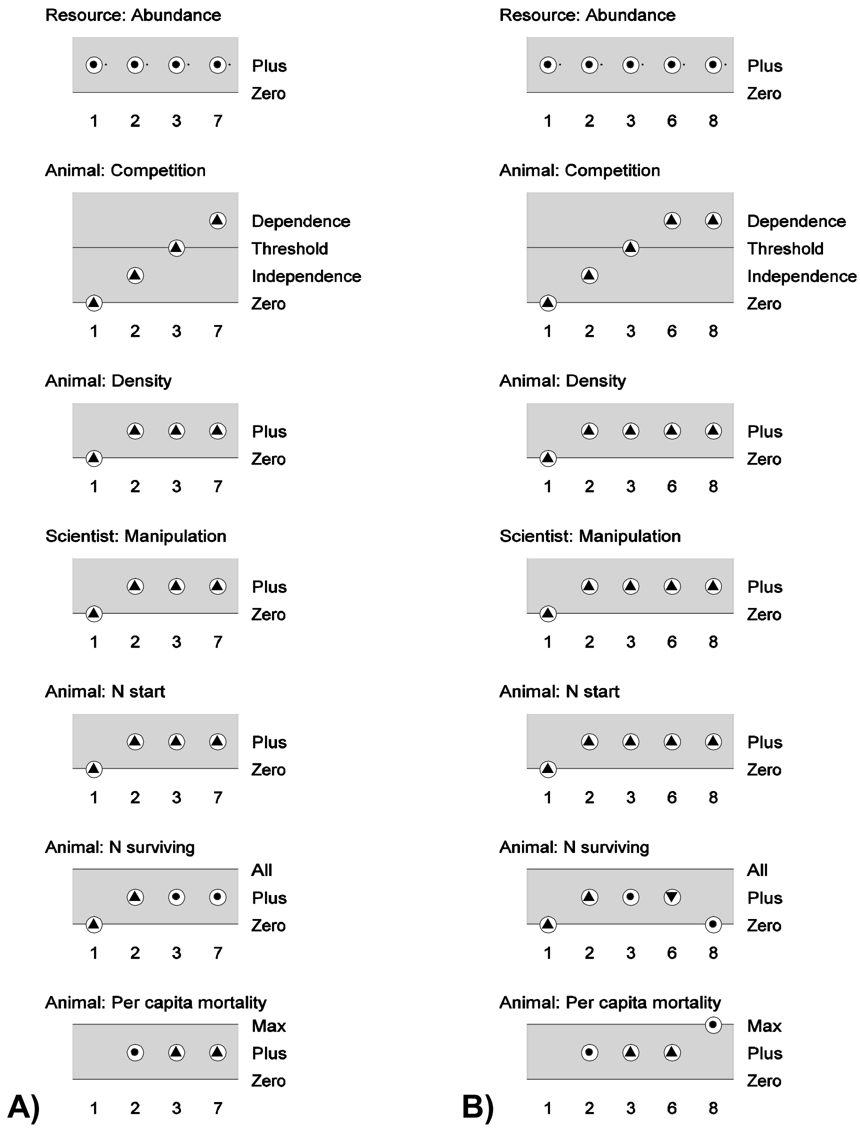


Figure 5.12 Value histories for two behaviour paths in the simulation of the "Intraspecific compensation experiment LS5" model. Path A) represents the concept of exact compensation in the density-dependent regulation of population size; Path B) represents the concept of over-compensation where density-dependent competition for resources can result in none of the population surviving (none of the individuals present at the start can compete to obtain enough of the resource to ensure survival).

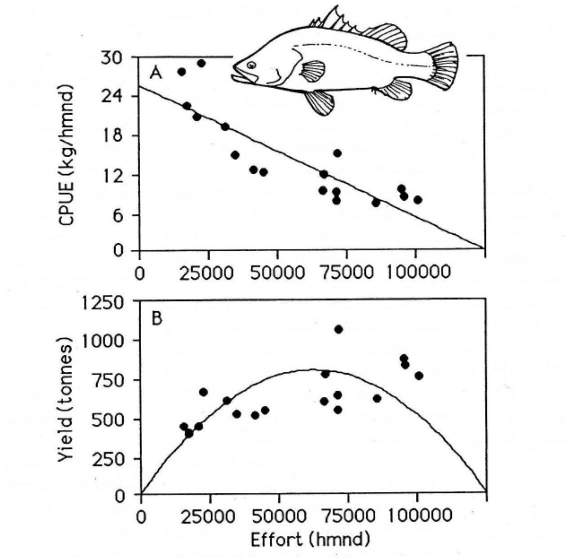
5.4.4. Summary and features for discussion

- The model is constructed in LS5 but uses a conceptual approach to causality and behaviour that is akin to the approach of LS2 and LS3. LS5 was required due to the need for conditional knowledge representation.
- A parsimonious approach was used for quantity spaces to minimise complexity in simulations. QS were only expanded where there was a need to clearly define different states or phases of behaviour in the model.
- The simulation required that the 2^{nd} order simulation settings were deactivated. This was so that the default assumption that unknown derivatives are set to zero was deactivated. In this model a certain ambiguity in the relative effects of proportionalities was required such that the relative effects of competing proportionalities in the model could be allowed to change during the model.

5.5. Fishery yield and catch per unit effort (CPUE)

5.5.1. Concepts and goals

One of the key concepts when considering the assumptions behind exploitation and sustainable yield models is that the average annual yield from a fishery is a function of both the availability of the stock (stock or population size) and the effort invested in harvesting from the fishery (King, 1995). One of the assumptions behind the maximum sustainable yield model is that there is a positive parabola relationship between yield and effort (Figure 5.14). This parabola relationship is due to catch per unit effort (CPUE) declining in a linear fashion with increasing effort (Figure 5.13 A). As such the maximum sustainable yield (MSY) can be linked to the fishing effort required to catch it, being the effort equivalent to the maximum value of yield in the Schaefer’s catch curve (Figure 5.13 B).

A) 

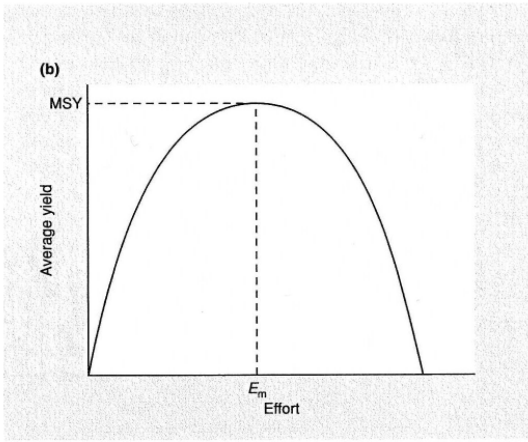
B) 

Figure 5.13 Example schematics and graphs of (A) the relationship between catch per unit effort, yield and fishing effort (reproduced from King, 1995) and (B) Schaefer's model of a symmetrical parabola relationship between average yield and the fishing effort (reproduced from Begon, Townsend & Harper, 2006).

The goal of this model was to replicate the Schaefer model of a symmetrical parabola relationship between average yield and fishing effort by considering the relationship between catch per unit effort and stock size.

5.5.2. Model design

This model was built in LS5 given that it was a structurally simple model in terms of the number of entities and quantities considered in the main model expression (Figure 5.14) but that exhibited complex non-linear behaviour (Figure 5.13) which required the use of conditional knowledge statements. Five conditional statement fragments were used in addition to the main model expression to control the symmetrical positive parabola relationship between yield and effort. The conditional expressions related mainly to the definition of the behaviour of the *Yield* value in relation to the *Biomass* of the *Fish stock*. This control was achieved by defining for each value of *Biomass* the value and derivative of *Yield*. The derivative of *Yield* was mostly controlled using derivative correspondences between *Yield* and *Biomass*. This derivative control defined the reasoning for the relative effects on yield of increasing effort contrasted with declining catch per unit effort (CPUE). *CPUE* itself was only introduced to the model once there was actually a positive value of fishing effort (Figure 5.15) given that it does not make sense to describe a CPUE value until there is actually a fishing effort.

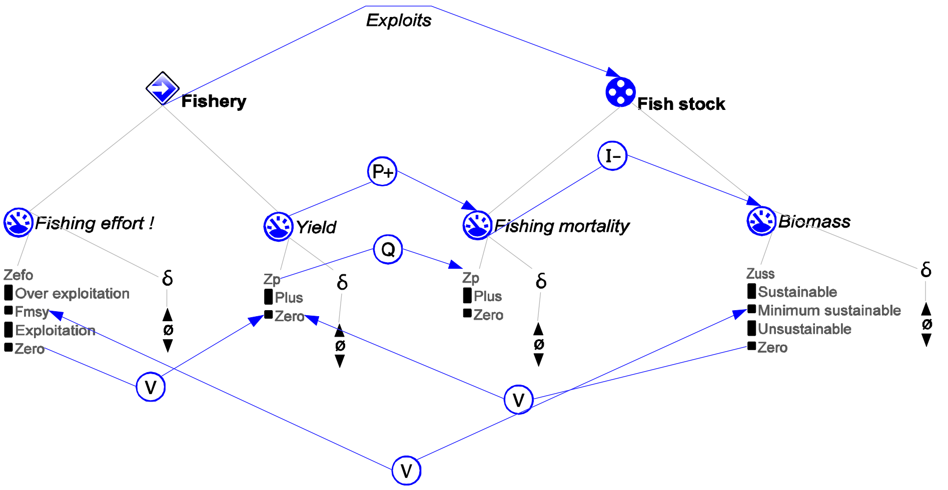


Figure 5.14 Main model expression for the Fishery Yield LS5 model considering the biomass of an exploited stock, the fishing effort and the fishery yield (considered as the annual yield). The model includes the concepts of a sustainable level of fishing effort (Fmsy) and a minimum sustainable stock biomass.

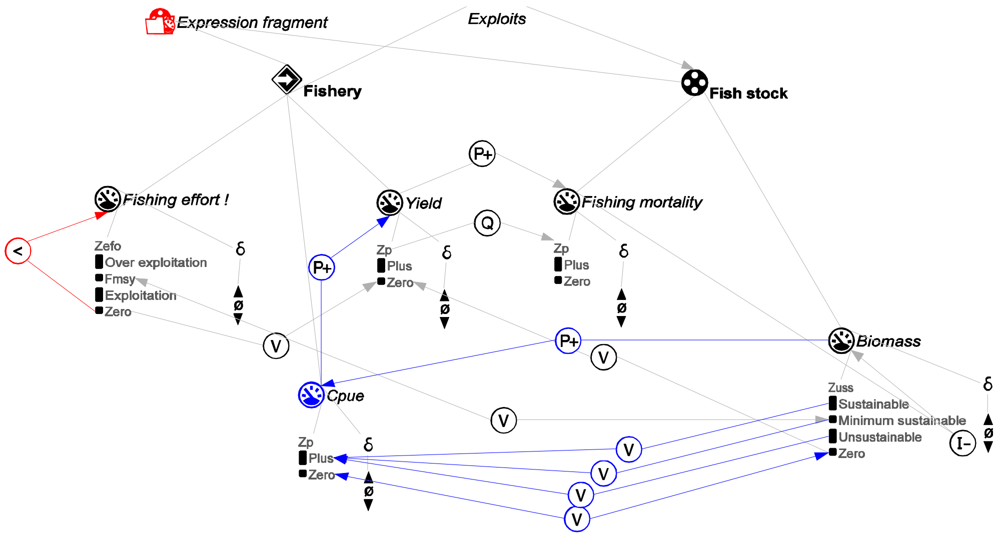


Figure 5.15 An example of a conditional model fragment for the Fishery Yield LS5 model introducing the relationship between stock biomass and catch per unit effort (CPUE). CPUE is only introduced as a concept when the fishing effort is greater than zero.

5.5.3. Scenarios, simulation and behaviour

The scenario defined for this model (LS5 models can only have one scenario predefined) was one of a new fishery being developed on an unexploited stock. The *Fishing effort* was initially zero and the *Biomass* was at a sustainable level and steady.

Table 5.3 Summary of the starting conditions generating the behaviour for a scenario for the fishery yield Schaefer model.

Type	Details
Exogenous control	*Fishing effort* exogenous increase starting from Zero *Biomass* sustainable and assigned a steady derivative
(In)equality	None
Ambiguity	None
Simulation settings	Default settings

The behaviour emerging from the model mimics the Schaefer catch curve with *Yield* exhibiting a positive symmetrical parabola relationship with effort (Figure 5.16). The behaviour of the *CPUE* also mimics the linear decline shown in Figure 5.13 A. The simulation shows key phases of exploitation, sustainable exploitation (where the yield is maximum but the population is still at a sustainable size), over exploitation and collapse of the fishery/extinction of the stock.

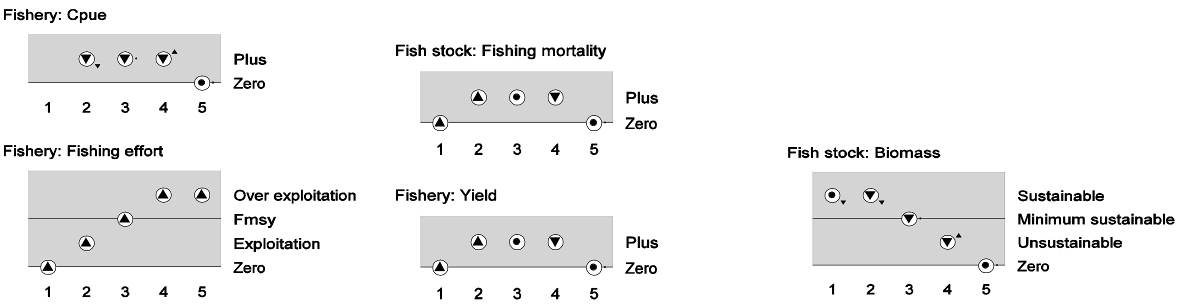


Figure 5.16 Value history of the behaviour of the Fishery Yield LS5 model for a scenario where a new fishery exploits a fish stock. The behaviour represents the typical surplus yield catch curve of an (over)exploited fishery, with an initial increase in yield followed by a declining yield and extinction during over exploitation.

5.5.4. Summary and features for discussion

- The model made use of LS5 as it comprised a simple system structure but exhibited a complex non-linear behaviour that necessitated the use of conditional model expressions.
- Quantity spaces were only expanded for key quantities where it was important to clearly differentiate different states or phases of behaviour in the model.
- The symmetrical parabola behaviour of yield in relation to fishing effort is only somewhat apparent when compared to the stimuli textbook diagram. However, the behaviour can be inferred from inspection of the value histories of all the quantities as the behaviour has all the characteristics of the Schaefer model.

5.6. Fishery and maximum sustainable yield (MSY)

5.6.1. Concepts and goals

The goal of this model was to integrate the model of intraspecific population regulation (Section 5.3) with the fishing effort and yield model (Section 5.5). This model would give a full representation of a fishery exploitation scenario.

5.6.2. Model design

This model is an integration of the models developed for intraspecific population regulation (Section 5.3) and the fishery yield and CPUE model (Section 5.5). The model reused all the mechanisms and expressions used in these two models with the intraspecific population model forming the static and process model fragments and the fishery yield model being contained within agent model fragments (Figure 5.17).

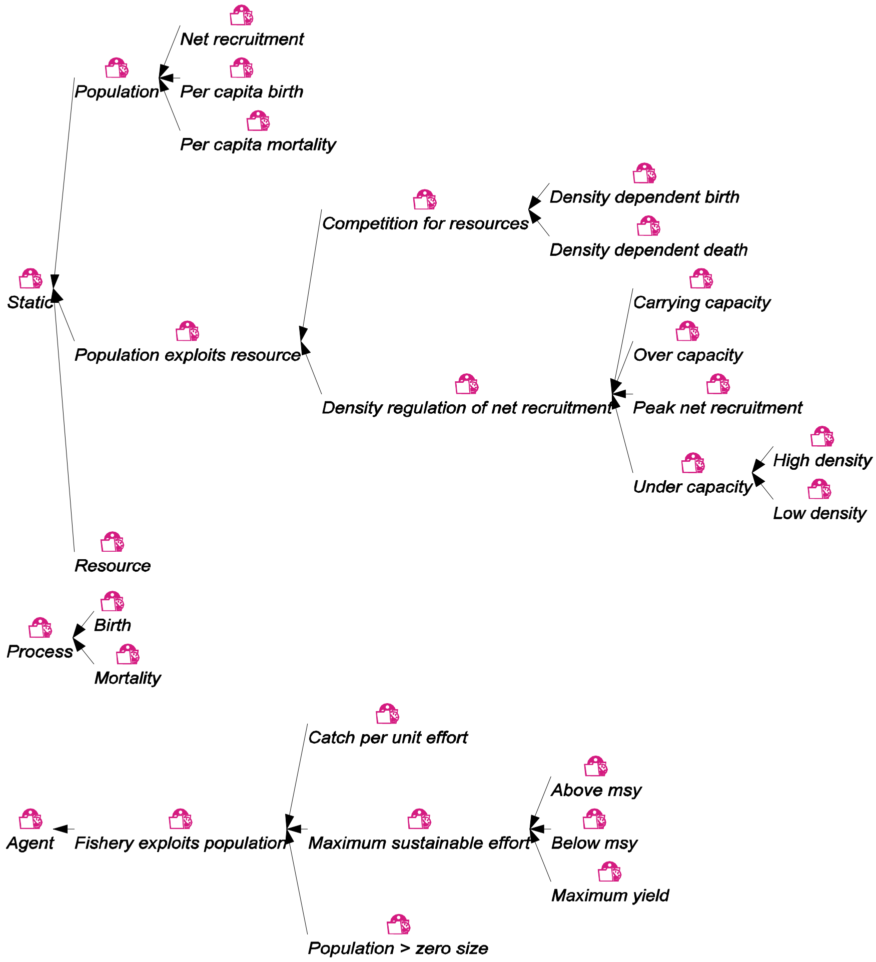


Figure 5.17 Model fragments used in Fishery MSY LS6 model. The model represents an integration of the intraspecific population regulation LS6 model and the Fishery Yield LS5 model. The concepts from the Fishery Yield LS5 model are represented in the Agent model fragments.

5.6.3. Scenarios, simulation and behaviour

The scenario developed for this model was based on that used for the fishery yield model with a new fishery being developed on an unexploited stock. The fishing effort was initially zero and the stock size as plus and at a density equal to carrying capacity (Figure 5.18).

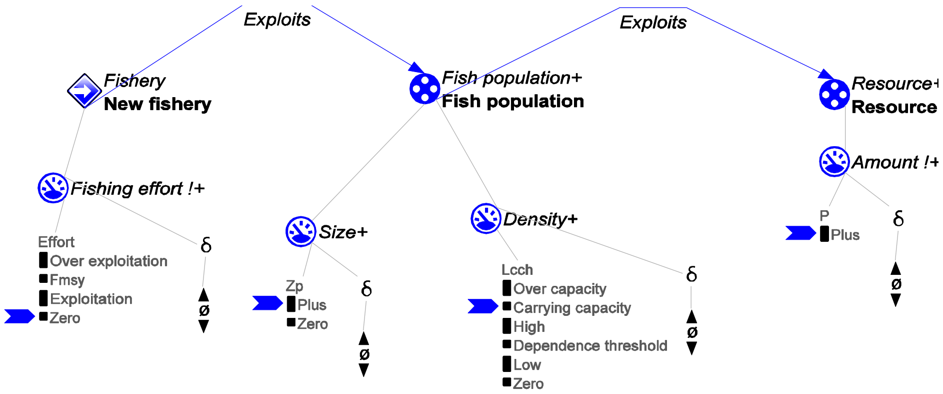


Figure 5.18 A scenario for a new fishery exploiting a fish stock in the Fishery MSY LS6 model.

Table 5.4 Summary of the starting conditions generating the behaviour for a scenario for the Fishery MSY model.

Type	Details
Exogenous control	Amount of resource exogenous steady Fishing effort exogenous increase from zero Density starts at carrying capacity
(In)equality	None
Ambiguity	None
Simulation settings	Default settings

This scenario and model generates a six state behaviour path that replicates all the features of the behaviour of a population with a sigmoid growth curve and an exploited fishery (Figure 5.19). Although the sigmoid population growth curve and positive parabola relationship are not immediately visible in the behaviour of any one quantity they can be inferred from the behaviour of density, yield and net recruitment. In the behaviour the maximum sustainable yield occurs when the net recruitment rate is also at its maximum.

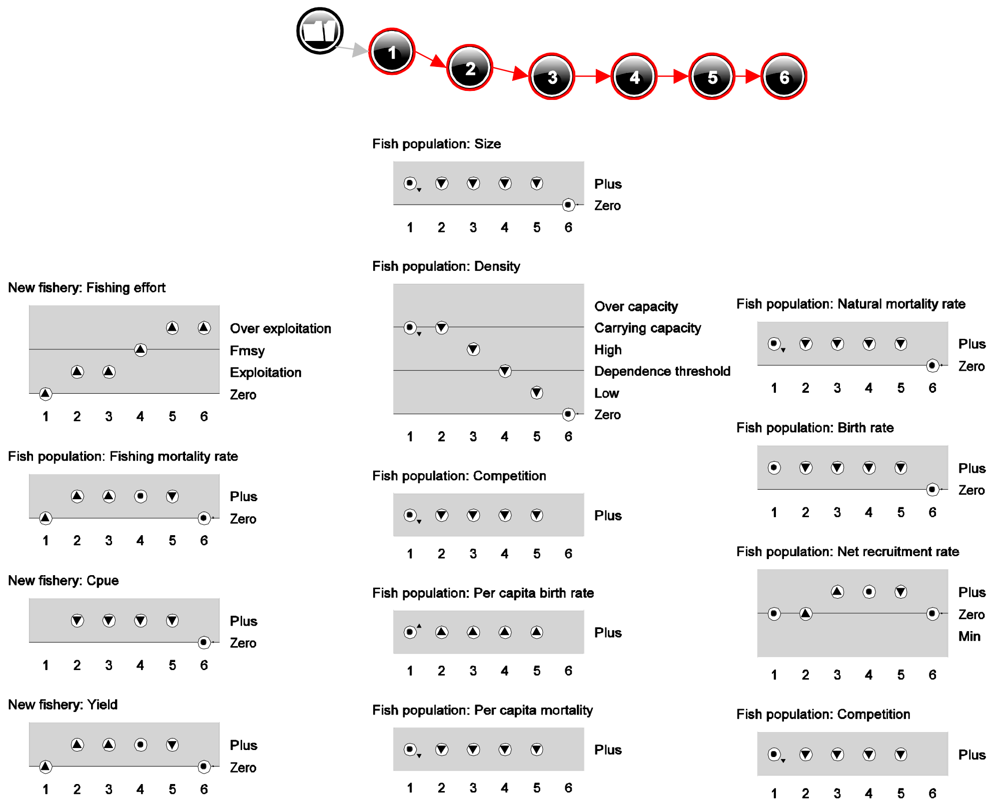


Figure 5.19 Behaviour graph and value histories for the new fishery scenario in the Fishery MSY LS6 model. The behaviour captures the typical catch curve and net recruitment curve for the development and eventual over-exploitation of a fishery.

5.6.4. Summary and features for discussion

- The compositional approach used to this model and previous models highlights the efficacy of the compositional approach in DynaLearn for combining different models considering different aspects of the same system.
- The model and scenario produces a behaviour pattern that has all the characteristics of a sigmoid density-dependent growth curve and the Schaefer yield model. However, the sigmoid pattern is not immediately obvious from inspection of the value history for the *Population size*. It can only be inferred by interpretation of the value history of a number of additional quantities.

6. Homeostasis & Adaption to environmental change

6.1. Topic and model metadata

Topic	Adaption to environmental change - Homeostasis		
Author	R Noble	**Version(s)**	DL 0.9.4
Advanced Models	Homeostasis equilibrium LS6 Homeostasis open system LS6 Regulatory feedback homeostasis LS6		
Links to basic models (D6.2.2)	Homeostasis_LS4.hgp		
Target users	A Level/Undergraduate		

6.2. Topic rationale

6.2.1. Curricula background

Adaption to the environment is one of the key themes within the AQA Environmental Studies A-Level curricula that consider life processes within the biosphere (AQA, 2007). There are almost no environments on earth which exhibit constant conditions. As such life has evolved to be able to cope with both extreme and fluctuating conditions. Within this context, adaption to the environment and homeostasis are linked to a number of related curricula topics:

- Species adaption, tolerance and ability to tolerate environmental change.
- Distribution and diversity of species.
- Responses of species to changes in ecosystems e.g. succession.
- Diversity and ecological stability.

Homeostasis can be seen in osmoregulation of biota in saline and freshwater environments and in regulation of body temperature (Withers, 1992). Additionally, within A-Level Biology curricula homeostasis is a key theme exploring the maintenance of a constant internal environment in animals, especially in relation to maintenance of body temperature and of blood glucose. In particular the curriculum looks at the importance of negative feedback mechanism of regulation. In particular students are expected to know that negative feedback helps maintain an optimal internal state in the context of a dynamic equilibrium. The students should also recognise that there are often separate mechanisms involving negative feedback controls regulating departures in different directions from the original optimum state. Furthermore, students should be able to interpret diagrammatic representations of negative and positive feedback. As such, given the link to a systems viewpoint and the concepts of feedback mechanisms and dynamic behaviours homeostasis, and in particular osmoregulation, represent highly suitable topics for exploration in DynaLearn.

6.2.2. Key themes

In general animals have evolved two strategies for coping with changing environmental conditions; either conforming to the external conditions or regulating their internal environment to maintain optimum internal conditions in the face of changing external conditions. Regulators attempt to maintain optimum conditions through homeostasis.

Animals exhibit three main adaptive approaches to changing environmental conditions:

- Behavioural – where the animal alters behaviour or location to avoid unfavourable conditions or attempt to alter the local conditions to better suit their needs (cooperative social behaviour or bioturbation)
- Morphological – the morphology of an organism may change in response to seasonal changes in the environment (e.g. leaf shape, fur etc.) (Dorit et al., 1991)
- Physiological – some organisms are capable of adapting physiologically to new conditions (acclimation).

In terms of applying a systems viewpoint to homeostasis Withers (1992) highlights that homeostasis (constancy of internal physiological conditions) should not be confused with regulation of the internal environment. Indeed, homeostasis may be achieved even without a regulatory mechanism, normally under stable environmental conditions. Furthermore, regulation does not imply absolute homeostasis, with very few regulatory systems acting perfectly. Therefore, there are patterns of how physiological variables alter with changes in the environment:

1) Conformation – the internal condition is in equilibrium with the external environment.

2) Regulation – where the internal environment is maintained at a different value to the external environment.

This leads to three classes of mechanisms or systems that act to control the internal environment in the face of external environmental variability (Withers, 1992):

- Equilibrium homeostasis – there is no regulatory mechanism and the internal physiological condition is wholly controlled by, and equal to, the external environment (Figure 6.1 A).
- Steady-state homeostasis – an open system where there is no apparent regulatory mechanism. For example a system where the production or elimination of a metabolic product is independent of its concentration and yet the average concentration remains constant over time (Figure 6.1 B)
- Regulatory feedback homeostasis – this is a closed system where a physiological mechanism used feedback controls to maintain a variable at an optimum condition or set point. This system is characterised by a sensor mechanism that detects disturbance to the variable and an effector mechanism that compensates for external environmental change through a feedback mechanism (Figure 6.1 C) (Withers, 1992).

The models built in this section were built to represent the characteristics of these three main classes of homeostasis and regulation.

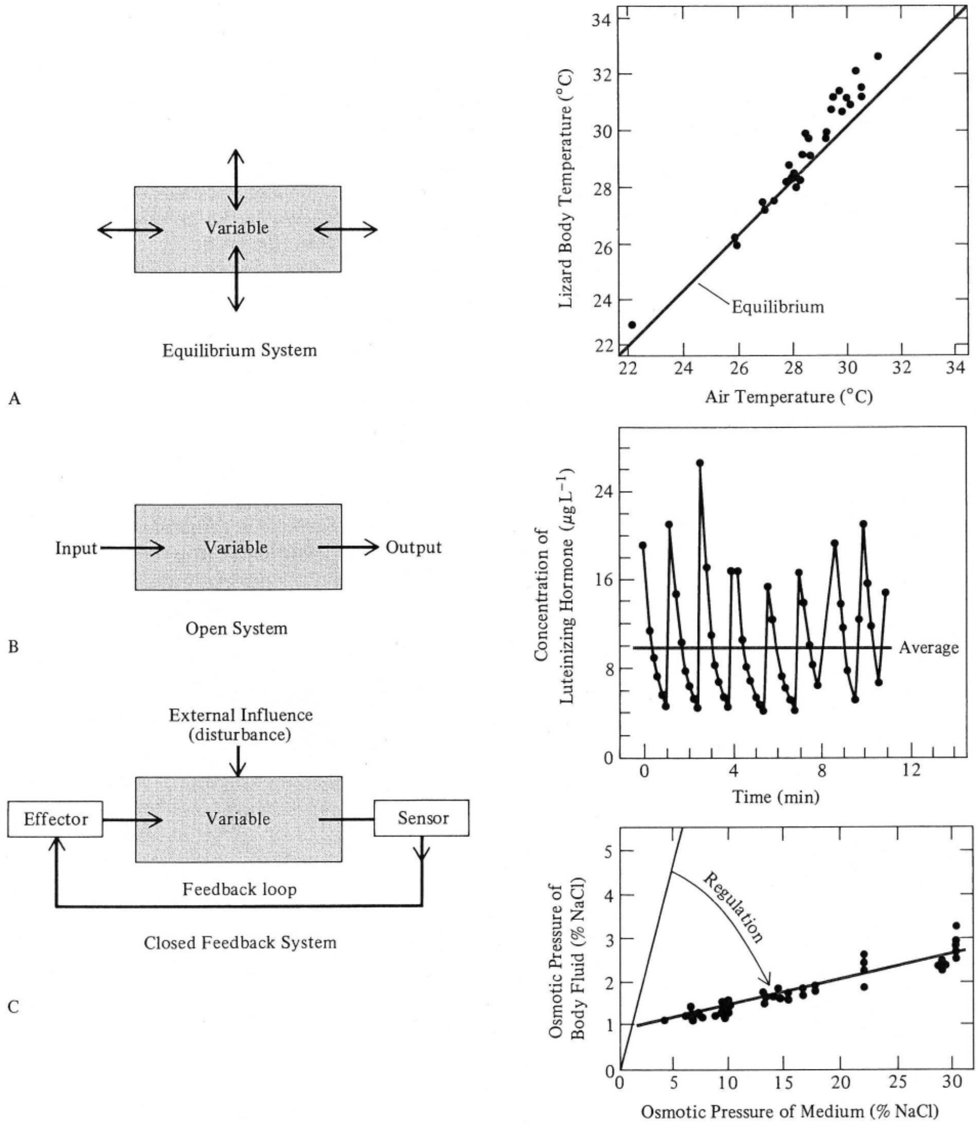


Figure 6.1 Schematics and examples of three models that result in relative homeostasis (A) a static equilibrium system; (B) an open loop dynamic equilibrium system; (C) a closed feedback control system (reproduced from Withers, 1992).

6.3. Equilibrium system homeostasis

6.3.1. Concepts and goals

The main characteristics of an equilibrium homeostasis system are that the internal environment is in equilibrium to the external environment and that the internal environment changes purely in response to changes in the external environment. The changes in the internal environment are linked purely to the difference between the external environment and the internal environment and are not linked to the internal environmental conditions per se. The aim of this model was to represent a simple equilibrium system (using principles from the previous models built for osmosis and diffusion) and to exhibit the pattern shown in Figure 6.1 A. This model uses salinity and osmotic concentration as a focal system although the same model pattern could be applied to thermal conditions and body temperature.

6.3.2. Model design

The model was developed from the osmosis and diffusion models presented in D6.2.2 (Noble, 2010) and in Section 4. However, a couple of fundamental design decisions were made to simplify the representation and possible behaviours:

1) The flow across the boundary between the internal and external environments was considered as a single net quantity (with a {Minus, Zero, Plus} QS to represent directional flow) rather than a competing inflow and outflow as used in the osmosis and diffusion models (Figure 6.2).

2) The flow across the boundary was assumed to only influence the internal concentration. This assumption was made from a semi-quantitative viewpoint that the physical size of the external environment was so much larger in relation to the internal environment that the influence of the flow on the external environment was so much lower that it would be on the internal environment that the change to the external environment in the equilibrium system could be ignored (the change in the external concentration caused by dynamic equilibrium would be negligible compared with the change to the internal environment) (Figure 6.2)

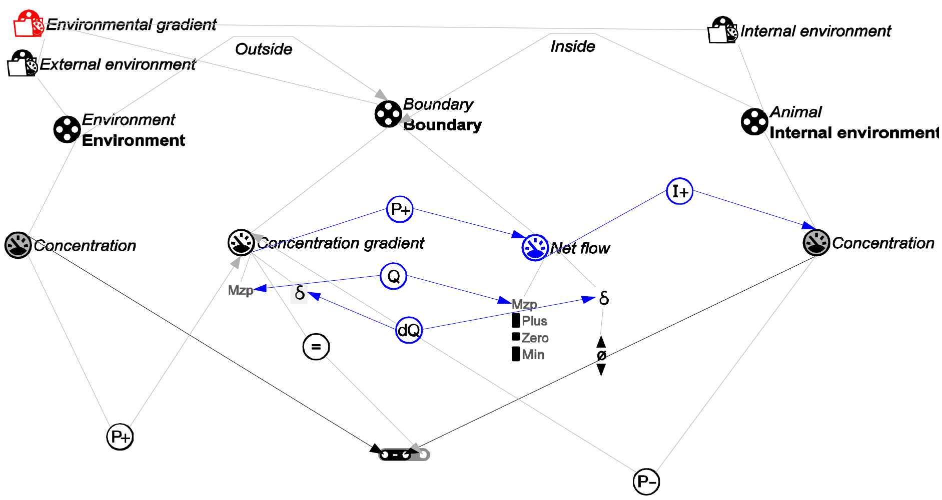


Figure 6.2 Model fragment representation of concentration gradient and flow between an internal and external environment subject to equilibrium homeostasis. The net flow across the membrane is represented as a single quantity rather than a separate inflow and outflow.

Apart from the {Minus, Zero, Plus} QS of the flow quantity only one quantity used a QS expanded beyond a simple {Plus} interval. The system was controlled by an agent representing environmental change, and this variable had an expanded QS of {Min, Minus, Zero, Plus, Max} to represent periods of decreasing and increasing salinity (Figure 6.3).

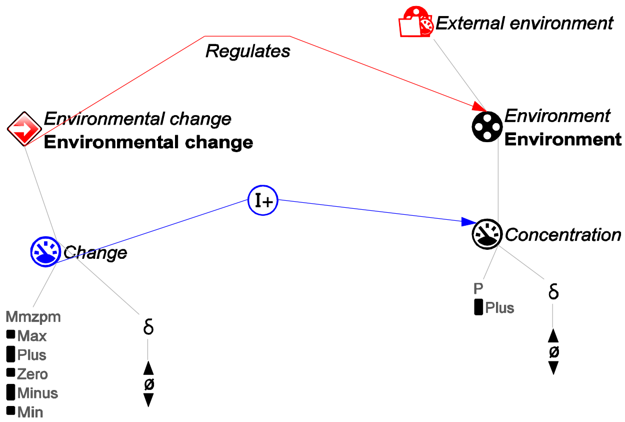


Figure 6.3 Agent model fragment used to represent an external factor acting to cause change in the environmental conditions.

6.3.3. Scenarios, simulation and behaviour

A simple scenario was used to represent dynamic equilibrium homeostasis (Figure 6.4). Environmental change was itself controlled with an exogenous sinusoidal behaviour to replicate oscillations in environmental conditions. The use of the exogenous sinusoidal control necessitated the use of LS6 despite the model being simple enough to be represented in LS4.

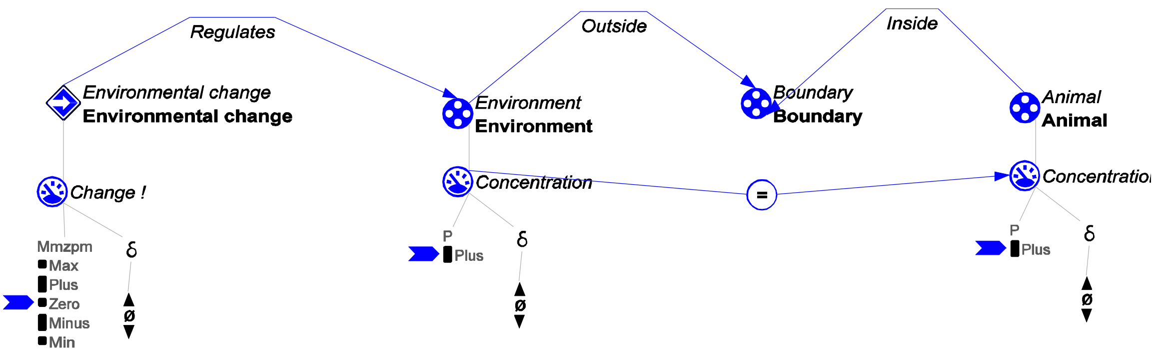


Figure 6.4 Scenario of fluctuating environmental change and the effects on an animal that functions with equilibrium homeostasis.

Table 6.1 Summary of the starting conditions generating the behaviour for a scenario for the equilibrium homeostasis model.

Type	Details
Exogenous control	Exogenous sinusoidal control over Environmental change Agent quantity
(In)equality	Environmental Concentration = Animal Concentration
Ambiguity	None
Simulation settings	Fastest path heuristic

The behaviour exhibited by the model when simulated using the default simulation preferences (Figure 6.5 A) was a fairly complex set of different oscillations related to different possible behaviours within the confines of the exogenous behaviour, the expanded QS of environmental change and the possible relative concentration of the internal and external environments. Whilst completely valid, with all loops showing oscillations with a tendency to equilibrium with the external concentration the behaviour path is quite difficult to explore and interpret. The behaviour was simplified using the fastest path heuristic simulation preference (Figure 6.5 B). Use of this setting produced behaviours which all resulted in a single oscillating loop representing fluctuations in the internal concentration which were regulated by changes in the external concentration and showed a tendency to equilibrium (although exact equilibrium was never achieved since the external environment never stabilises) (Figure 6.6).

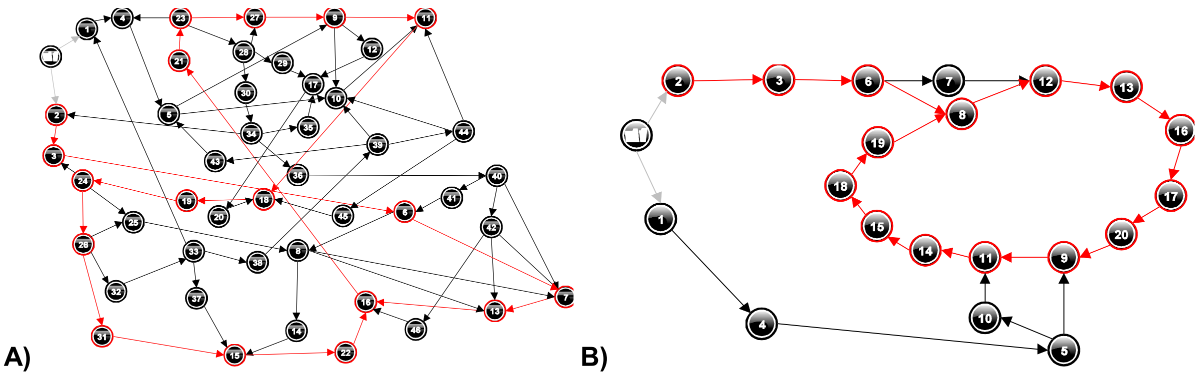


Figure 6.5 Behaviour paths for a system exhibiting environmental fluctuations and equilibrium homeostasis using A) default simulation settings and B) fastest path heuristic.

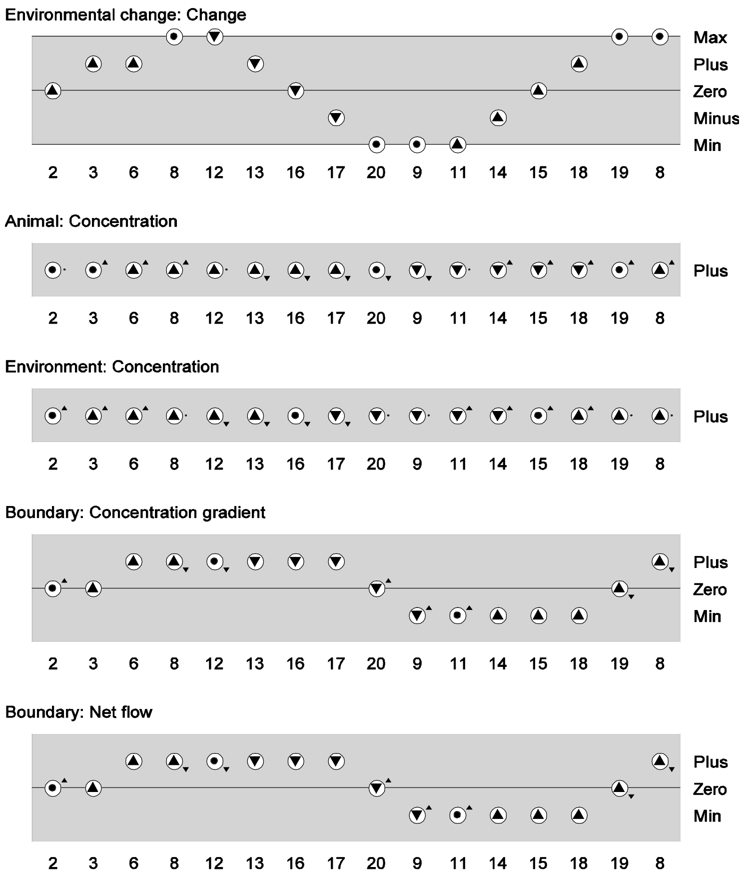


Figure 6.6 Value history representing environmental fluctuations and equilibrium homeostasis (value history from behaviour B) in Figure 6.5).

6.3.4. Summary and features for discussion

- This model was built from those developed for osmosis and diffusion. However, the model representation has a different scale and granularity in that it represents a single net flow quantity rather than a competing pair of flows.
- The model also assumes the influence of diffusion from the environment to the animal on the environmental conditions themselves to be minimal (based on the relative scales).
- The model makes use of an agent-based exogenous representation of change within the system, with an expanded quantity space to denote key phases of environmental change.
- The fastest path heuristic is used to clarify the behaviour generated which, despite the parsimonious definition of QS, is still complex.
- This model could have been built in LS4 or LS5 since it had a relatively simple structure and behaviour, however LS6 was required for the exogenous sinusoidal behaviour of Environmental change.
- The simulation only shows a tendency to equilibrium rather than the system re-equilibrating, this is because the environmental conditions are constantly changing.

6.4. Open system homeostasis

6.4.1. Concepts and goals

Open system regulation homeostasis is characterised by the absence of a regulatory mechanism that is directly related to the variable that is regulated (Withers, 1992). In this context the long term average value of the variable is fairly stable yet the actual value of the variable fluctuates over time (Figure 6.1 B). An example of this system given by Withers (1992) is the average blood concentration of luteinizing hormone in female mammals. In this system the hormone is released into the blood stream in pulses by a gland and it is eliminated by a number of mechanisms related to tissue uptake and excretion. In this context the production mechanism is independent of the actual concentration in the blood whilst elimination (particularly in the form of excretion) is related to the concentration. As such, when the gland is secreting production is greater than elimination hence causing a build up of concentration in the blood. When the gland is not secreting then the concentration is reduced due to the elimination of the hormone. The aim of the model was to replicate the phased releases and the pattern of concentration shown in Figure 6.1 B.

6.4.2. Model design

The majority of the quantities used in the model for an open system used {Zero, Plus} quantity spaces for simplicity. However, two expanded quantity spaces were used for Release rate {Inactive, Zero, Low, Critical, High, Max} (the secretion by a gland), and the quantity related to the phases of the external agent {Inactive, Zero, Active, Max} that represented the external system controlling the gland. These expanded QS were chosen for two reasons:

1) To clearly differentiate, and extend, periods of inactivity by the gland (hence the negative inactive phase).

2) To clearly enable a point to be described (Critical) where release of the hormone exceeds the elimination (to ensure all paths had periods of build up).

The model was controlled by two main processes (Figure 6.7). Firstly, the release of the hormone from the gland, where there was only a release (direct influence on blood concentration when the *Release rate* was higher than zero (Figure 6.7 A)). Secondly, the elimination process, a negative direct influence on the blood concentration, which is proportional to the actual concentration (similar to the concept of diffusion) (Figure 6.7 B).

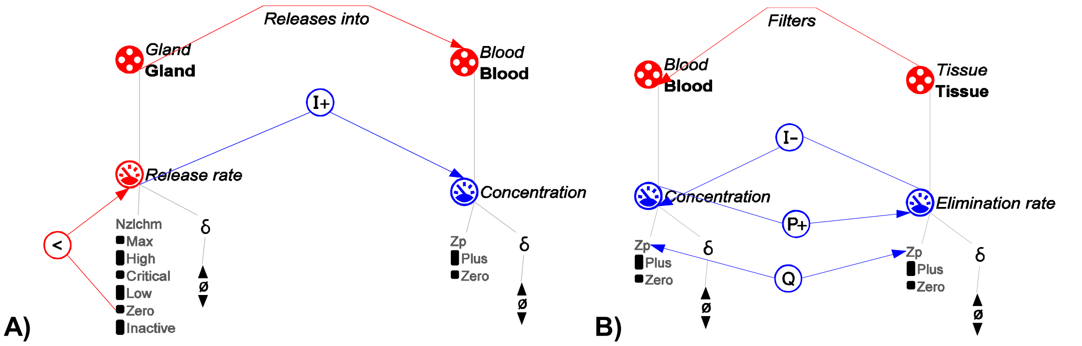


Figure 6.7 Model fragments representing A) a phased release of a hormone from a gland and B) the elimination of the hormone from the bloodstream, used to represent an open system homeostasis.

6.4.3. Scenarios, simulation and behaviour

The scenario for the model used an exogenous sinusoidal behaviour control over the *Phase* of the *External factor* that was deemed to control the release of the hormone (Figure 6.8). The use of the sinusoidal behaviour necessitated the use of LS6 for the model despite the fact that the model ingredients were simple enough to construct in LS5.

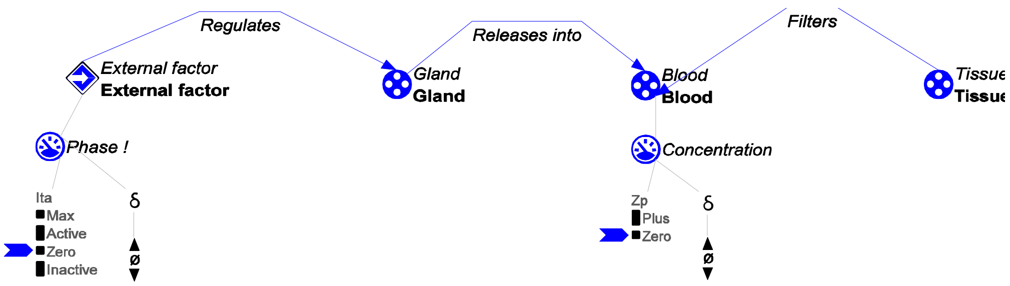


Figure 6.8 Simple scenario representing a phased hormone release and open system homeostasis.

Table 6.2 Summary of the starting conditions generating the behaviour for a scenario for the open system homeostasis model.

Type	Details
Exogenous control	External factor phase controlled by exogenous sinusoidal behaviour
(In)equality	None
Ambiguity	None
Simulation settings	Fastest path heuristic

Despite the relatively simple model structure and the simple scenario, simulating this model using the default simulation settings and the exogenous sinusoidal behaviour gave a relatively complex simulation with a number of looping paths and also an inconsistent end-state termination (Figure 6.9 A). This inconsistent termination resulted from the independence of the release and elimination processes such that in one path where the *Release rate* should become larger than the *Elimination rate* it could not first become equal to the *Elimination rate*. In this situation the transition would be inconsistent as the behaviour would move from a situation where *Concentration* is decreasing due to elimination exceeding release to a state where *Concentration* would increase due to release exceeding elimination, without first being in a state where concentration is stable. The complexity is reduced and the inconsistent termination is removed by using the fastest path heuristic (Figure 6.9 B).

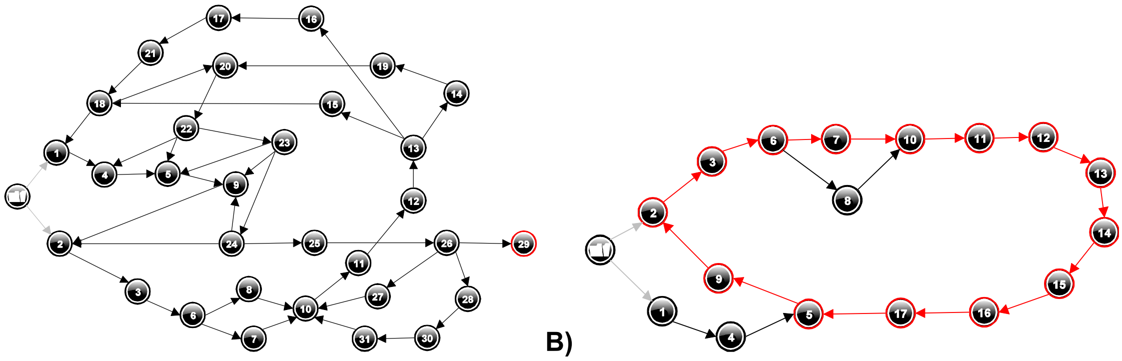

A) B)

Figure 6.9 Behaviour paths for a simple representation of open system homeostasis (Figure 6.8) with A) default simulation settings and B) fastest path heuristic applied. The single end-state shown in A) is not a true end state and represents a transition that would lead to an inconsistent state (immediate transition of a quantity from increasing to decreasing without first becoming stable).

When using the fastest path heuristic a single loop behaviour is revealed, where the concentration of the hormone in the blood oscillates in relation to the phased release from the gland (Figure 6.10). This behavioural pattern reflects that shown in Figure 6.1 b.

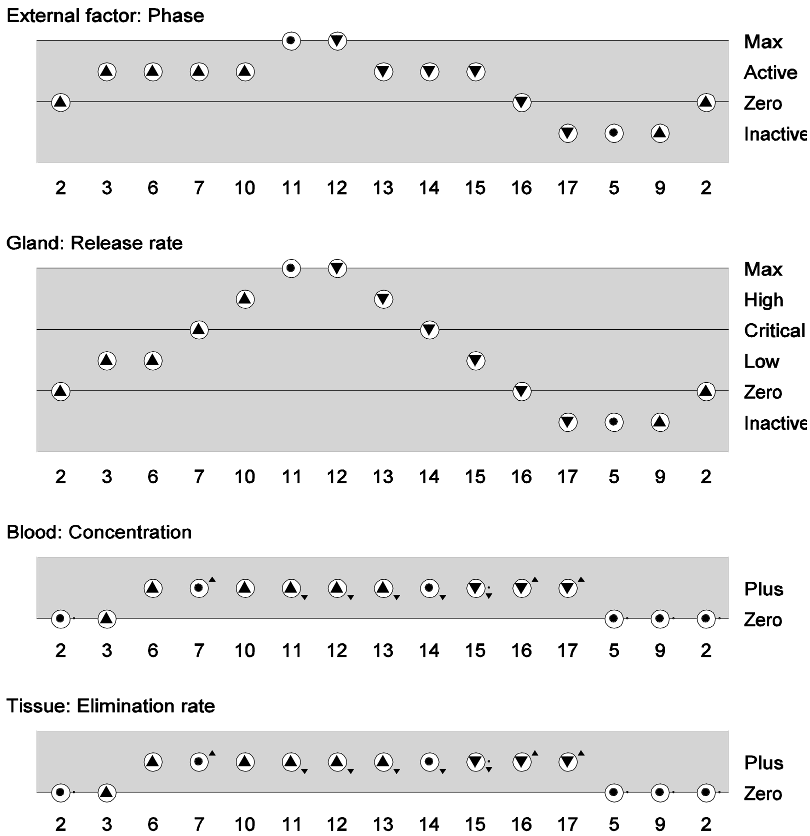


Figure 6.10 Behaviour graph for an example of open system homeostasis using the scenario in Figure 6.8 and the fastest path heuristic simulation preference.

6.4.4. Summary and features for discussion

- Behaviour in the model is generated by an agent based exogenous behaviour and QS designed to specify different states/phases in the behaviour.
- The model was built in LS6 as it required the exogenous sinusoidal behaviour to mimic oscillations in hormone release. The actual model structure and causal representation could have been built in LS5 were the predefined exogenous behaviours available there.
- The fastest path heuristic was used to clarify the key behaviour in the simulation. In addition to clarifying the behaviour the use of this setting also removed a behaviour path with an inconsistent end state termination from the simulation. This inconsistent termination was related to continuity constraints for a quantity being influenced by two competing direct influences. In an ideal model this inconsistency would be solved in the model expressions and not by the simulation preferences.

6.5. Closed feedback system homeostasis

6.5.1. Concepts and goals

Regulatory feedback homeostasis is characterised as closed system with a set point, sensor, effector and feedback system as essential features. Withers (1992) presents control of hemolymph osmotic concentration in *Artemia* brine shrimp as an example of regulatory feedback homeostasis, where the regulated variable is hemolymph osmotic concentration and the effector mechanism is the branchial salt pumps. The key principles of this mechanism that the model incorporates are that:

- There is an optimum value for the regulated variable – the set point.
- A sensor mechanism detects any changes or disturbance in the internal variable (in relation to changes in the external variable.
- A feedback control operating through an effector mechanism that regulates the variable compensating for changes in the external environment.

The model presented here represents this (negative) feedback system using the brine shrimp example as the model system.

6.5.2. Model design

The model used a parsimonious approach to defining quantity spaces for variables with most variables having a single {plus} interval. Given that the system considered salinity and concentration of solutions a basic representation of diffusion into the animal was used to indicate how the changes in the external environment could affect the internal environment. Similar design considerations were used as for the equilibrium model of homeostasis (Section 6.3). Therefore, concentration gradient and net diffusion rate had {Minus, Zero, Plus} quantity spaces and concentration gradient was equal to the calculated difference between the internal and external concentrations (Figure 6.11). The concentration of the hemolymph had an expanded quantity space of {Low, Setpoint, High} to represent the concept of the set point optima for the variable.

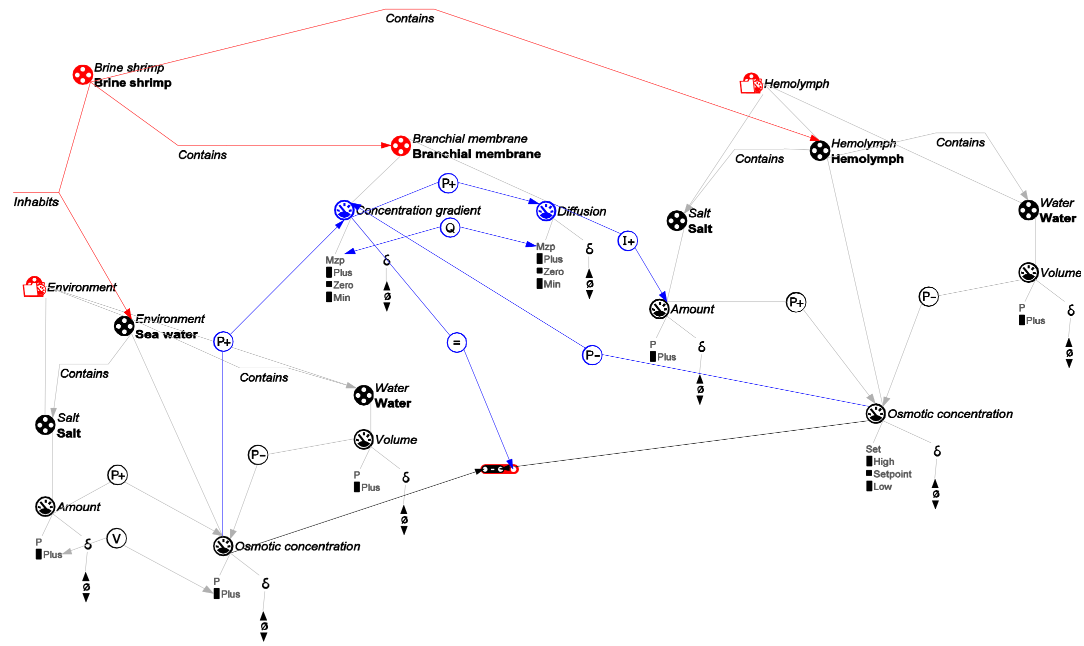


Figure 6.11 Model fragment representing the diffusion process across branchial membranes in brine shrimps. Diffusion is represented as a single net flow rather than a pair of inflow and outflow.

The sensor and effector mechanism are represented by a quantity "*Disturbance*", representing the deviation away from the set point optima (derived as a calculus on the value of the *Osmotic concentration*), and the *Activity* of the *Salt pumps* (both utilising {Minus, Zero, Plus} quantity spaces). This model design is fairly unusual here (Figure 6.12) in that it is a paired sequence of direct influences acting from *Disturbance* to *Activity* (positive influence) and from *Activity* to *Amount* of *Salt* in the *Hemolymph* (negative influence). This is unusual as *Disturbance* is not nominally a "rate" variable and is itself acting on a "rate". This representation is used so that the *Activity* of the salt pumps is initiated by a disturbance but can remain active even when the feedback mechanism has compensated for the disturbance (maintained compensation).

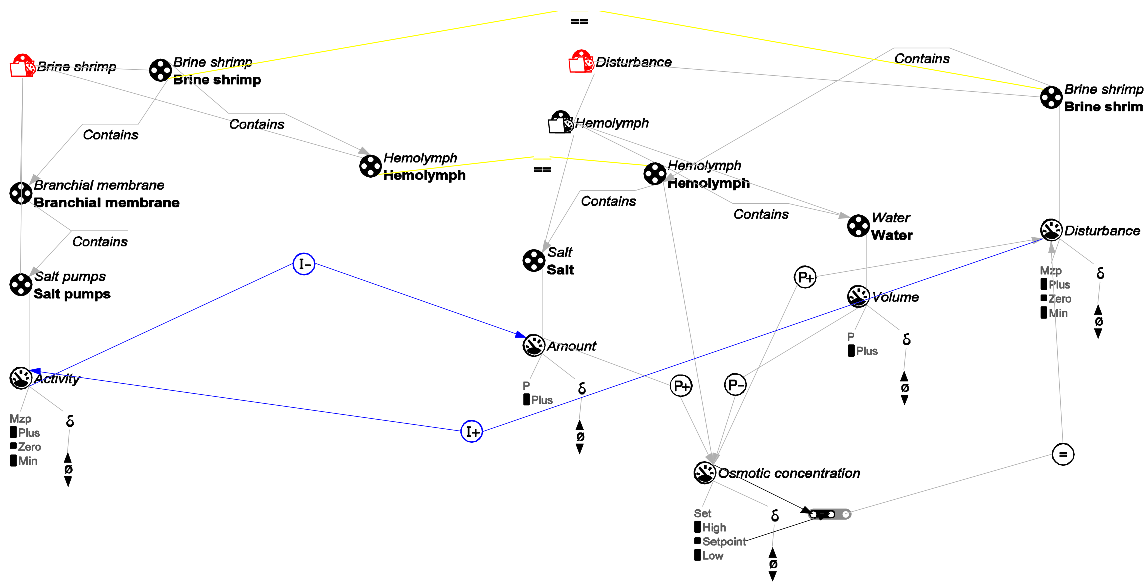


Figure 6.12 Model fragment representing the sensor and effector mechanisms of closed system feedback homeostasis. This fragment re-uses two other model fragments and identity relations are used to link the fragments to show that both fragments refer to the same *Hemolymph* and *Brine shrimp* entities. The expression also represents the relationship between "*Disturbance*" (the sensor) and the *Activity* of the *Salt pumps* (effector) as a direct influence I+.

6.5.3. Scenarios, simulation and behaviour

Five different scenarios have been defined for the regulatory feedback model: hyper salinity; hypo salinity; increasing salinity; decreasing salinity and fluctuating salinity. Three examples A) Increasing salinity; B) Hyper salinity and C) Fluctuating salinity are shown here.

Table 6.3 Summary of the starting conditions generating the behaviour for the scenarios for the regulatory feedback homeostasis model.

Type	Details
Exogenous control	A) External Amount of Salt exogenous increase; Internal volume of Water exogenous steady B) External Amount of Salt exogenous steady; Internal volume of Water exogenous steady C) External Amount of Salt exogenous sinusoidal; Internal volume of Water exogenous steady
(In)equality	A) Hemolymph osmotic concentration equals osmotic concentration of sea water B) Hemolymph osmotic concentration < osmotic concentration of sea water; Set point of Hemolymph osmotic concentration < osmotic concentration of sea water C) Hemolymph osmotic concentration equals osmotic concentration of sea water
Ambiguity	None
Simulation settings	Fastest path heuristic

A) Increasing external salinity

In this scenario the system starts in equilibrium with the internal osmotic concentration (at its set point) equalling the external osmotic concentration (Figure 6.13). The external osmotic concentration is increasing due to an exogenous control. In this model exogenous steady behaviours are applied to the amount of water in both the hemolymph and the sea water as, for simplicity, the effects of osmosis are not considered.

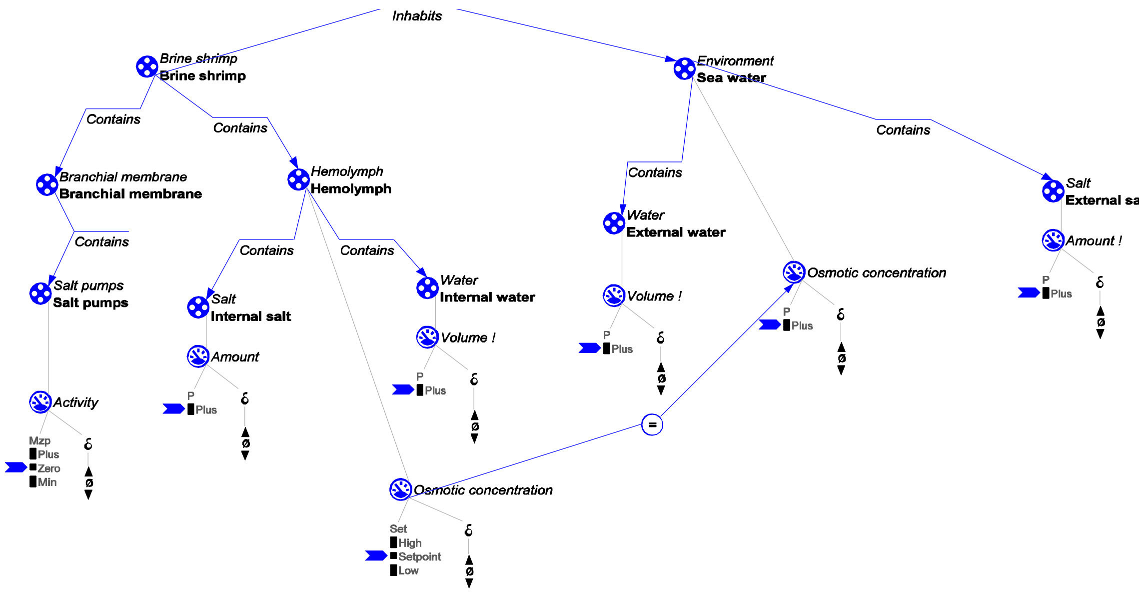


Figure 6.13 Scenario representing a brine shrimp at equilibrium with the environmental osmotic concentration but subject to increasing salinity of salt water.

This scenario above generates a simple four state simulation where the increase in the external salinity causes a disturbance to the internal environment and triggers the salt pump activity to regulate hemolymph osmotic concentration. Although this simulation does not show a tendency for the internal osmotic concentration to return to the set point it does mimic the pattern shown in the textbook representation (Figure 6.1 C). It can be seen that although both the internal and external concentrations are increasing, the regulatory feedback mechanism means that change in the external environment is larger than the change in the internal environment. This is most apparent from interrogation of the concentration gradient values which continue to increase, meaning the external concentration is increasing faster than the internal concentration (Figure 6.14).

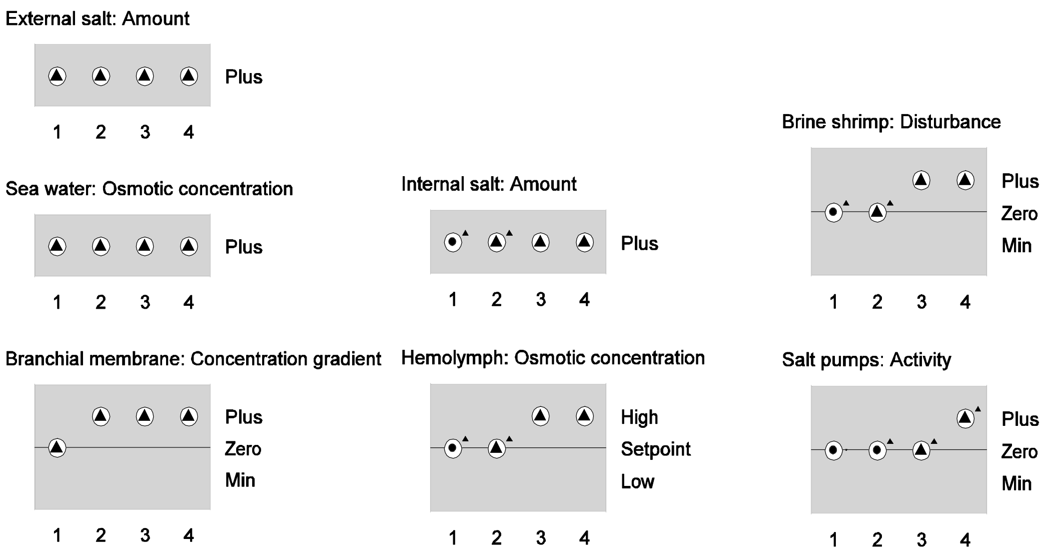


Figure 6.14 Value histories for a simulation of a brine shrimp subject to an increase in salinity in the environment.

B) Hypersaline exposure

This scenario was designed to represent a hypersaline saline challenge to the brine shrimp. In the scenario the hemolymph concentration is in the set point but that has a concentration that is lower than the concentration of the sea water environment (Figure 6.15).

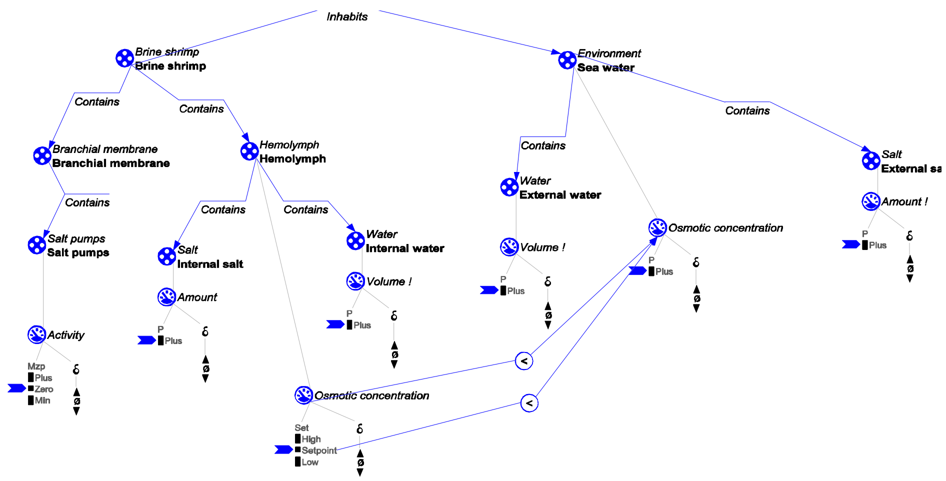


Figure 6.15 Scenario representing a brine shrimp subject to a hypersaline environmental shock. In the scenario a pair of inequalities are used to represent a) the hemolymph concentration is < the environmental salinity and b) the set point of the internal osmotic concentration is < the environmental salinity. The set point inequality statement is essential for consistency in the reasoning.

The scenario uses two key features, one an (in)equality statement between the set point value and the external concentration, and the fastest path heuristic simulation setting, to control the complexity of the behaviour and also its efficacy. The use of the (in)equality statement between the point value of the quantity space of the internal osmotic concentration and the quantity of the environmental osmotic concentration might seem redundant given the initial value assignment of the set point and the general inequality statement made between the two concentration quantities, however without it (and without the fastest path heuristic) the simulation generates three stable end states (Figure 6.16 A). Two of the three end states in this case are inconsistent with the initial logic in that all paths return the system to the set point after the initial disturbance caused by fluctuating external environmental concentration, except that the three end states generated are differentiated by the set point now being equal to, less than or greater than the external concentration, despite initially being specified as less than the environmental concentration which itself hasn't changed. Use of the point value inequality statement and the fastest path heuristic respectively maintains logical consistency in the equality of the set point to the external concentration throughout the simulation and makes the behaviour representation simpler (Figure 6.15 B).

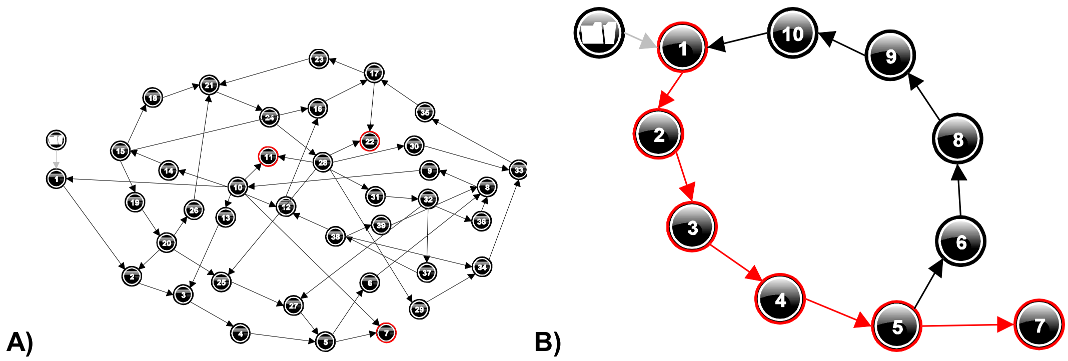


Figure 6.16 Behaviour paths for the scenario in Figure 6.15 with A) default simulation settings and no (in)equality statement between setpoint and environmental concentration and B) fastest path heuristic and the set point (in)equality statement.

The behaviour generated using the fastest path heuristic (Figure 6.16 B) demonstrates two possible behaviours. Firstly, a path [1, 2, 3, 4, 5, 7] where the regulatory feedback mechanisms compensates for the disturbance caused by the saline challenge and returns the system to stability with the internal osmotic concentration back in the set point. The second possible behaviour is an oscillating loop [1 → 6 → 1] where the feedback system is imperfect and causes the system to dynamically oscillate around the set point. This represents the feature of "hunting" in a closed feedback system where some of the elements have inertia or delays in the feedback loop (Withers, 1992) (Figure 6.17).

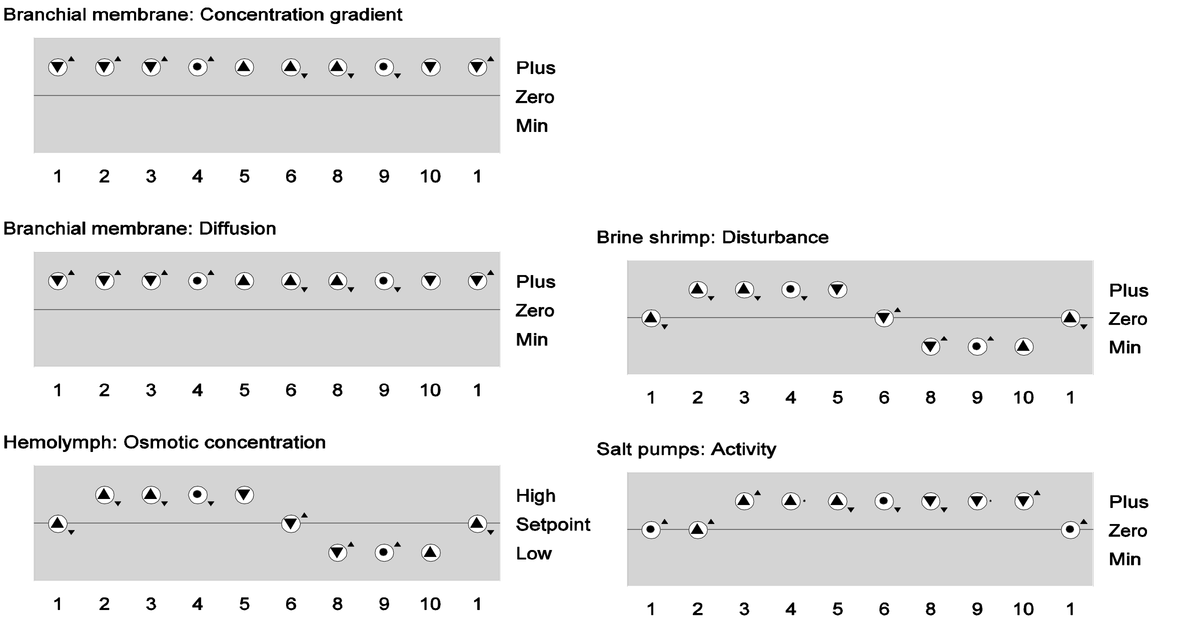


Figure 6.17 Value history for the scenario of a brine shrimp exposed to a hypersaline challenge. The feedback response is shown with the salt pump effector mechanism responding to the disturbance in the internal osmotic concentration and stabilising the system back to its set point. Note that in this context the path [1 → 10 → 1] represents cyclical behaviour where initially the activity of the salt pumps over corrects the hemolymph concentration and a cyclical behaviour of oscillations (hunting) around the set point occurs.

C) Fluctuations in external salinity

This scenario is similar to the scenario used for increasing salinity except that an exogenous sinusoidal behaviour is applied to the external amount of salt, hence causing fluctuations in the environmental conditions. Even using the fastest path heuristic this generates a fairly complex behaviour path (Figure 6.18) that comprises a number of paths that result in oscillations in internal osmotic concentration as a result of environmental disturbance and also hunting of the feedback system around the set point (Figure 6.19).

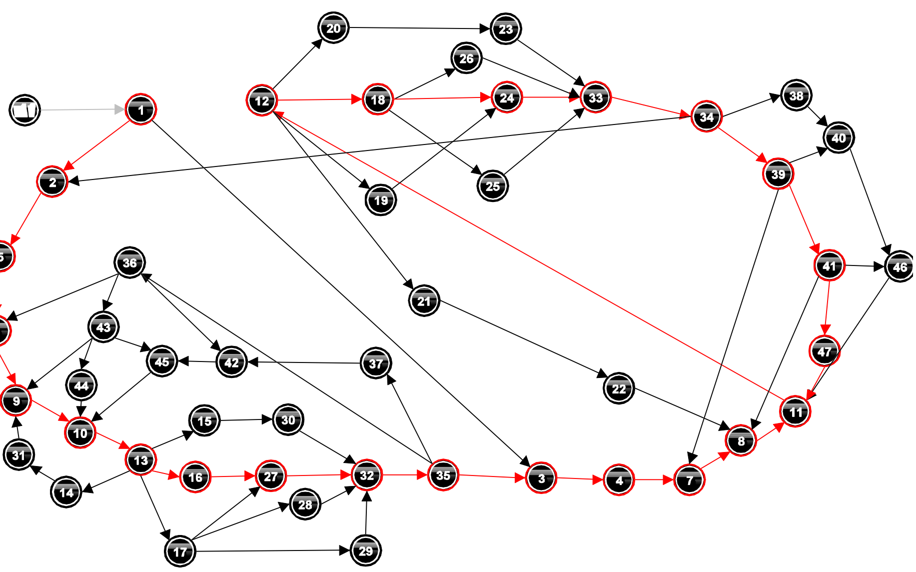


Figure 6.18 Behaviour paths for a scenario where a brine shrimp is exposed to fluctuating salinity. The behaviour path exhibits a range of possible oscillating loop behaviours.

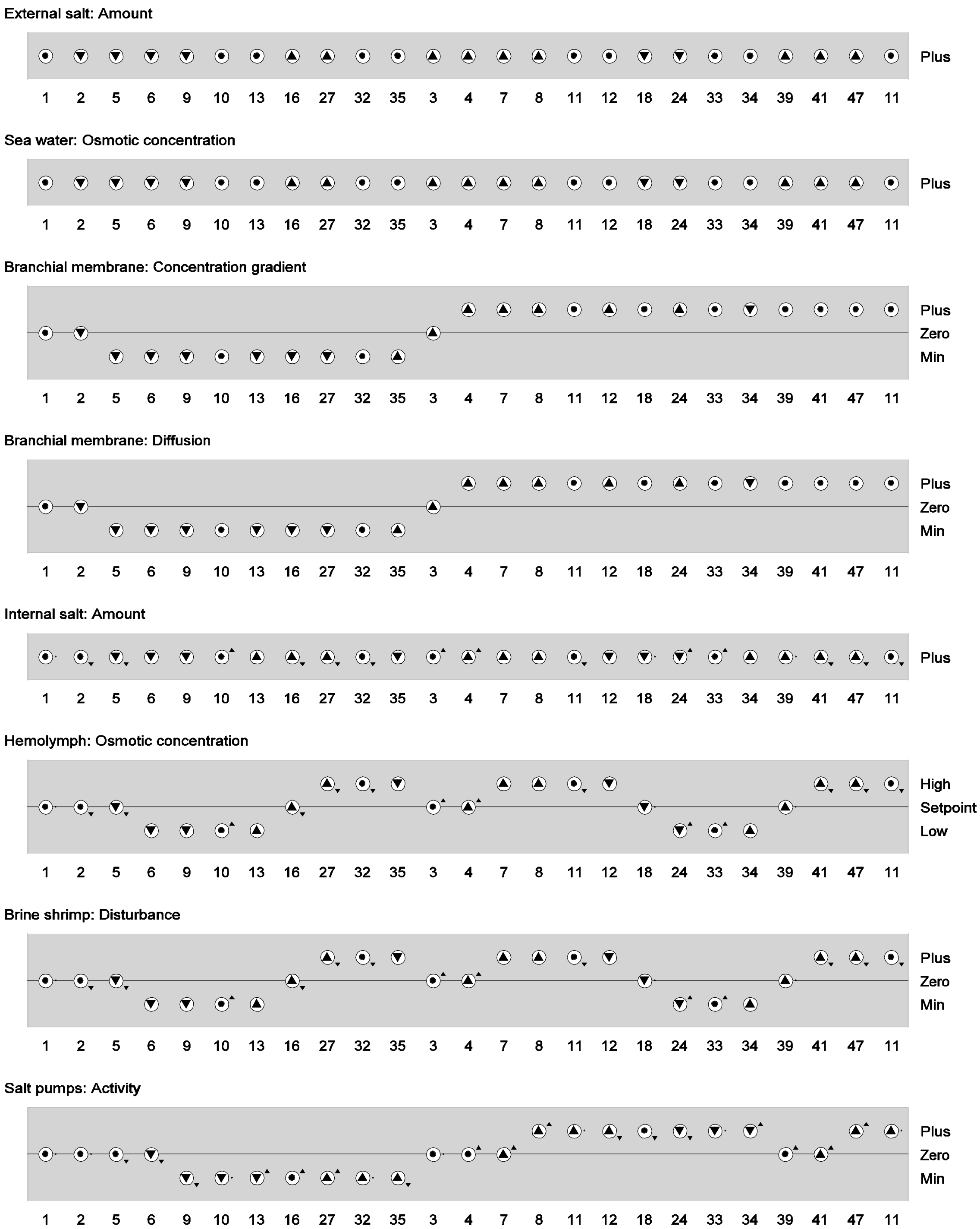


Figure 6.19 Value history for a single behaviour path for the simulation of a brine shrimp exposed to fluctuating salinity. The behaviour shows that the regulatory feedback homeostasis mechanism tends to result in the hemolymph osmotic concentration oscillating around the set point, partially independent of the external salinity.

6.5.4. Summary and features for discussion

- A parsimonious approach to QS definition was used to reduce simulation complexity and also make clear differentiation in key states and phases of behaviour in the system.
- The simulation required exogenous control to generate a fluctuating behaviour; hence the model was constructed in LS6 although the other knowledge expressed in the model could have been expressed in LS4.
- The fastest path heuristic was used to simplify the behaviours generated.
- The model scenario here necessitated the use of an (in)equality statement between a point in the QS of hemolymph osmotic concentration and the environmental osmotic concentration quantity. This was despite this information being implied by the (in)equality statement between the two quantities themselves and the initial value assignment to the set point. Without this additional (in)equality statement the simulation does not retain consistent reasoning regarding the relative size of the set point and the external concentration.

7. Discussion

The advanced models presented here all stem from clearly defined topics set within existing curricula and are derived from stimuli related to curricula goals and text books. The topics and models chosen for development into advanced models can be clearly differentiated from those developed in task 6.2 and presented in D6.2.2 (Noble, 2010) in both the level of complexity and the approaches used for defining the system to be modelled. All of the models developed here were motivated by and based on clearly defined system behaviour or phenomena, whereas the majority of the basic models presented in D6.2.2 were motivated by and developed as representations of a system and its structure rather than a specified behaviour. This behaviour (scenario and simulation) focus rather than system structure focus enhanced the value of the models produced and also aided the development of clear and efficacious simulations. Clearly specified expected behaviours acting as a stimulus for developing the models also influenced the model design in a positive way, with the modelling effort focused on the quantities and entities essential to describing the desired behaviour rather than initial detailed representations of systems having to be changed to match loosely defined *aposteriori* scenario ideas. The identification of clear behaviour and phenomena to be modelled also acted to focus the selection of which topics could be best suited to exploration with conceptual models within a DynaLearn curriculum for environmental science. Whilst conceptual diagrams of system structure and causality are possibly valuable tools for learning about many topics, it is probably only for topics where concise conceptual models of dynamic behaviours can be defined that the real benefits of simulatable models will be seen over and above static system diagrams. This approach to selection of topics limited the number of topics identified in D6.1 that were suitable for development as advanced models.

The advanced models presented here highlight the potential modelling applications that the compositional modelling approach and entity hierarchy available in LS6 of DynaLearn offer. The two models presented here for the diffusion & osmosis topic and the photosynthesis & respiration topics attempt to make appropriate use of the entity hierarchy and the inheritance mechanisms that this approach enables. In both models an entity hierarchy is defined, with an ontological approach, such that in both cases the models can have model fragments and scenarios built comprising of either generic knowledge applying to the supertypes of entity within the hierarchy or specific knowledge attributable to the sub-types of an entity. The strength of the DynaLearn entity hierarchy is that all knowledge expressed in relation to the supertypes applies to all of the subtypes (the knowledge is inherited by the subtypes). For example, in the lake oxygen concentration model the expressions made relating to the entity biota are inherited by and applicable to all the specific types of biota presented in hierarchy and used within specific model fragments or scenarios. This approach means that the advanced models can easily be re-used and applied to different specific scenarios.

The compositional approach used here focussed on an initial decomposition of the system into its basic entity elements and a single static model fragment was built for each individual element. These individual model fragments were then reused and/or combined into other static or process fragments to describe system structure. Where possible the design of model fragments and inherent knowledge within them was such that the scenario structure required to activate them was as simple as possible. The compositional approach used in LS6 enabled some of the models that had been expressed in LS4 during the development of the basic models to be decomposed into their key elements. This decomposition of knowledge also makes it much easier to interrogate and interpret the knowledge they contain. Where model fragment knowledge is re-used the new model fragment can be viewed with either all inherited information shown or with only the relevant information for the model fragment shown. In this way the model fragments become much clearer even when they can contain a large amount of inherited information. Additionally, the full causal dependency model that is available for each state within a simulation is also much easier to interrogate than were the whole model system to be presented within a single model expression. The compositional modelling approach also allows the integration of different models within the same model framework (for example the integration of the fishery yield model with the density-dependent population growth model). This enhances the capacity of LS6 models, especially those with a more generic focus to be re-used and applied to different specific perspectives and scenarios within the topic.

Within the models presented here a large proportion of the model fragments, and indeed a large proportion of the modelling effort, are focussed on defining the behaviour of the system rather than just the system structure or the representation of causality. This is particularly true of the models that represent complex non-linear behaviour such as the models representing diurnal fluctuations in lake oxygen concentration and the sigmoid growth curve of a density-dependent population. The majority of the model fragments are concerned with defining the magnitude and derivatives of individual quantities, or sometimes defining second order information of the relative size of the derivatives of two quantities. The importance of the proportion of modelling effort and model design that contributes to defining the behaviour found in the simulation of a scenario highlights the importance of the model having clearly defined behaviours as part of the modelling stimuli and goals. Even with clearly defined system behaviours as a modelling goal a significant amount of effort and trial and error modelling can go into getting a successful representation of the desired behaviour.

The models presented here show two approaches to defining the behaviour of the system in terms of the magnitude and derivative behaviour of quantities under different conditions in the model. The lake oxygen fluctuation model utilises condition value assignments for both magnitude and derivatives e.g. if x is plus and increasing then y is plus and increasing. With this approach a model fragment is required for each individual combination of the magnitude and derivative of “x” that is important to the model. The density-dependent population growth model utilises a different approach where conditional value assignments are used for magnitudes and derivative correspondences are used to define derivative behaviours e.g. if x is plus and then y is plus and there is a derivative correspondence between x and y. The second approach is probably more efficacious in terms of clarity and also reasoning potential, although it should be noted that the derivative correspondence does not imply any form of causality and the quantities between which the derivative correspondence is applied should be carefully chosen. In addition to the derivative correspondence approach the Population growth model also makes use of the single derived quantity (net recruitment) for controlling and expressing the second order behaviour of the birth and death rates in the system. As net recruitment is a quantity calculated from the birth and death rate its derivative behaviour is an expression of the combined second order behaviours of the birth and death rates (i.e. which one is changing faster than the other). This shows that with appropriate definition of derived variables and derivative correspondences it is possible to regulate second order behaviour within DynaLearn.

The modelling approach here followed a parsimonious approach to defining quantity spaces. In all cases all quantities were initially assumed to consist of a single interval and were only expanded for a specific modelling reason. Therefore, the majority of quantities had either a {Plus}, {Zero, Plus} or {minus, zero, plus} QS. This was done primarily to restrict the level of complexity in the model and the potential complexity in the model. Key quantities were given expanded quantity spaces for four specific reasons:

- Enable a visual pattern to be established within the value history of simulations;
- Enable (in)equality and calculus reasoning, or representation of rates (I+ or I- relations);
- Representation of a domain concept (e.g. {Zero, Minus} for water potential);
- Enabling clear differentiation of distinct states and phases in behaviour that require conditional knowledge.

Therefore, it can be seen that the quantities with expanded quantity spaces in these models are those that either determine some aspect of the behaviour based on their magnitude or state, or those that are the focus of the simulation and value history. This approach to defining quantity spaces is essential for controlling complexity in simulations, as even when only one or two quantities have complex quantity spaces the simulations produced can be extremely complex and difficult to interrogate containing extraneous behaviour paths that whilst possible do not contribute to the goal of the model. Additionally, appropriate choice of scale and granularity can be important in creating models. For example, although the homeostasis models were based on concepts such as osmosis and diffusion the modelling approach used for these topics was not applied to homeostasis models. In the case of homeostasis these were represented as single flow quantities rather than a pair of inflows and outflows. This was because this level of granularity was not required in this context. Furthermore, to reduce the complexity further the homeostasis models assumed that diffusion processes had no influence on the environmental concentration of the substance diffusing. This was assumed as the relative magnitude of the effect of diffusion on the internal environment of a small animal compared with the large external environment was disproportionate and not required to explain the behaviour in the model. As such although the models can be linked in the course of a curricula the representations of the system can be different depending upon the level of complexity required.

The majority of the models presented here follow a similar approach to initial causality within the scenario (from a technical modelling point of view). Most of the models utilise an agent-based quantity with an exogenous behaviour on it. This is especially true for those models that utilised the exogenous sinusoidal behaviour together with an expanded quantity space to define and replicate oscillation and fluctuation in a system. The use of the exogenous sinusoidal behaviour often meant that models that could easily have been built in LS4 or LS5 were required to be built in LS6 (since most of the exogenous behaviours are only currently implemented in LS6). This meant that three considerations were made to choose which learning space a model was built in:

- Complexity of the system structure (complex systems require the compositional approach of LS6);
- Complexity of the behaviour (non-linear behaviours require conditional knowledge LS5 or LS6);
- Complexity of the exogenous behaviour in the scenario (all complicated exogenous behaviour necessitates LS6).

For this reason only two of the models presented here were built using LS5 although were the more complicated exogenous behaviours available in this learning space all of the homeostasis models could have been built in LS5.

Whilst the vast majority of models presented in D6.2.2 used the default simulation settings in DynaLearn, many of the advanced models here make use of different simulation settings to alter the simulations obtained. In most cases this was merely the application of the fastest path heuristic to condense all the possible behaviours available based on the scenario into the main behaviour(s). Generally this did not alter the key behaviours observed and merely helped to clarify the behaviour path into something more easily interrogated. Even with a parsimonious approach to defining model quantity spaces the models concerning oscillations and fluctuations could generate many different looped behaviours that in reality represent the same basic behaviour. Only in one case did the fastest path heuristic significantly alter the simulation and in that case it actually acted to remove an inconsistent end state termination from the behaviour. Whilst in an ideal model the inconsistent end state termination would be corrected by altering the model implementation in the model fragments, the use of this simulation setting can be seen to be efficacious for resolving the issue in a context where only the main behaviour is required. The use of some of the other simulation preferences in models and their simulations is however to some extent questionable. Whilst there is no doubt that they are valid, especially those that maintain consistency of behaviour in extreme points (e.g. a quantity cannot still be increasing in a maximum point value) or those that control the appearance of inactive quantities in behaviour paths/value histories, the selective use of some of the background reasoning preferences could be problematic in education. Indeed altering the simulation preferences is something that needs expert understanding of the internal reasoning logic of the DynaLearn engine. From an educational viewpoint the internal reasoning preferences need to be consistent or made explicit assumptions in the model environment. For example, the deactivation of the 2nd order derivative reasoning preferences enabled the expected behaviours to be observed in a model that required ambiguity in the 2nd order derivative behaviour rather than for unknown derivatives to be assumed to be zero. Whilst this choice is valid, it required expert knowledge of the preferences to identify why the same model did not initially give the behaviours expected. Additionally, to a certain extent these preferences are hidden from students and as such will not be available to them through semantic feedback and model comparison. Ideally, the default simulation preference settings in DynaLearn should be the most appropriate to an educational context.

In addition to the use of the different simulation preferences to control the output of the simulations the modelling effort here only identified one issue with the default simulation reasoning. This was identified as the retention of (in)equality reasoning during a simulation. For the regulated feedback homeostasis model a scenario was developed where the hemolymph osmotic concentration was regulated in response to a “salinity” challenge where the environmental salinity was either greater than or less than the internal salinity. In this scenario the initial value of hemolymph salinity was set to the set point using a value assignment and an (in)equality statement was made between the two concentration quantities. The result of this simulation was that the disturbance caused by the saline challenge caused the internal concentration to deviate from the set point and then the homeostatic regulation compensated for the disturbance and returned the internal concentration to the set point. However, this simulation produced three possible end states where the internal concentration was at its set point but was now >, <, or = to the external concentration, despite the external concentration not changing and the fact that the set point was inferred by the value assignment and (in)equality statement to > or < the external concentration in the initial scenario. Therefore, the simulation failed to retain inequality information in the simulation despite this being inferred in the initial scenario. This was solved by adding an additional inequality statement directly from the set point value of the hemolymph concentration to the quantity of the external concentration. From a simplistic viewpoint this inequality statement seems superfluous and ideally the reasoning engine would infer this from the initial scenario.

Following the use of the fastest path heuristic to clearly show the basic behaviours it is clear that even models with parsimonious quantity spaces have potentially complex behaviours, especially when considering loops and oscillations. Ideally for some models some mechanism would be developed for determining which loop is generated under certain conditions. For example, in the lake oxygen concentration an ideal model would be able to replicate that the magnitude of the fluctuation in the oxygen saturation variable was somehow linked to the magnitude of a quantity representing the nutrient status (Eutrophication of the lake or biomass of the plants). However, this semi-quantification is very difficult to achieve in qualitative models. Therefore, to a certain extent these models need to be interpreted that all the behaviours are possible and that some un-modelled concept controls which path might be taken.

The complexity of behavioural outputs of simulations and the tools available to interrogate the behaviours (e.g. value history, equation history etc.) sometimes mean that the pattern defined by the stimulus material or key behaviour is not immediately visible. This is most obvious for the sigmoid population growth curve and less so for the Schaefer positive yield parabola. In particular the sigmoid curve cannot be observed merely from the interrogation of only the value history for the size or density of the population. In this way the value history is probably less visually striking or immediately informative as the diagrams in the stimulus material from which it is derived. However, in the case of both the sigmoid curve and the positive parabola all the key characteristics of the behaviour are represented in the model and the curved relationships can be inferred from the simulation provided the value histories of a number of different quantities are interrogated. Given this, it is likely that these sorts of models have a high efficacy when presented alongside the stimuli diagrams as they both represent and explain the behaviours observed. In this way the conceptual models capture the true reasons for the behaviours that might not necessarily be obvious in either a static diagram or a numerical equation representing the lines in a graph. As such all the models presented here can be seen to successfully capture the characteristics of a described behaviour although such behaviour may not be immediately obvious.

8. Conclusion

- Identification of topics with clearly defined stimuli behaviours is fundamental to producing good conceptual models in DynaLearn and identifying which components of the curricula are most appropriately covered by conceptual models.
- The advanced models presented here provide good representations of the characteristics of the stimuli behaviour they were intended to reproduce and explain, even if the behavioural pattern is not immediately observable in the value history.
- Use of the simulation preferences added value to some models and helped clarify others, however extensive use of these internal reasoning settings needs to be defined and the most appropriate default settings chosen for an educational setting.
- The exogenous behaviours available at LS6 should be made available in LS4 and LS5 to enable optimal use of the different leaning spaces.
- Appropriate use of entity hierarchy, compositional modelling and most importantly the definition of appropriate quantity spaces are fundamental to producing good and efficacious conceptual models.

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