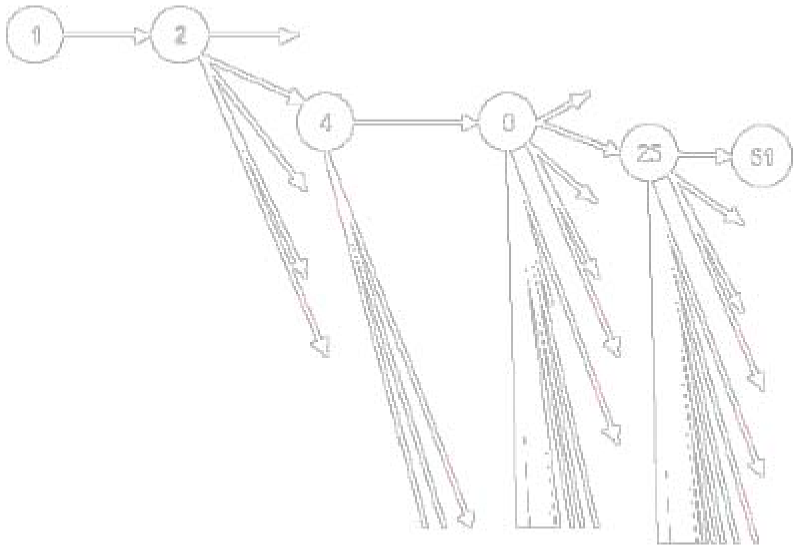
An Articulate Model of the Water Cycle

Using qualitative reasoning



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Contents

Abstract

This study describes several qualitative models capable of reasoning about the behaviour of the ecological domain of the water cycle. Qualitative models are useful in terms of explicit knowledge communication, and they can form a component of an intelligent tutoring environment. Particular methodological aspects of the design of qualitative models support the construction of simulation models that are suited for didactic purposes. Given this purpose, conceptual knowledge is captured in model fragments, which describe structures and processes. The domain of the water cycle can be viewed and explained with various scopes. Following ideas on how to structure the communication of knowledge, qualitative models inhabiting different levels of detail and perspective have been developed, each resulting in a particular simulation. The simulations are discussed and analysed, focusing on knowledge communication with the use of computer systems that are based on theories from cognitive science, artificial intelligence and instructional science.

1. Introduction

When interacting with the physical environment, people need knowledge of the behaviour of systems and processes. The specific type of knowledge that people need depends on the tasks they have to perform in the environment, e.g. controlling, constructing or diagnosing, see also (Breuker & Van de Velde, 1994), and the particular nature of the domain being dealt with (e.g. thermodynamics or biology). The thesis presented here concerns the development of an interactive simulation model as a tool for humans to learn about a system and its behaviour.

Research on the use of computers in instructional settings, or Intelligent Tutoring Systems (ITS), relies on both theories of human learning and automated reasoning. Integration of these theories has been an important context for the development of systems that are directed to facilitating knowledge communication between computers and human actors (Wenger, 1987). To transfer knowledge and to interact with a human being on the level of knowledge *content*, an educational system should posses a dynamic internal representation of the knowledge (Bouwer et al. 2002; Newell, 1982). Usually these representations take the form of models or, more specifically, simulation models. With simulation models, a central issue with respect to guiding effective knowledge communication is the format in which knowledge can be communicated.

The use of *numerical* (simulation) models to express behavioural features is most eminent in mathematics and other quantitatively oriented sciences. An alternative way of representing behaviour comes from the strand of research generally referred to as *qualitative reasoning* (Forbus, 1984), which has its origins in the field of artificial intelligence. Qualitative representations form the essence of the model presented. There are several issues from which qualitative models show their utility and usefulness with respect to automated educational settings, see also (Bouwer et al. 2002).
First, when designed to be articulate about the knowledge communicated, qualitative models in educational settings can provide a basis from which guidance to the user can be established, for instance in the form of generating explanations. Constructing *articulate models* means that a simulation model should contain sufficient detail about the domain at hand, be explicit about the topics to be learned, and facilitate feedback or explanation where necessary, see also (Falkenhainer & Forbus, 1992; Winkels & Bredeweg, 1998). Second, in an educational setting, qualitative models provide a way of acquiring knowledge on the conceptual level, which is seen as a prerequisite in order to move on to numerical analysis. Finally, qualitative models can be applied to less formalised domains in order to identify and depict conceptual (e.g., causal) structures that explain the behaviour of a system. This means that qualitative models can be helpful in acquiring specific insights in various domains.

From an educational perspective, interaction with qualitative (simulation) models focuses on the notion of behaviour analysis. This analysis is based on both prediction and post diction of system behaviour. With qualitative models, the tasks of prediction and post diction can be associated with various skills that a learner should master in order to reason about specific (physical) phenomena. These skills include generation of causal accounts, reasoning from structure, and reasoning with multiple perspectives (Bouwer et al., 2002; Dekleer & Brown, 1984).

Typical domains in qualitative reasoning research are physics problems, such as pressure regulators or steam engines (Collins & Forbus, 1987). Researchers such as (Guerrin, 1991) and (Heller et al. 1995), have developed models that are focused on ecological problems. They have shown the usefulness of using qualitative reasoning in non-physics domains. However, to date the amount of qualitative models produced in other domains than physics is relatively low. There is a need to go beyond the scope of classical physics problems and show the added value of qualitative models in non-physical domains.

Summarising, there is increasing attention being paid to the notion of communicating domain knowledge through ITS. Qualitative reasoning is frequently associated to ITS, but it is a framework for knowledge representation that is traditionally used for reasoning about physics problems. Given this context the research question is formulated as follows:

Design and implement a simulation model which comprises a new qualitative ontology for the ecological domain of the water cycle, which inhibits a knowledge organisation that allows the model to function as expert module in an educational setting.

In addition to working out this research question this thesis will provide theoretical context on intelligent tutoring systems, qualitative reasoning and constructing simulation models.

The next Chapter provides context on the research field of ITS. The third chapter introduces and discusses the concept of qualitative reasoning. In chapter 4 the functioning of the qualitative simulator and its knowledge representation is explained. Chapter 5 goes into detail about the issues involved with model construction, in particular qualitative models. The domain model of the water cycle is described in chapter 6. In chapter 7 the simulation of the water cycle is discussed. A review of the models is given in chapter 8. Chapter 9 forms the conclusion and discussion of the research.

2. Knowledge Systems in Education: An Overview

The context of research on Intelligent Tutoring Systems is multidisciplinary. It is linked to the fields of cognitive psychology (Anderson, Boyle, Farrell & Reiser, 1987), pedagogy (Rittle-Johnson & Koedinger, 2001), computer science and subject matter domain theories. In order to communicate knowledge to students, ITS's typically rely on several components, such as the student model, the curriculum planner, the simulation engine, the user interface and a model of the subject matter. Research fields need to collaborate in order to produce a working system out of several modules, which can be considered as expert systems individually.

From the beginning of research on ITS's, effort has been put in producing tutorial dialogues, communication strategies, and in principles for knowledge representation (Wenger 1987). In order to establish interaction between a computer in the role of a tutor and a human in the role of student, one of the most fundamental problems is the explicit representation of the knowledge that should be taught and the curriculum for teaching it (Lesgold, 1988). Issues concerning curriculum are generally dealt with by the use of theories from pedagogy or cognitive psychology. The research on human knowledge acquisition and problem solving is a still ongoing topic of investigation. Next to research on the use of for example procedural knowledge in problem solving, other questions have risen: How and to what extent for example are heuristics used in problem solving? What tacit or common sense knowledge underlies certain problem solving capabilities? One of the issues is to identify and make explicit how common sense knowledge is utilised in dealing with physical problems. For example, Falkenhainer et al., (1986) researched the use of analogies with subjects when experimenting in physical domains. A commonly recognised shortcoming of the older instructional systems was the failure to incorporate this common sense knowledge that people use in solving problems.

The question of how to represent the right kind of knowledge has been a source of debate since the first ITS's were developed (Wenger, 1987). Early ITS were able to represent domain knowledge by the use of frames and slots, which are linear descriptions. The curriculum as a consequence was very rigid and not sensitive to the knowledge of students. The systems failed to give articulate accounts for what they were teaching. An alternative to this *frame-oriented paradigm* was proposed by (Carbonell, 1970) in defining the *information-structure-oriented paradigm*, along with the SCHOLAR system, a geography tutor. The structure of knowledge representation used in SCHOLAR is a semantic network (Quillian, 1968), including relations such as super part, super concepts, et cetera. In terms of knowledge communication, Carbonell pioneered on issues that are still relevant in Intelligent Computer Aided Instruction (ICAI), such as mixed-initiative dialogues, explanation generation and diagnosis of learner behaviour.

In another system called WHY, developed by (Collins and Stevens, 1977) special attention was given to learner diagnosis, more specifically the construction of Socratic Dialogues, in which functional analysis plays a fundamental role. The knowledge representation in WHY is achieved by using hierarchical scripts and the generation of questions is based on these scripts, which actually allowed a kind of evolutionary curriculum on the subject. In evaluating the system, Collins and Stevens raised some important issues. Of particular importance was the lack of incorporating high level goals in tutoring, a result of only local applicability of question generating rules. This led to the appraisal of the role that causal models and procedural knowledge play in pursuing high level goals, next to just declarative knowledge. The use of subgoals and backtracking are common examples of procedural knowledge in resolving problems, and should thus be incorporated in instructional systems.

The use of artificial intelligence in tutoring systems has shifted the focus form encoding decisions to the encoding of knowledge and how knowledge can be communicated (Wenger, 1987). An important contribution from the A.I. community was made by the investigation on how certain types of knowledge (e.g. procedural, causal) may be encoded in generic form. When considering most domain knowledge, different views may focus on different aspects of a system, and various levels of detail may be required for particular views. A more dynamic kind of encoding has a one to many mapping, and makes use of explicit knowledge about the applicability of certain knowledge. The idea of multiple viewpoints on a system relates to the notion of a mental model that is able to simulate the behaviour of (physical) systems to a certain extent. An important feature of these models is that they usually incorporate multiple viewpoints on the same subject. From a computational point of view, this is called the cognitive modelling approach.

Work on ITS's focuses on development of simulations that mimic human problem solving, including humanlike deployment of knowledge (Anderson, 1993). The model therefore requires reasoning abilities about it's own content. Research on mental models, as used by people in reasoning tasks, supported the work on computational models. The idea here is that people conceive of models in different scopes e.g. planetary → climates → water cycle etc., and then an approach could be to develop a view of the mental model with models that are decomposed at the functional, aggregate and molecular level, which can help explain each other. And indeed, these ideas have proven to be essential to questions about sequencing the knowledge to be conveyed to learner i.e., to resemble the way a teacher would plan a lecture when trying to explain a subject, successively addressing deeper levels and higher complexity (Collins & Gentner 1983).

An important task emerged from the standpoint of computational models, namely a formalised framework being able to represent the knowledge that people use in reasoning about dynamic physical phenomena. The framework should be able to derive the same general conclusions about physical problems as mathematical models, albeit in a less complex fashion, from an algebraic point of view. This trajectory of research that was established came to be known under several different names, the most common are Naive Physics and Qualitative Reasoning. As for Naive Physics Patrick Hayes (1985), introduced the topic most seriously in the field of A.I. and expert systems. He expressed the need to abandon 'toy world problems' in favour of more complex formal models of the world as it is intuitively perceived by us, in terms of objects, change, events and processes. Among the motivations for developing qualitative models lies, much the same as with WHY, the desire to communicate causal knowledge to learners. The SOPHIE project (Brown et al., 1982) serves as a good example. For Qualitative Reasoning, the focus is on implemented models containing causal knowledge needed to reason about physical processes, and among the initiating efforts to do so are (Forbus 1984, Kuipers 1986). The potential for qualitative simulation models in tutoring paradigms is a research topic itself (Anderson 1993). The most clear potential lies in terms of explanation, curriculum sequencing (see also White & Frederiksen, 1986; Salles & Bredeweg, 2001) and the generation of articulate simulations of specific systems. When we want subjects to learn about how to interact with a physical system by means of a tutoring system, it is necessary to mimic human mental models of systems. Qualitative representations are well suited to communicate causal knowledge and are able to support the notion of curriculum sequencing multiple perspectives. By giving a model an explicit purpose we should be able to limit the amount of inferences and concepts needed to create a sufficiently sophisticated model for the (instructional) purpose or goal at hand.

The research on ITS is nowadays directed to the development of formal systems that can perform humanlike reasoning about systems and at the same time be explicit about the reasoning steps it performs. An important issue forms the models being articulate about the knowledge, which is facilitated by developments in qualitative physics (Forbus et al. 2000). An example of such an articulate learning environment, or virtual laboratory, is CyclePad (Forbus & Whalley, 1994) where thermodynamic cycles can be analysed.

Many different types of tutoring systems have been developed. At this stage, the research has not only benefited from the diverse offer in tutoring systems; lots of systems have been developed independently and at this moment the sharing of knowledge is problematic. As a reaction, effort has been put in the development of frameworks for interoperable and component-based systems (Ritter & Koedinger, 1997; Koedinger, Suthers & Forbus, 1998). Next to easier maintainance and easier re-use of components, the functionalities can be constructed by composition of components such as simulation models, learning agenda's. An important requirement that follows from the above is the need for a shared semantic between different components in a learning environment, so that components can communicate and share information smoothly.

3. Qualitative Reasoning Paradigm

Qualitative reasoning is now a well-established field within artificial intelligence. At this time a whole range of approaches and methods within qualitative reasoning have emerged. Among its goals is a qualitative computational framework for reasoning about physics. This means as much as rephrasing traditional physics in an alternative way, while preserving its laws and observations. Several motivations form the basis of research on this alternative framework, (Forbus, 1988). One of the original motivations came from the research on cognitive models. Here efforts have been done to create computational accounts for the mental models (Gentner & Stevens, 1983) that people have when interacting in complex physical systems (White & Frederiksen 1990; Dekleer & Brown, 1984). The mental models that people use, are conceived of as runnable which means that some kind of simulation is involved. This simulation is sometimes explained as qualitative simulation, involving general common sense inferences.

Another motivation comes from the field of robotics, where these ideas are put to practice in order to allow robots to move in their physical environment (Hayes, 1978; Zhao, 1995). When acting in the physical world, the plain use of a set of equations to analyse and act on their environment is not sufficient to deal with complex surroundings. Equations in themselves contain no information about their applicability in physical situations. Robots have to rely on so called tacit or common sense knowledge in order to determine what kind of knowledge is applicable to a certain situation, and to mentally simulate and reason about dynamic processes.

A third motivation for qualitative physics research lies in the field already discussed in section two, namely research that is directed to knowledge communication for educational purposes. Qualitative physics provides an articulate vocabulary that corresponds to people's tacit conceptions of phenomena. Qualitative knowledge is usually modelled in terms of intuitive components like causal relations, processes, etc. As such they provide a basis to facilitate knowledge communication to learners through knowledge intensive educational systems. Qualitative models form a basis for developing dialogs and other forms of interaction, such as explanation generation (Wenger, 1987; Aleven & Koedinger, 2000).

The idea to develop an alternative physics stems from the fact that traditional physics lacks to produce a causal account of phenomena, something that is a core feature of mental models as deployed by humans. Although this looks relatively straightforward the question of how for example to represent causal ordering remains widely discussed within the QR community. When modelling a domain, choices such as 'X causes Y, and not the other way around' are sometimes difficult to prove, and therefore several representations of causality have been proposed (Forbus & Gentner 1986, Iwasaki & Simon 1986). It is generally agreed to that traditional physics or mathematics do a good job when it comes to generating precise descriptions or simulations of physical situations. However, a very accurate set of input values that apply to physical equations is required. When no precise information is available, the use of numerical simulations tends to become computationally expensive, as large ranges of values must be simulated. In qualitative physics methods exist for representing partial information about numerical values, abandoning traditional use of numbers. These methods include the use of signs and ordinals (Forbus, 1984). Furthermore, traditional descriptions based on incomplete information gives no guarantee that all possible behaviours will be found, and the very availability of a set of (exhaustive) alternatives is required in many reasoning problems. Typical to qualitative models is that an exhaustive set of alternative behaviours can be generated, in particular under circumstances with incomplete information. The formulation of explicit modelling assumptions (Falkenhainer & Forbus, 1991) under which a model is applicable provides the means to specify the boundaries of the analysis, and thereby automatically controls the amount of possible behaviours found. Between these boundaries the analysis is exhaustive.

Another feature of the alternative physics through qualitative reasoning is reasoning from structure (Dekleer, 1984). Physical phenomena are represented in terms of local descriptions of objects and processes that can be combined to form complex structures. Behaviour is derived from the interconnection of different objects and processes. Most qualitative models rely on a blend of both generic components and domain specific components. The development of generic knowledge allows models to have wide coverage and multi-purpose, so that the inferences captured by qualitative models are not particular to certain instances of a physical situation, but to classes of similar situations. People in general do use some general principles when coping with the environment, however, the link between human mental reasoning and the use of generic knowledge has not been shown directly. It seems likely that people use some domain-independent laws and principles when reasoning about the physical world (Forbus & Gentner, 1997). The modularity of the knowledge in itself allows for composition theories, which account for a high degree of reusability of the knowledge. Components of knowledge in qualitative physics will be referred to as model fragments subsequently.

The above has sketched some general motivations and purposes of qualitative physics as well as concepts that are at the basis of qualitative physics. In general they are concerned with formalising aspects that constitute the mental processing involved with reasoning about the physical world. The next section will outline some general methods of qualitative reasoning.

3.1 Describing change

The representation of dynamics within qualitative physics itself varies considerably. Generally speaking, (qualitative) representations of dynamics involve numbers, equations and functions. One of the most influential theories on qualitative dynamics is the Qualitative Process Theory (Forbus, 1984), which comprises a qualitative ontology for the representation of physical processes. A technical discussion on the representational primitives used in this research will be provided when discussing the knowledge and reasoning framework used for this research, see chapter 4. Some general features of dynamic representations are discussed next.

Quantities in qualitative reasoning have an amount and a derivative which both have signs. The most widely used method of reasoning with changing quantities used in QR is the sign algebra, which uses measurements like minus, plus or zero for the derivative of a parameter. By using sign algebra for the representation of ordinary numbers in qualitative models, precise predictions cannot be made anymore, but they allow abstract descriptions of behaviour. The representation of a set of continuous variables that a quantity may have is done with a partial ordering. A partial ordering contains a set of ordinal values, with zero or chosen landmarks as points of comparison. This type of representation is called a quantity space. Within the partial ordering, the values with no values between them are called neighbours. Between neighbours intervals exist, which have no defined length. A quantity space is unique for the quantity it is assigned to.

In order to describe quantities and the values that they may have, inequalities are used. This way, values of quantities may be compared to each other or to certain limit points that may exist, such as the boiling point of a certain liquid. While each quantity space is unique, we need to be able to express that some values of quantities correspond. It is possible by defining for example that for a particular quantity ‘volume’, the values *low*, *medium* and *high* can be set equal to the value *positive* for the quantity ‘pressure’.

In order to induce change, the use of functions and equations is required. The equations that are used in most qualitative reasoning concern straightforward arithmetic equations. The functions that are used most in qualitative reasoning are monotonic functions. A *correspondence* for example is a function that derives the value of a parameter from the value of the parameter that it corresponds to. *Qualitative proportionalities* are used to relate the derivative of parameters. When processes are being modelled, their effect are specified using *influences*. Influences affect the derivative of a parameter for a particular number of states. This type of influence is independent on changes in other quantities and are therefore called direct influences. Other influences depend on changes in a related quantity and are therefore called indirect influences.

3.2 Compositional Modelling

One of the desiderata for a theory of qualitative dynamics is composability of system models, which aims to comply with the no-function-in-structure principle (DeKleer & Brown, 1984). This principle states that partial models do not assume the functioning of the system as a whole. In modelling dynamic systems, a now common strategy is the compositional modelling approach by (Falkenhainer & Forbus 1991), where models can be generated by assembling several model fragments of domain theories. The main benefits of this modular-based development of models are the possibilities of re-use of components, easier maintenance and extension of the models. All model fragments contain a condition part and a given part. An assembly of model fragments is instantiated on the basis of an initial scenario, which contains knowledge of the model fragments of interest. When the elements in the scenario correspond to the condition part of a particular model fragment, it becomes instantiated. The elements in a scenario may match with multiple partial models. A scenario typically activates multiple partial models, which together form a system description at a particular time. Decomposition of the domain into separate components provides the conditions for approaches to automated modelling of a domain. Automated modelling constructs the most efficient model of a particular scenario, by controlling the amount of instantiated knowledge. Composability of the model components has the advantage that not every possible scenario has to be anticipated.

The domain theory itself is written down in model fragments, which can be combined to form descriptions of particular physical phenomena, given an initial scenario description. With respect to the applicability of model fragments in some models, *modelling assumptions* can be defined. In general, modelling assumptions constrain the amount of detail considered in an analysis. Simplifying assumptions can be used to control the set of model fragments that will be instantiated, and therefore can provide global structure in the model by specifying and controlling ontology, grain size or perspective of a model under consideration. Another type of modelling assumption is operating assumptions, which describe the kinds of behaviour relevant to a task, such as a steady state assumption. The main advantage of using of modelling assumptions is that incompatible or competing views on individuals may exist side by side in a library of model fragments. Modelling assumptions are written down in the format of model fragments. In logical form, a model fragment is encoded as a first order implication (Falkenhainer & Forbus, 1991 p.103):

$$\mathbf{I} \wedge \mathbf{A} \wedge \mathbf{O} \rightarrow \mathbf{R},$$

where

- **I** is a set of structural conditions.
- **A** is a possibly empty set of assumptions concerning the fragments relevance to questions of interest.
- **O** is a possibly empty set of operating conditions including inequalities between parameters, conditions on activity of other model fragments and operating assumptions.
- **R** is a set of relations imposed by the model fragment.

3.3 Qualitative simulation

The tasks that people perform in their environment often depend on the notion of behaviour analysis, which involves, among others, predictive or postdictive reasoning steps. A problem with traditional physics is that there is no means to show how a particular state of affairs has come about, and which trajectory or history is tied to a certain parameter. Qualitative simulation produces a set of qualitative states and the transitions between them. The result is an explicit causal account of events. Qualitative states are used to represent change over time in a particular system. When nothing changes, than there will be no new qualitative state. A state thus is a qualitative description of a system at a particular moment. In order to perform behaviour analysis, it is necessary to identify the various actors that are involved in the environment and how they interact over spans of time. Conversely, the question of what can be assumed to have no effect is equally important. In terms of QR, what to include in an analysis and what to leave out is captured in the frame problem (McCarthy 1963; McCarthy & Hayes 1969). Patrick Hayes introduced the notion of histories into the description of events (Hayes, 1985). Histories describe events in a temporally unbounded and spatially bounded way. The result is that events can be analysed locally over time, which makes it possible to examine the causality of subparts of systems.

Using QR, the causal account of the behaviour is one of the main interests of building the models. In a qualitative simulation, a causal path is usually generated by a set of possible state transitions form a given input. This kind of simulation allows to handle incomplete information, or information with low resolution, which is typical with common sense reasoning. The collection of all possible state transitions is called a qualitative envisionment (DeKleer 1977). A qualitative envisionment should retain the same conclusions about behaviour as the actual behaviour found in the referent, the real world system. The relation between histories and envisionment remains debated in the QR community. Generally speaking, one can say that each history resembles a path through an envisionment but not the other way around (Forbus, 1988).

3.4 Ontology

With the idea of a broadly applicable qualitative physics that was discussed earlier, ontologies containing useful and common abstractions are of great utility. The task of creating an ontology capable of representing qualitative physics is a central theme in the field of qualitative reasoning. We have seen that with qualitative kinematics different worldviews may exist on how to model interconnections between components. In a more fundamental sense, three of the most influential approaches within qualitative modelling have become the component-based approach (Brown & de Kleer, 1984), the process centred approach (Forbus, 1984) and the constrained based approach (Kuipers, 1986). Although each of the approaches has its own merits, for a detailed comparison between the methods the reader is referred to (Bredeweg ,1992). Salles et al. (1996) compared the approaches on their individual suitability for modelling ecological systems.

When modelling dynamic systems qualitatively, various commitments have to be made about how the world is represented, and thus which qualitative ontology will be used. Collins and Forbus (1989) for example, show that the process-centred ontology developed by Kenneth Forbus (1984) in the Qualitative Process Theory (QPT), adopts well to the field of thermodynamics, where most of the behaviour can be interpreted in the sense of processes that produce heat flows, energy exchanges, or work. Another modelling ontology used in qualitative physics is the device centred ontology advocated by (De Kleer & Brown, 1984). They have adopted the approach with the modelling of electric circuits. Here the system is divided into components that have a set of equations related to them, and a network of components can be analysed by for example a constraint propagation method. By using local descriptions of components it should be avoided that the behaviour of components assume the functioning of a device as a whole, rather than explaining the local interaction between components. When considering ecological or biological domains, see for example (Guerrin, 1990), yet again a different ontology can be used. Of special relevance in these domains are phenomena that have to be modelled in terms of orders of magnitude. Orders of magnitude can be used when it is needed to say that for example one process is submissive to another process and need not be considered in the outcome. For example the amount of rain droplets that evaporate when falling towards the earth can be neglected compared to the amount that reaches the earth.

Furthermore, different levels of granularity may be appropriate depending on the purpose of the model. For example the representation of liquids in relation to the objects containing them alone has led to representations at the molecular level, e.g. the piece of stuff ontology, the contained stuff ontology (Hayes, 1979) and more recently the bounded stuff ontology (Kim, 1993). In our work we will introduce a particular configuration of contained liquids, which deals with vertical differences between contained liquids. Our ontology therefore is based on the general notions provided by Hayes´ ontology for liquids.

With a wide field of application area’s, no method is sufficient to capture all sorts of systems in which qualitative physics is used. As Forbus (1988) puts it, combinations of methods may be made given particular domain modelling purposes.

4. Garp: a specific simulator

This section discusses qualitative primitives and the way reasoning is performed within a specific qualitative reasoning approach. Therefore the *general architecture for reasoning about physics (GARP),* will be introduced. GARP integrates the various approaches on the representation of knowledge of dynamic systems. The reasoning engine has been recently extended with a visual simulation inspection tool, VisiGarp and for this thesis, also a graphical model building environment, HOMER has been used that produces models that can be executed by GARP.

4.1 GARP

As a framework for qualitative knowledge representation, GARP (Bredeweg, 1992) interprets and simulates qualitative descriptions of real world domains. In the framework the general qualitative vocabulary is implemented using PROLOG. It supports the use of model fragments and the definition of scenarios, which makes it useful for adopting a compositional modelling approach. The organisation of knowledge in GARP involves several types of knowledge:

- The static description of the actual entities involved in the system: the system elements in GARP. The entities are specified in an *isa*-hierarchy, and structural relations may be declared by using *has-attribute* statements
- Primitives that can represent behaviour: parameters, values and dependencies in GARP,
- Specification of the behaviours that may occur: in terms of GARP they are called partial behaviour models (model fragments), scenario's (input systems) and transformation rules.

The remainder of this section illustrates the qualitative statements that are used in the GARP environment. In the last section, the concept of model fragments and their role in the framework are revisited.

4.2 Quantities

The most widely used method of reasoning with quantities used in QR is the sign algebra, which uses measurements like zero, plus or minus for the derivative of a parameter. Quantities have an amount and a derivative which both have signs. The representation of the continuous set of variables that a parameter may have is done with a partial ordering, using point and intervals. Each quantity has it's own set of values, which doesn't mean that for some parameters the values may correspond. Quantities are declared as follows:

```
pressure( instance_name, Pressure, _, zp )
```

The first predicate name specifies the parameter type, the second argument a variable to which the pressure is assigned. The third argument is the unique name for the combination of the parameter and the variable. The last argument represents the quantity space that is assigned to the quantity.

Whenever a value of a quantity must be specified, a statement is made which sets the value of a quantity to a particular point. Also the qualitative derivative can be set in the same statement. The value and derivative can be described as follows:

```
value( quantity_instance, _, value, derivative )
```

Value statements like this are often used for scenario's, in which a particular status of the system may be set. The dynamic representation of behaviour is done by the introducing quantities that affect the objects and entities of the system over time. This change is the consequence of a shift in the (qualitative) value or derivative of a parameter. The direction of change is stated through the derivative (*min, zero, plus*) of the value of the influenced quantity.

Two or more parameters can be dependent on each other or constrain each other through various *functional relationships*, called quantity relations. An exhaustive listing and discussion of the possible dependencies between parameters can be found in (Bredeweg, 1992). The following will give the reader a short overview of the available relations.

4.3 Equality

The equality function allows quantities to be set to *smaller*, *equal* or *greater* than a referent. Quantities may be set equal to a value or two parameters may be set equal, the latter meaning that the qualitative values are equal:

```
equal( Temperature, zero )

smaller( Temperature, Heat )
```

A Quantity may also be assigned a particular derivative:

```
d_equal( Temperature, plus )
```

Equality statements are also used to express equations involving two quantities. The equations concern arithmetic operations such as adding and subtraction.

```
equal( Pressure_difference, min( PressureA, PressureB ) )
```

This equation will result in a qualitative value for the quantity 'pressure difference' as 'Pressure B' is being subtracted from 'Pressure A'. In the case that both 'Pressure A' and 'Pressure B' have equal qualitative values but 'Pressure B' is increasing, the equation will assign a positive value to 'pressure difference'.

Two points may be equal but belong to different quantity spaces. This means that a point A from quantity space 1 is equal to point B of quantity space 2. These points can be set equal by using a value statement of the type:

```
equal( top( LevelA ), bottom( LevelB ) )
```

4.4 Functional relationships

In a similar way, when two quantities have different quantity spaces, their values can be related as follows

```
dir_value_correspondence( Pressure, plus, Level, max )
```

The relation is directed, which means that the value of 'Pressure' will be set to plus whenever 'Level' reaches max. When two quantities share the same set of values a relation of the type quantity space correspondence may be defined:

```
dir_q_correspondence( Pressure, Volume )
```

The relation given here is a directed quantity correspondence. which means that the value of 'Pressure' can only be determined if the corresponding value of 'Volume' is known. A similar relation is an undirected value correspondence:

```
q_correspondence( Pressure, Volume )
```

It will result in the pressure and volume obtaining the same qualitative value each subsequent state. Not only the values of quantities may be related; the signs of derivatives can be functionally related as well.

```
prop_pos( Level_liquid, Amount_of_liquid )
```

This proportionality means that Level_liquid is increasingly monotonic in its dependence on 'Amount of liquid'. The inverse of this function can also be specified.

```
prop_neg( Pressure, Outflow )
```

This is a reverse proportionality, where an increase or positive sign for 'Outflow' leads to a decrease, or negative derivative for 'Pressure'.

When processes are active, their effects are usually specified by direct influences. These relations usually form the basis of the propagation chain.

```
inf_neg_by( Liquid_source, Flow_rate )
```

The statement means that the value of 'Flow_rate' has an opposite effect on the derivative of 'Liquid source'

4.5 Model Fragments

The partial models as defined in GARP that must contain the knowledge about the behaviour to be predicted are comparable to the notion of model fragments as defined by (Falkenhainer & Forbus 1991), and will be referred to as such subsequently. Model fragments are descriptions of components of the system and may be considered as units that can be combined to describe a greater part of the system. Model fragments may describe views or processes and consist of conditions and actions. For a model fragment to become instantiated the conditions that may consist of system elements, system structures, parameters, parameter relations, parameter values and supertype relations must hold;

- System elements are the descriptions of the static elements involved; generally objects and structural relations.
- System structures refer to other partial models that must be instantiated
- Quantities are the quantifications that belong to system elements
- Quantity relations specify the relations that exist for or between parameters in the description

- Quantity values state the exact value and derivative that must hold
- Supertype relations are named when the partial model is a subtype of another partial model

The action, or *givens*, that a model fragment will give as output is expressed in terms of system elements and parameter relations that are to be instantiated. This is almost equal to the logical definition,

$\mathbf{I} \wedge \mathbf{A} \wedge \mathbf{O} \rightarrow \mathbf{R}$, cited earlier in chapter three.

There is more to say about the structure of model fragments. Model fragments describe parts of systems and can be either structural or behavioural descriptions (process fragments). A structural or process description may in itself be a part of a more complex system part. A flow process for example is usually part of a system component where descriptions of a source and destination are required. By describing the distinct parts of a system in a generic fashion, the descriptions become reusable for other system model descriptions as well. GARP, for instance, just searches for model fragments by comparing a given description of some elements to the conditions of existing model fragments. It than automatically completes such a system model description with model fragments that have the same elements named in the condition part. The same model fragments can be instantiated on the basis of different system model descriptions, and this advantage is maximised when the model fragments contain generic information. Model fragments can be made more generic by using a hierarchy of model fragments. Very basic principles can than be extracted from more complex descriptions and a set of simple descriptions may be combined to form a complex structure. In either way, the use of generic knowledge bans out redundant descriptions of similar principles, and results in generally applicable descriptions. System model descriptions represent the state of a system at a particular moment in time, and are the effect of the actions described in a model fragment. A scenario, or input system, is a specific type of system model description. It is typically an incomplete description of the real world system, from which the simulator tries to generate a full state description with all relevant system elements, partial models, etc that must be instantiated according to the conditions in the scenario. The actual change from one system model description (a qualitative state) to the next is determined by the library of transformation rules. It is sufficient to say for the moment that the transformation rules resolve all the parameter relations and determine which object and parameters will remain throughout the next state and which not (termination rules), that some terminations must be ordered or merged (precedence rules) and the things that have not been part of any termination must be unchanged in the next state (continuity rules).

5. Model construction

A few issues will be raised on the design of a model, and design methods in particular. Although some research has been conducted on which particular knowledge representation frameworks can fit a particular model design problem (Schut & Bredeweg 1996), much less is written down on subjects involving how the formal representation language and domain knowledge synthesise into a coherent model, the process of designing. Somewhat typically, most resources in this respect can be found in the field of Computer Aided Design. In this area, a lot of research is done on developing formal and structural accounts for the design process, a prerequisite for automating the design process. The result is a bulk of literature that attempts to characterise methods used for design. In the following some issues will be discussed that seem useful in the current scope; to characterise and define the design process that is conducted to map the features of the water cycle to a qualitative simulation model.

5.1 Model design process

The design process is an exercise in mapping needs to function to structure, and in general the process deals with the satisfaction of constraints imposed by different actors, thus, it may be considered a problem solving process. A design space has as input some knowledge source and some problem-solving strategies. In the article on intelligent computer-aided design (D.C. Brown 1996), Brown lists several common of types of design. The most standard types of design are *routine*, *innovative* and *creative* design, where each successive type requires less preliminary knowledge in terms of the above named knowledge sources or problem solving strategy. Other characterisations of these design types focus on what is known about the variables and their values. From this point of view, an innovative design for example is done with fixed variables and changing values, see also (A. K. Goel, 1997). Another typology of the design process mentioned by Brown is conceptual versus parametric design. The former depends on abstract specifications of requirements, whereas the latter is more focused in terms of specification of parameters, values, and variables. A special form of the parametric design method is the *propose and revise* method, comparable to iterative design. In another form of design, configuration, the design language is already pre-specified, and components of the language can be put together to satisfy requirements.

A special kind of creative design involves exploring the utilities of using analogies in proposing solutions to design problems in the conceptual phase of the design process (A.K. Goel, 1997). Following his definition, "*..analogical design involves reminding and transfer of elements of a solution (S_old) for one design problem (P_old) to the solution (S_new) for another design problem (P_new), where the selected design elements can be components, relations between components, or* *configurations of components and relations."* Furthermore, Goel poses four questions in considering analogical design; *Why? What? How?* and *When?*. The questions pertain to the tasks, content, methods and control of processing when using analogy in design. By asking *why* to use analogical design methods, it is possible to think of a number of design tasks that it may support, including proposing new solutions, decomposition, anticipating possible difficulties etc. *What* can be analogically designed refers to the content of the model, e.g. components or relations between components, and it may support design proposition or modification. An issue that is certainly related to this type of analogical design, which refers to domain or strategic knowledge is the problem of shared knowledge, more particular shared logic, ontology and/or computation pointed out by (Sowa, 2000). Certainly on the ontological level *"...different systems may use names for the same kinds of entities; even worse, they may use the same names for different kinds."* (Sowa, 2000; p. 408).

A common answer to *how* to perform analogical design is the use of case-based reasoning. In the literature, distinction is made between transformational and derivational case-based reasoning, where the latter not only transfers and modifies S_old to S_new, but the trace of problem-space search that led to the solution S_old for P_old is included. The general flow of the tasks of the design process can be characterised as:

Requirements Formulation → Synthesis → Analysis → Evaluation

Other perspectives see the design as incremental refinement, for example (Tong 1987). One of the core tasks in design, however, is the task of decomposition and especially decomposition guided by the use of hierarchies; see (Lee et al. 1992; Umeda & Tomiyama) for a detailed discussion on types of hierarchies and decomposition. A whole range of decomposition methods can be used in the design process, ranging from structural decomposition to functional decomposition or behavioural decomposition (for example an influence diagram). In addition, the direction of processing with respect to the development of models is a issue of interest. Both bottom-up and top-down ways of processing may be combined to resolve goals. An example is the hybrid-opportunistic technique mentioned by (Stefik, 1981). In terms of knowledge types the use of ontologies can provide clarification of the concepts and relations within a domain of application. Besides functioning as domain-specific catalog of concepts, another virtue of ontologies concerns the sharing and reuse of knowledge between various actors. The latter are usually referred to as task ontologies. The techniques associated with qualitative modelling may be considered as task ontology in this respect.

5.2 Classification

A rigid classification, or ontology, of the things in the world has not been agreed upon as of yet. Most of the philosophers from our time and from the past have made propositions about how to classify the things around us. So it is not very surprisingly that the qualitative or naive physics enterprise has some holistic features as well. This means that entities, structures, relations or conceptual clusters in general cannot be defined indiscriminately from others. A related and sometimes even more distressing issue concerns the characteristics of entities and their relation with respect to space and time, which sometimes need to be defined. A discussion of shortcomings of the (computational) application of common sense theory in knowledge-intensive systems is given in (Smith & Casati, 1994). The attempts to produce realistic theories of the 'naive' physical world using formal theories and logical inferences seem to be in some contrast with theories of the common sense world as defined by for example Gestalt psychologists. There exists a risk that the purpose of efficient representations will lead to the neglect of the contributions of other disciplines to the theories of common sense.

From the current point of view, an approach to classifying phenomena is needed to distinguish the concepts we want to incorporate in our model. Thus when building a model for a particular purpose, decisions have to be made on which ontology is used. A more or less common list of (relatively discriminable) clusters in naive physics is the following (see for example Hayes 1979, pp. 187-97):

- Objects, Natural Kinds
- Events, Processes and Causality
- Stuffs, States of Matter, Qualities
- Surfaces, Limits, Boundaries

The list specified above gives handles to start decomposing the concepts we engage in a particular domain in the world. But we also need criteria or definitions of the clusters in order to assign a particular concept to a cluster. This task is commonly referred to as ontological engineering (Sowa, 2000). As for the formalisation of naive physics, there exist ontologies to classify concepts such as the ones mentioned above, for example the ontology for liquids developed by Patrick Hayes (Hayes, 1978) or the qualitative process theory by Kenneth Forbus (Forbus, 1983). In modelling the water cycle we will use aspects of the formal ontologies previously mentioned in order to classify the domain.

5.3 Organisation of models and ontology

So far the focus has been on theories about how to represent different types of knowledge that people use in reasoning and problem solving. Qualitative reasoning methods in general and the compositional modelling approach in particular well suited to represent phenomena that are associated with physical processes. In terms of the formal encoding of qualitative knowledge, the possibility of reusing partial models has been discussed and in terms of model design the concept of analogical design and ontologies have been given some attention in the last paragraph. In this paragraph we will turn to the content of the model, by looking at how knowledge is classified (ontology) and which organisation of knowledge fits the type of model (i.e. didactic) that is developed.

Usually, multiple perspectives apply to a certain knowledge domain. Different perspectives for example may emphasise various levels of analysis with respect to granularity of a domain. Being able to reason about a domain from different perspectives typically should improve the understanding of a domain.

Another issue, particularly relevant for didactic systems is the dimensions along which knowledge is (re)presented. Such an approach is outlined by (Salles & Bredeweg, 2001) by the idea of constructing progressive learning routes in the domain of the Cerrado vegetation. They propose the implementation of learning routes that evolve from static to dynamic and from less complex to more complex. Therefore the simulation model of the domain is subdivided in smaller units that can be termed model dimensions. The model dimensions that are defined are *zero-order* (static knowledge), *first order* (behaviour), and *second order* (relative behaviour). Mapping the subject matter to student's mental model clearly is an issue that has to be incorporated in the design of the domain knowledge simulator. Implementing these views contributes to keeping the interaction between the student's mental model and the simulation on the same perspective and granularity. The approach is an integration of various perspectives on organising the subject matter model, see for example *causal model progression* by (White & Frederiksen) and the *didactic goal generator* by (Winkels & Breuker). It is argued that the resulting clusters of models will support knowledge communication with qualitative models in ecological domains to a better extent.

In practice, an effort has to be made in terms of ontological engineering with respect to classifying the knowledge in the domain if we want to be consistent in issuing knowledge to the student along various dimensions. It means that it is not only necessary to define the categories and dimensions of knowledge, but also a consensus about the method of actually classifying the knowledge under certain headings, a typology of the knowledge. Related to this observation is the article by Mizoguchi and Bourdeau (2000) in which they describe the use of ontological engineering to overcome common AI-ED problems. They observe the lack of consensus about the conceptualisation of knowledge in various knowledge intensive systems, and they argue for explicit representation of the conceptualisation on which the system is based on, and to a certain extent even a standardisation. The hypothesis is that it will support the adaptability and reuse of various components of knowledge intensive systems. They argue for abandoning a mere heuristic-driven knowledge engineering toward increasingly model-based approaches. ”The power lies in the knowledge” proposed by Feigenbaum is a principle that suits the vision. This new approach to knowledge modelling has it’s origins in projects as KADS and PROTEGE, and it introduces the notions of ontologies, being divided into a task ontology, which specifies the problem solving architecture of knowledge-based systems, and domain ontology which specifies the domain knowledge. The idea of this knowledge sharing between people and computers at the conceptual level is not new. The approach of Brown & de Kleer (1984), *a framework for a qualitative physics*, is an approach that puts effort into defining conceptualisations that are used for representing the world in a qualitative way.

5.4 Qualitative modelling of a domain

"Solving a design problem efficiently requires an adequate representation (...). One of the major tasks (...) is to identify all the pieces of knowledge used by the system and map them onto the most convenient representation provided by AI." (D.C. Brown & D.L. Grecu, 1996).

According to Schut & Bredeweg (1996), in their article on approaches to qualitative model construction, we can distinguish between the real world (the referent), and the model of the real world. A model of a referent can be made to represent certain chosen features of the referent, and the goal of representing this information is that it can be retrieved more efficiently. Typical to model construction thus is the task of selection of relevant features to be incorporated in the model. Specialising on qualitative models, their aim is to compare two approaches to qualitative model building: the model composition approach, and the model induction approach, and consider the comparison a general frame of reference for comparing approaches to model building in a qualitative way.

In modelling a domain, the main focus lies in the relation between the referent and the model, which is a representation relation. This means that for some distinguished aspects at the least, the referent and the model must correspond. The things from the referent that will be represented in the model are thus dependent on the representation primitives available in the reasoning formalism (see chapter 4), and also on the *purpose* of the model. The way in which representational primitives shape the representation relation is important to the conceptual closure of the model (Schut & Bredeweg 1996). The purpose of the model requires a typical way of conceptualising the referent, which means that the purpose of the model specifies the perspective taken on the referent.

In this research, the goal is the design of a qualitative simulation model for *educational purposes*. More specifically, the educational part in this research is directed to facilitating progressive learning routes through a qualitative simulation of the water cycle. In technical terms, the educational perspective requires the domain knowledge to be characterised by clusters of models, which vary with respect to certain dimensions such as granularity and complexity. The input scenarios to the simulator can be structured according to these principles, so that learners are confronted with models of increasing elaboration.

An important issue concerns the multiple views that may coexist in one model. Multiple views allow the same phenomena to be analysed on different levels of granularity or complexity. In more advanced compositional modelling the mapping from the scenario to the library of model fragments can be one-to-many. This has the effect that the generated model can be adjusted to the desired level of detail, i.e. the scope of the model may differ. These different levels of detail or completeness are called model dimensions. For this, multiple incompatible views on a phenomenon must exist side by side in the library, and the choice whether one or another model is selected depends on the information that is described by the goal for which the model is used. This information can be captured in formulating explicit model assumptions under which the model is applicable. The model assumptions involved in a particular simulation are characterised by taking the particular perspective on a system. The idea is depicted in figure 5.1.

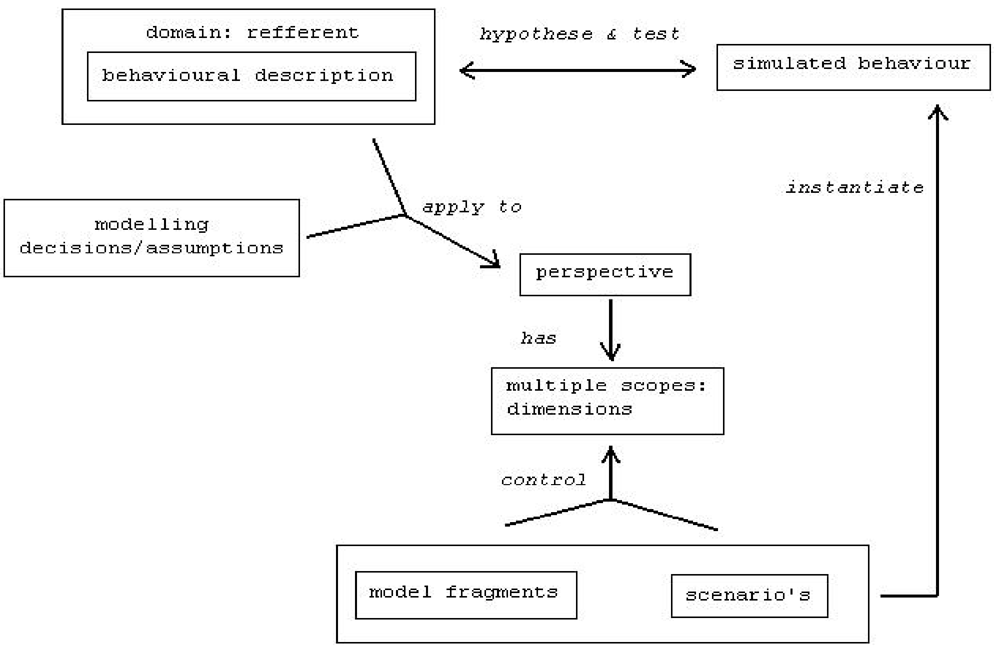

Figure 5.1. A central role for perspective.

The representation relation between the model and the referent can be adjusted by comparing the output of a particular simulation to the behaviour that is found in the referent. By using the procedure of *hypothese and test*, the model can be tuned more precisely to the phenomena it is supposed to represent.

Modelling a referent means depicting a real world system in terms of a (chosen) formalism. The modelling framework that is the result of a particular conceptualisation of the referent consists of a conceptual framework and an inference procedure. The conceptual framework must be materialised in the representation and reasoning techniques of qualitative reasoning.

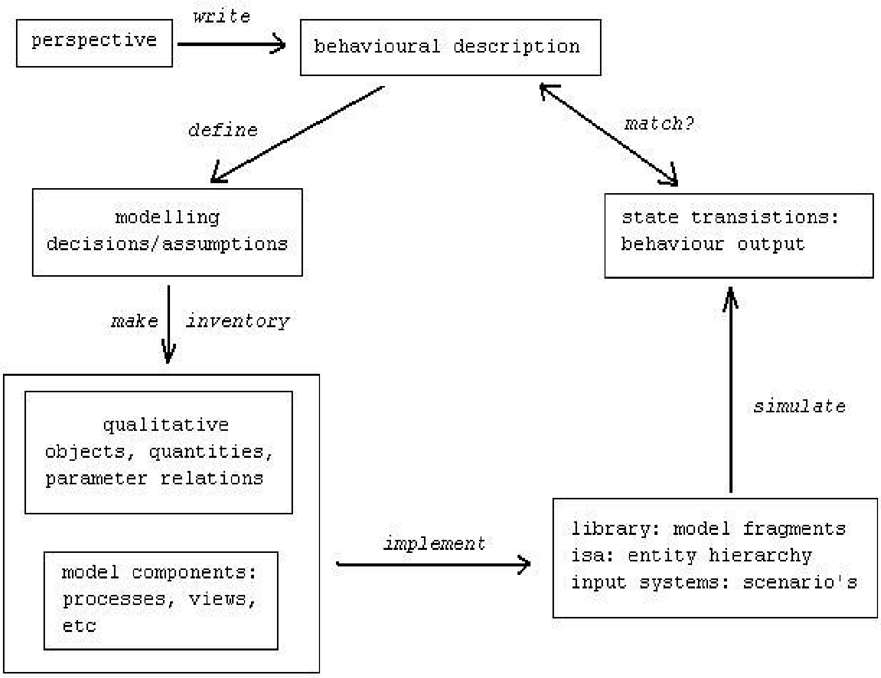

Figure 5.2. Tasks in model construction.

Figure 5.2 specifies some general tasks that are involved with translating conceptual ideas into the qualitative language before implementing and simulating the model. The behavioural description focuses on the parts of the referent that are relevant to the causal chain of events. In order to give these parts of the system a qualitative representation, a general inventory of processes and objects has to be made. Variables and the relations between certain variables are specified qualitatively as well, including ideas on what quantity spaces should be assigned. The implementation concerns the production of a library containing model fragments, an isa-hierarchy containing entities and a set of input systems that form the different scenario's in the simulation. The task after that is analysing if the output of the simulation matches the referent for the intended relevant aspects

6. The Water Cycle

With the goal of developing a qualitative model of the water cycle, capable of reasoning about causality and physical processes, the need for a mapping between the naive mental model and the computational model of a domain was addressed in the previous paragraphs, and the issues of knowledge engineering that are related to it. Before being able to these issues onto the particular domain of hydrology, an exploration of the fields of hydrology and meteorology must precede. Although the field of meteorology has been used for a number of applications in ITS, in the more recent work on qualitative reasoning only (Iwasaki, 1996) developed a system for answering prediction questions of rainfall in Japan, and it does not attempt to give a causal account of the water cycle in a more general way. An older example is the METEOROLOGY tutor, a system that made use of simulation based reasoning, where causality is implemented in sequences of events which are simulated by transition between states. On the other hand, a reasonable amount of research on qualitative representations has been performed in thermodynamical domains, see for example (Collins & Forbus 1989, Pisan, 1996). From the examples in the literature one can readily see that qualitative representation fits the type of domains that involve heat exchanges, substance flows phase changes, etc. well. The importance of processes and causality are apparent, and these can be described in an explicit manner, which is applicable to the theories of qualitative physics in general and qualitative process theory in particular. After describing the functioning of the water cycle it will be translated into a complete qualitative account.

6.1 Domain description: Introduction to hydrology and meteorology.

This discussion is meant to give an overview of the main processes and concepts that govern the water cycle. As such it deals with substances in the air as well as water on the surface. It is constantly tried to give a causal description of the processes, for the simple reason that a good causal account is a main ingredient in developing a knowledge-intensive simulation model of the water cycle. It must be seen to that all the factors that have a direct influence on the causal chain of events will be mentioned, insofar they are relevant to the learning goals. In the following stadium, it will be this description that will serve as reference from which the choices in knowledge representation and modelling assumptions will be argued, besides the framework of rules and constraints that will be posed on it by the theories of qualitative physics and automated modelling.

The water cycle is a dynamic process that governs the circulation of water on earth. The processes that occur in the atmosphere are part of the meteorological science, which is also occupied with describing the weather on earth. The three main processes that occur in the atmosphere relevant to the water cycle are evaporation, condensation and precipitation. A fourth process, transport of water in the air, plays a big role in the distribution of the water throughout the atmosphere. In the atmosphere, water can be present in the form of gas (vapour), liquid, and ice. Just like the air itself, water has a certain pressure that acts on a certain volume of air, which is indicated by vapour pressure. Under some circumstances the vapour pressure may reach a limit value, called the saturation vapour pressure. The saturation vapour pressure increases with higher temperatures, because warm air expands and can hold more vapour. It is also true that unsaturated air can become saturated when it cools down.

Whenever the saturation vapour pressure is reached, any further evaporation of liquid water in that part of the air will cause condensation of the vapour. Another measure to discover the amount of moist that the air can hold is called the relative humidity, which is the ratio of the actual vapour pressure to the saturation vapour pressure. thus it represents the amount of moisture in a space compared to the amount it could hold if it were saturated. The temperature at which vapour starts to condense is called the dew point, and the combination of temperature (T, in degrees Celsius) and the dew point serves as an indication of how far the temperature of the air is from the point where it will be saturated.
Cloud formation is the result of water vapour being condensed. The transformation from vapour to water droplets and vice versa requires an energy-transfer. Energy is needed to evaporate water (like in boiling) but inversely, it is also true that the condensation of vapour releases energy to the environment. So if for example a droplet falls through an unsaturated layer of air, the droplet can vaporise and thereby cool down the air layer. This also means that air can become saturated at temperatures above the dew point, as a consequence of an increase in water supply. The most common cause of air becoming saturated is the cooling of air. For water droplets to form, i.e. condensation, the condition is not only that the air is saturated, but also the presence of so-called condensation nuclei, which are very tiny particles of salt or acid solutions in the atmosphere. The water molecules will attach to these nuclei. An important thing is also that the normal cloud droplets are not big enough to reach earth's surface before being evaporated again. The droplets that we call rain are much bigger than the cloud droplets, the main reason for this is that bigger droplets catch smaller droplets and grow because of that. Through continuous movement of the water in the clouds some droplets will grow until they are so big that the air cannot hold them anymore.

Condensation is the direct cause of all forms of precipitation. It occurs under various conditions that in one way or another are associated with a change in one of the linked parameters of air, volume, temperature, pressure and humidity. This brings us to the movement of air in the atmosphere. The vertical movement of air can be explained with the specific gravity of various volumes of air. Air volumes with lower specific gravity will rise and air volumes with higher specific gravity will sink. The difference in specific weight is solely caused by difference in temperature. An air volume with higher temperature has a lower specific gravity and vice versa. Extra complications with vertical movements are the difference in temperature at various height in the atmosphere and the change of temperature within the vertically moving volume of air. The latter is the consequence of the fact that a rising volume of air will be surrounded by lower pressure and a sinking air volume will have higher pressure in the surrounding. In the first case the volume of air will expand and cool, in the second case it will be compressed and therefore heated. The change in temperature that occurs within the vertical moving air is therefore not caused by external heat supplies and called adiabatic movement. The relative difference between the temperature of a volume of air and the temperature of its surroundings is called the vertical temperature gradient. The ratio of this gradient will either repress or encourage vertical movements. In the fist case the air is said to be stable, and in the second case air is said to be unstable. the occurrence of condensation within these vertical movements means that the air is saturated. if saturated air is forced to rise, it will cool and the water would become supersaturated. Instead, the water will condense to the extent that the saturation vapour pressure is maintained at the corresponding temperature. This process releases heat to the air volume which positively affect the elevation. On the other hand, if a condense-holding volume of air is forced downwards, it will become unsaturated and some of the condense turns into vapour again and the air volume cools down.

In order for water to evaporate, a heat source must be present. This can be the sun, an overlying air layer that is warmer, the ground and water itself. Note that the sun is an external influence to the cycle in this respect. Evaporation is the process by which a liquid or a solid is changed to a gas, and energy has to be added to accomplish the change of state. Ultimately the source of this energy is current or recent solar energy impinging on water, the soil-water complex, and the plant-life-water complex. Evaporation of water from a given surface is greatest when the air is warm and dry, and smallest when the air is cold and moist, because in warm conditions, the saturation deficit is large and conversely in cold conditions it is small. There is thus an underlying relation between the rate of evaporation and the saturation deficit. Since the process of evaporation involves the net movement of water vapour molecules from an evaporating surface into the overlying air, it will eventually lead to the saturation of the lowest air layers of overlaying air and the termination of evaporation. This termination of evaporation mostly does not occur, because of convective movements, which create wind, and therefore reducing the water vapour content in the lowest layers, so that evaporation will continue. Water can evaporate from the oceans, lakes, rivers or from the leafs of plants. Together these processes are called evapotranspiration. Once in vaporised form the water will behave in accordance with the meteorological laws.

The second major part of the water cycle concerns the processes that occur on the earth surface. Moist of precipitation that reaches the ground surface is usually absorbed by the surface layers of the soil. The remainder, once any depression storage has been filled, will flow over the surface as overland flow, reaching the stream channels quickly. The water that infiltrates into the soil may subsequently be evaporated or it may move under gravity and percolate downwards to the groundwater zone or else flow laterally close to the surface as through flow. The ability of the soil to absorb and retain moisture, the permeability, is crucial. Precipitation enters the soil at the ground surface and moves downward to the water table, which marks the upper surface of the zone of saturation. Immediately above the water table is the capillary fringe in which almost all the pores are full of water. The zone of aeration is a zone of transition in which water is absorbed, held or transmitted either downwards toward the water table or upwards towards the soil surface, from where it can be evaporated.

At a general level, the relation between runoff and precipitation can be regarded in terms of the continuous circulation of water through the water cycle. Specifically, we can recognise that in natural conditions each river and stream receives water only from its own drainage basin or catchment area. Each catchment area can therefore be regarded as a system receiving inputs of precipitation and transforming these into outputs of evaporation and runoff. Precipitation may arrive in the stream flows through either, direct precipitation onto the water surface, through overland flow, through shallow subsurface flow (through flow),or through deep subsurface flow (groundwater flow).

The process of infiltration concerns the water from precipitation that will be infiltrated in the soil. Effective rainfall is all the water that is left after infiltration and other losses as interception and evaporation. For water to infiltrate the soil must be permeable and not already saturated. if soil is saturated, a runoff over land is created.

6.2 Conceptual model

Having described the core features of interest within the hydrological domain, we turn to the conceptual design of the simulation model. The basic idea is to form an abstract definition of the objects and processes including their relations, which form the essentials of the domain. The water cycle as a system inhibits features of thermodynamic systems including heat flows, phase changes, energy for example. From an educational point of view, the emphasis with introductions on meteorology usually lies on a set of core processes that govern the water cycle. The learner has to master (causal) models of evaporation, wind, precipitation and transport of air. In addition, the storage and flows of water on land are an integral part of the curriculum. These processes, depicted in fig 6.1, will form the central part of attention in the simulation model.

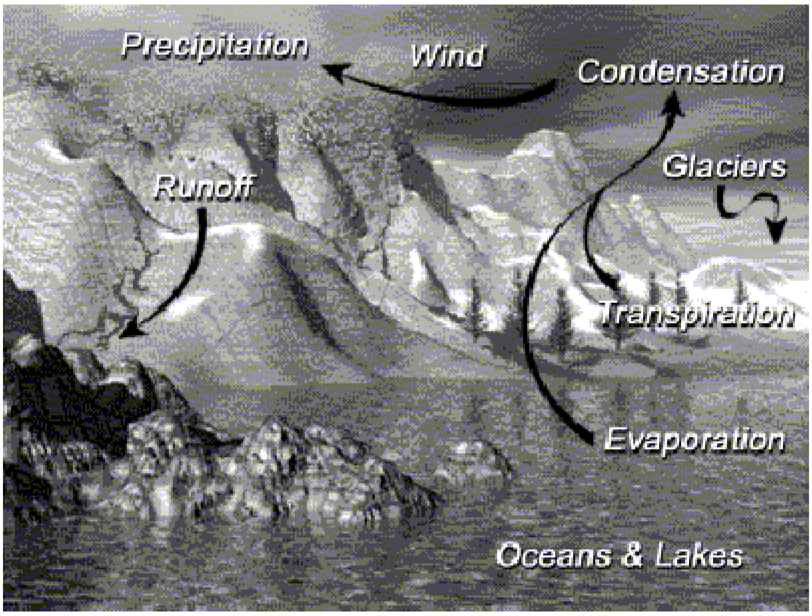

Figure 6.1. Standard picture of the water cycle.

The behaviour to be modelled is briefly the following: In order to get water from the sea to the air above, we need a heat source, in this case the sun, to evaporate the water. Once in gas form, continuous heating will cause the air with vapour to rise. The rise of air also causes cooling which in its turn causes the water to condense. Condensed water may be transported to parts of the air with lower pressure. Because transportation involves further cooling, the water holding ability of the air will decrease. In the case of no water holding ability the precipitation process becomes active which will cause rain (precipitation). Once precipitation reaches the surface, it will be caught in storages on the surface, either puddles or rivers. It can also fall directly back into the sea but that is not modelled at this time. Figure 6.2 forms the starting point of the conceptualisation, giving a global schematic idea of the water cycle.

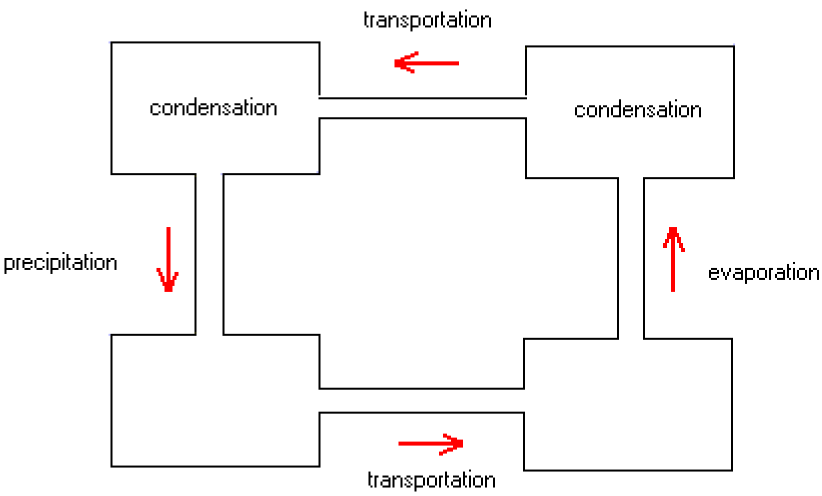

Figure 6.2. schematical representation of a water cycle.

The schematic representation of the water cycle can be mapped onto qualitative representations. There exists previous work on qualitative modelling of thermodynamic processes (Collins & Forbus, 1997; Skorstadt & Forbus, 1998), and contained stuffs in general (Hayes, 1979), in which certain analogies exist with the current research. The main difficulty here lies in putting the individual processes together in a model that also inhibits more global domain knowledge of context and therefore also global constraints. This means that all processes should function given the same global set of constraints. The first concern is the mapping of the entities in the world to entities that are qualitatively interpretable.

6.3 Decomposition and models of different complexity

When modelling a domain qualitatively, decisions have to be made on which particular parts of the system can be described in a more or less independent way, complying with the no-function-in-structure principle. Modelling also means specifying what components will be considered, i.e. 'exist', in the model, and this makes up the representation relation between model and referent, see section 5.3. This section concerns the decomposition of the domain of the water cycle, and formalising the components in model fragments. The model composition is done in different levels of detail. The ultimate goal is to combine several models and inspect different levels of detail using assumptions applying to different levels of analysis. With an educational point of view, controlling the level of detail of a model facilitates curriculum design by allowing model progression. Model progression can be achieved by organising the content of a library along certain dimensions that represent particular levels of refinement of one's knowledge of a system component. Dimensions depend on explicit definition of so-called building blocks (knowledge chunks) of the system, which again correspond to various levels of understanding and skill. As a consequence the general purpose of the model can be controlled, e.g. is it meant to reason on the level of expert or novice? Simple models can be extended and altered to a certain extent to create bigger and more detailed models. In this case, two separate models of the water cycle have been made. The first model incorporates the idea of the core processes of the water cycle in a very abstract and simplified manner. For example, influences from the atmosphere and height differences are not being modelled. The second model introduces more knowledge and reasons more precisely and detailed about certain processes.

6.3.1 Homer

Homer is a model building environment that allow users to construct qualitative models using visual representations of the entities and primitives used in GARP. Far and by large, the primitives in Homer map one-to-one to the primitives in GARP. Whereas the functioning of most of the primitives have been discussed in chapter 4, their representational equivalent in Homer is summarised briefly:

- Model fragments fall into three categories, static, process and agent fragments.
- The condition part of model fragments in homer is depicted in red colour in homer, and the consequence part is shown in blue colour.
- Supertype model fragments are depicted in green colour.
- Structural relations are defined by using *configurations* between entities.
- Dependencies between quantities are the same as in GARP, and their direction is visualised by means of arrows. The dependencies map one to one with their definition in GARP as discussed in chapter 4.
- Calculations are defined as relations between quantities, and dependencies can be related to the sign of the calculus.
- In Homer, identity relations can be defined in order to specify that two entities refer to the same instance.

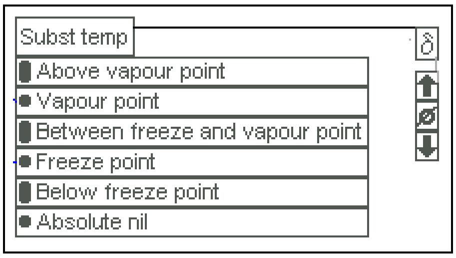

Figure 6.3A quantity space in Homer.

Each quantity in Homer has a specified and fixed quantity space, which means that Homer doesn't allow the use of free variables. An example of a quantity space as defined in Homer is shown in figure 6.3. It shows the quantity space of substance temperature, and the possible values of the derivative (δ), *zero-plus-max*.

6.3.2 Model 1

The central processes in the water cycle are evaporation condensation, cooling, heating, movement (flows) and precipitation. In order to classify the entities that take pat in these processes, an isa-hierarchy is constructed. Figure 6.4 depicts the isa-hierarchy for the Model 1 of the water cycle.

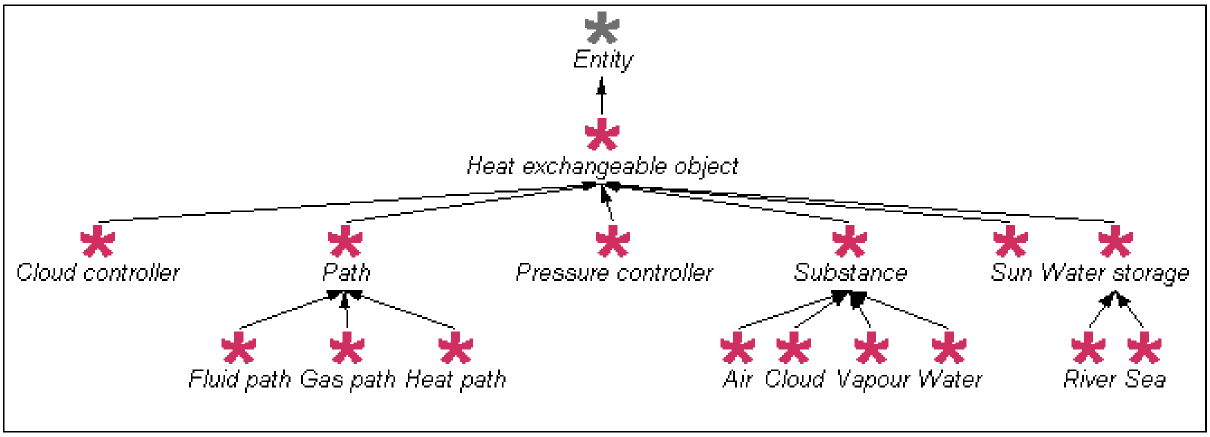

Figure 6.4. Entity hierarchy simple water cycle.

It is assumed here that all the objects of interest in the model are heat exchangeable entities. The hierarchy contains a substance 'cloud', which in principal is the same as water and usually not considered a substance[1]. Another comment is that 'Air' is in fact also a kind of 'water storage', since 'Air' may contain water[2] in this model. There are two controller entities in the hierarchy, which refer to types of modelling assumptions. When the main processes *evaporation*, *condensation*, *transportation* and *precipitation* are considered independent from their context, some of these models already exist. For example, ideas on how condensators or evaporators are modelled qualitatively are ongoing themes in the literature, (Nayak, 1992; Schut & Bredeweg,1993).

A simple model of the water cycle should minimise the use of global constraints and focus on the individual functioning of the processes. The model therefore leaves implicit the causal interdependencies that the processes have. This would be modelled by stating the model fragment of a process explicitly in the condition of a model fragment of another process.

A model of a groundwater flow, or runoff, when not including vertical differences and the size of containers, is that of two water storages communicating through a fluid path, see figure 6.4. All quantity spaces are defined as *zero-plus-max*, except for the flow rate which is *zero* or *plus.* For each water storage, the amount of water corresponds to the level and changes in amount are proportional to changes in level. The same dependencies hold for level and water pressure. By comparing the pressure on the bottom of each container, the flow rate between the containers is calculated.

The model fragment depicted in figure 6.5 is a subtype of the general fragment liquid flow. In this case the water pressure on the left-hand side is greater than the water pressure on the right hand side. The amount on the left in figure will be influenced negatively as a consequence of the flow rate becoming *plus.* This effect finally propagates back to pressure difference. The positive proportionality between

[1] The reason for adding cloud as a substance lies in the fact that in this implementation, GARP fails to instantiate 'water' as a new entity when it is already added in the system model description as being contained by a water storage.

water pressure and pressure difference means that less water pressure causes the pressure difference to decrease. Note that the water pressure on the right hand side has a negative proportionality with pressure difference. In this case *increasing* water pressure on the right side in the picture means a *decrease* in the pressure difference.

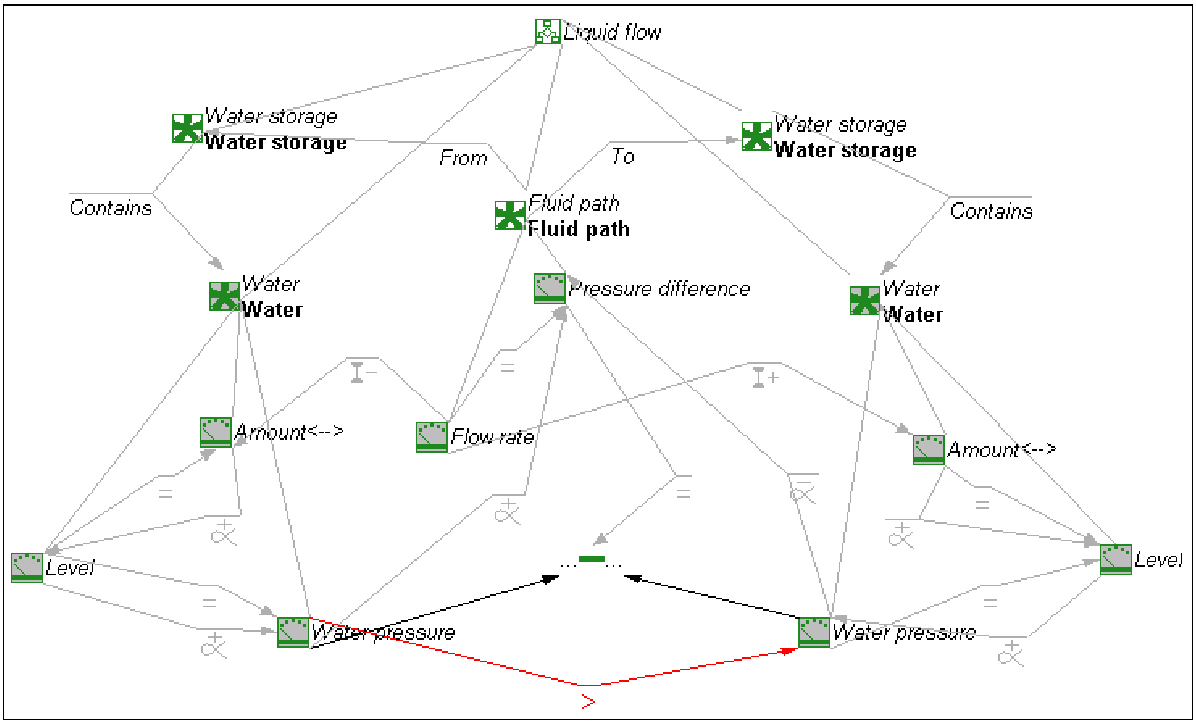

Figure 6.5. Groundwater flow in the simple water cycle.

The representation of the process of evaporation decreases the amount of water in liquid phase in favour of the amount of the water in gas phase when the temperature of water reaches the threshold *max*, see figure 6.6. The phase of the substance is usually determined by constraining the value of for example temperature or pressure. Such constrain would limit the existence of vapour to for example the quantity value *max* for temperature. This constraint is applied here by saying that whenever the temperature of water reaches max, vapour will develop and its temperature corresponds to that of water, which is *max*.

[2] Garp does not support multiple inheritance.

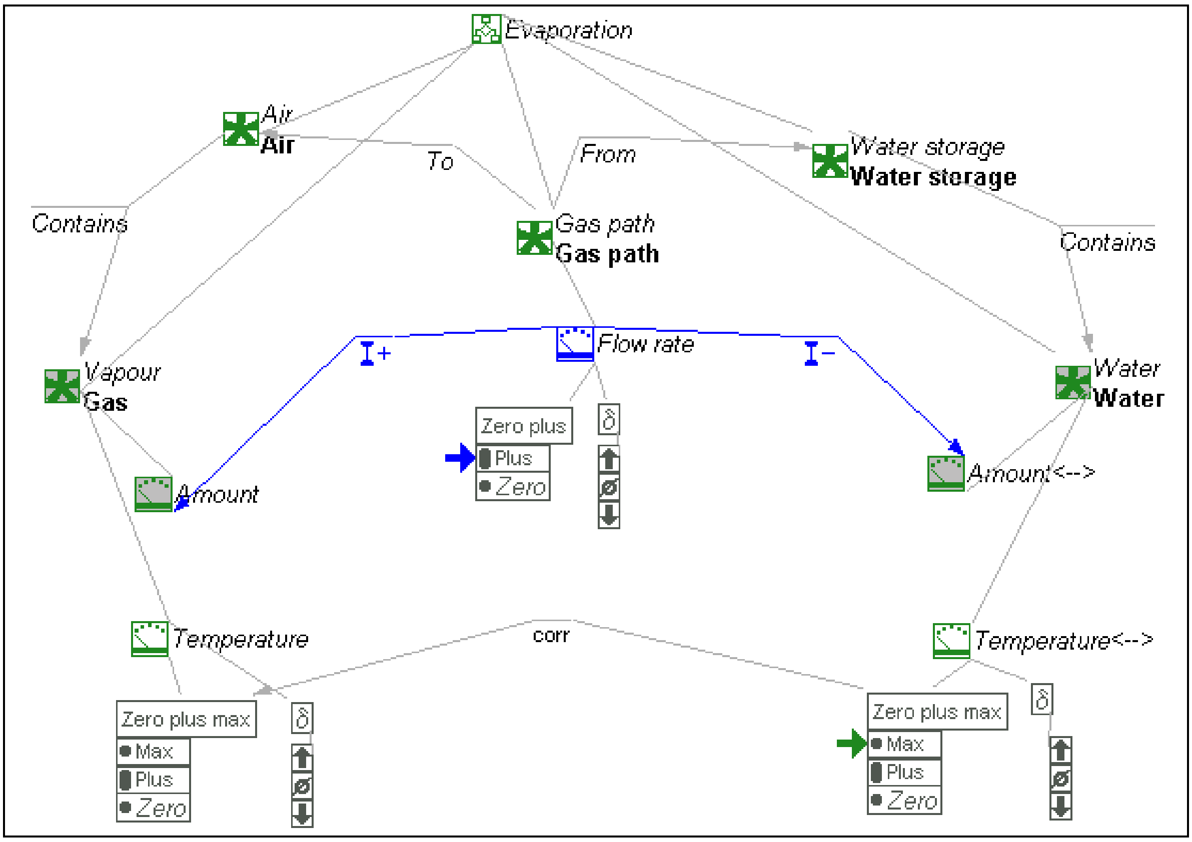

Figure 6.6 evaporation in the simple water cycle model.

Note that the model fragment doesn't mention the occurrence of a process of heat exchange in the condition. The purpose of the model discussed here is to model the processes in such a way that the effects of the context are minimised.

By adding the entity 'Air', the vapour can be contained by air. There is a directed correspondence between the temperature of water and vapour. The underlying assumption is that the incoming vapour determines the pressure of the surrounding air, see figure 6.7.

We will assume that evaporation, which results in an increase in amount of vapour, has a positive proportionality with vapour pressure. And vapour pressure has a proportionality with vapour temperature and air pressure. In addition the values of vapour pressure and air pressure correspond. Here the influences of heat exchanges of both vapour and air with other substances are left out, seeing them as submissive to the main effect of evaporation itself.

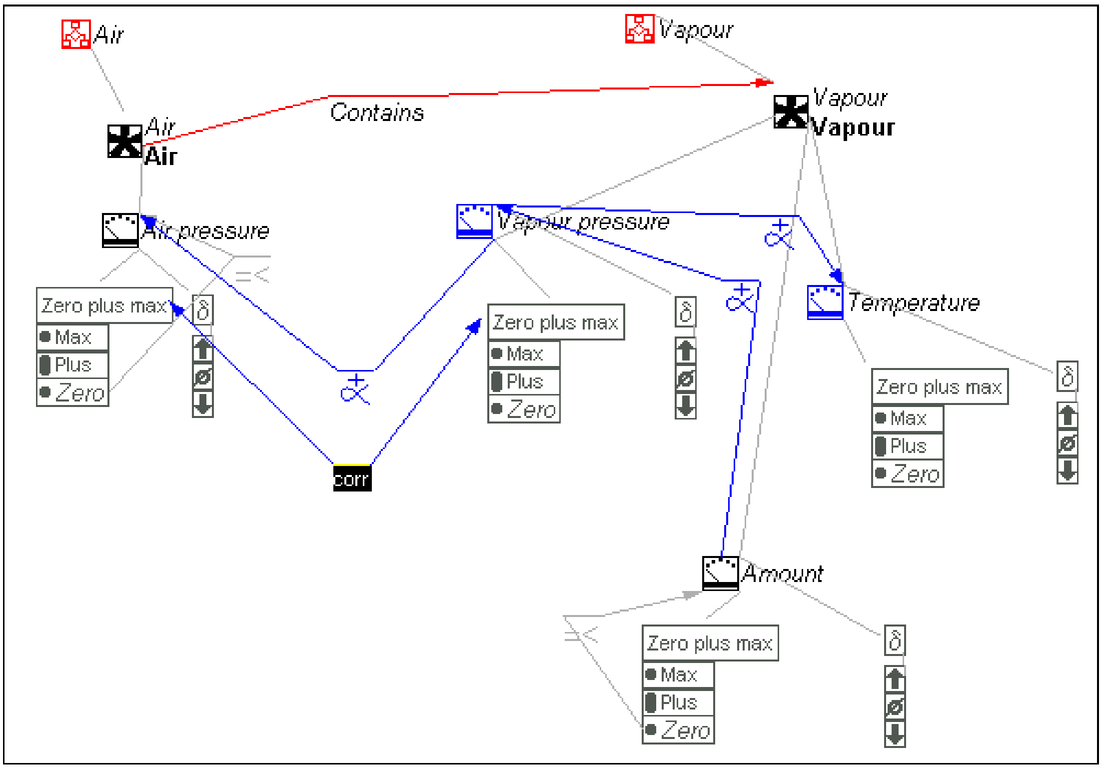

Figure 6.7. Vapour that is contained in the air.

The next phase in a water cycle can be that movements of the air can cause the vapour to condense again. For that to occur, there must exist concurrency of cold air (low pressure) and warm air (high pressure). Two entities of air can exchange vapour on the basis of a pressure difference, which accounts here for a model of transportation of air containing vapour, see Figure 6.8. Typical for the model here is that the temperature of the vapour corresponds to the vapour pressure, in a sense adjusting to the circumstances in the air and thus abstracting away the actual energy exchange. The effect is that the temperature of the vapour adjusts to the vapour pressure, which in its turn corresponds to the amount of vapour. The model thus says for example that vapour coming into cold air will lose energy to this air by decreasing its temperature. A model of a more complex energy exchange between substances would provide more detail about how the vapour and its context of air interact. In this model, the transportation model *functions* as an energy-exchange but leaves the process implicit.

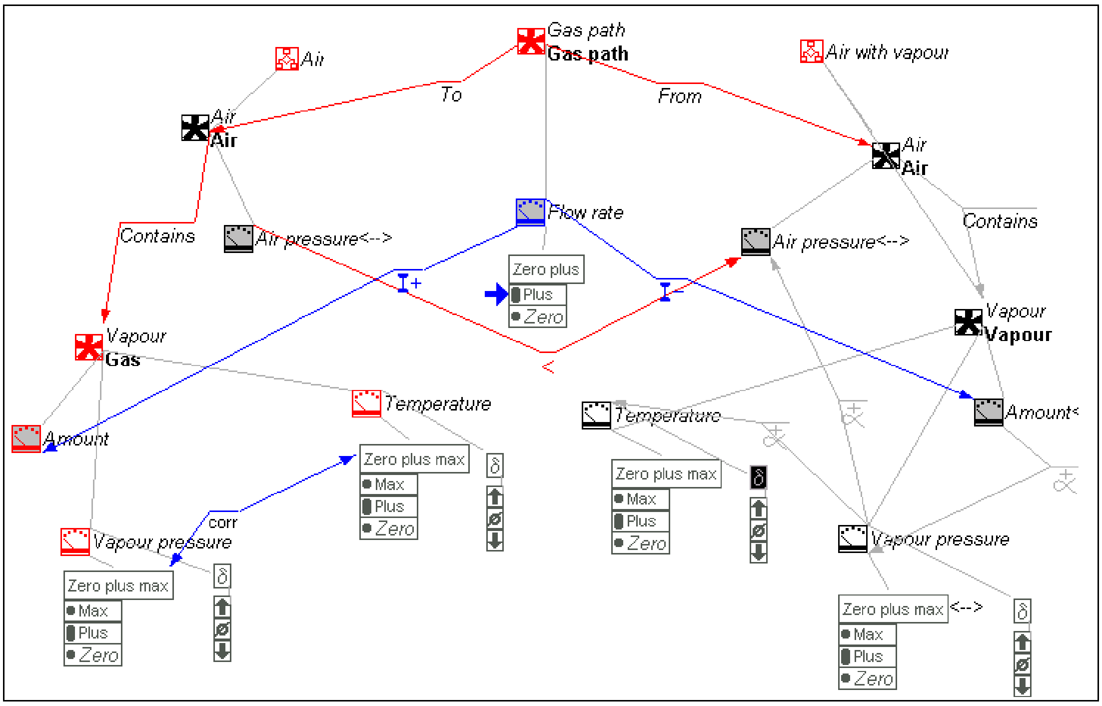

Figure 6.8. A model for transporting air containing vapour.

The reverse of the evaporation model is a phase change from gas to liquid when the temperature of the vapour drops below a the threshold *max*. The transportation process causes exactly this effect, and the result is that the vapour will condense, see Figure 6.9. In order for condensation to occur must be that the amount of vapour is greater than *zero*. The water that is contained by the air has no interactions with other substances held in the air. It cannot exchange energy with other substances, causing it to for example evaporate while it is in the air.

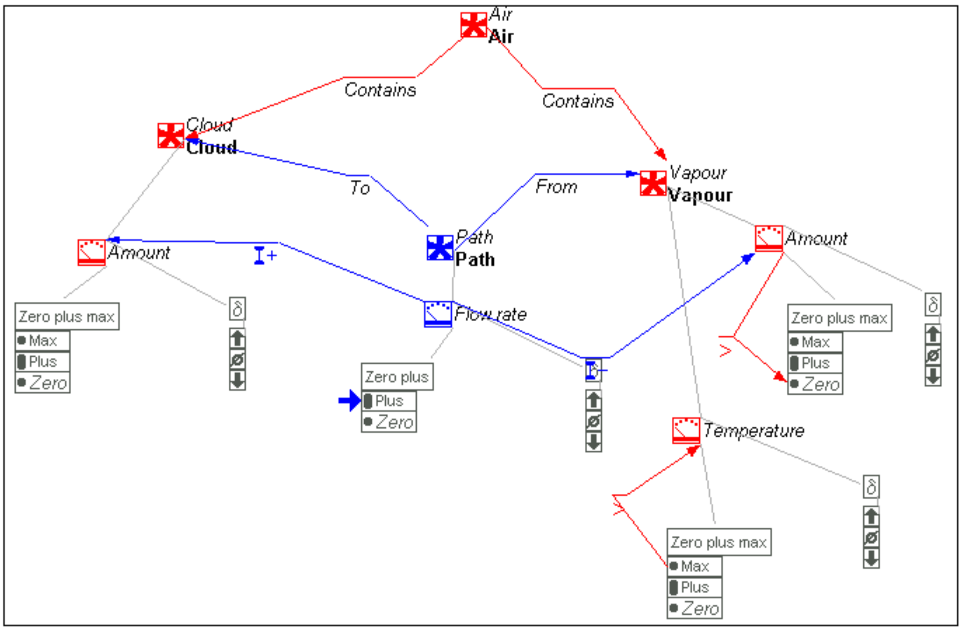

Figure 6.9. A model of condensation.

Much in the same way, precipitation (Figure 6.10) occurs when the amount of clouds become greater than zero. This is of course an overly simplified model of precipitation. However, the current model focuses on quantities such as temperature and pressure, which do not exclusively influence the occurrence of precipitation. The precipitation process completes the water cycle by influencing the amount of water in a surface water storage.

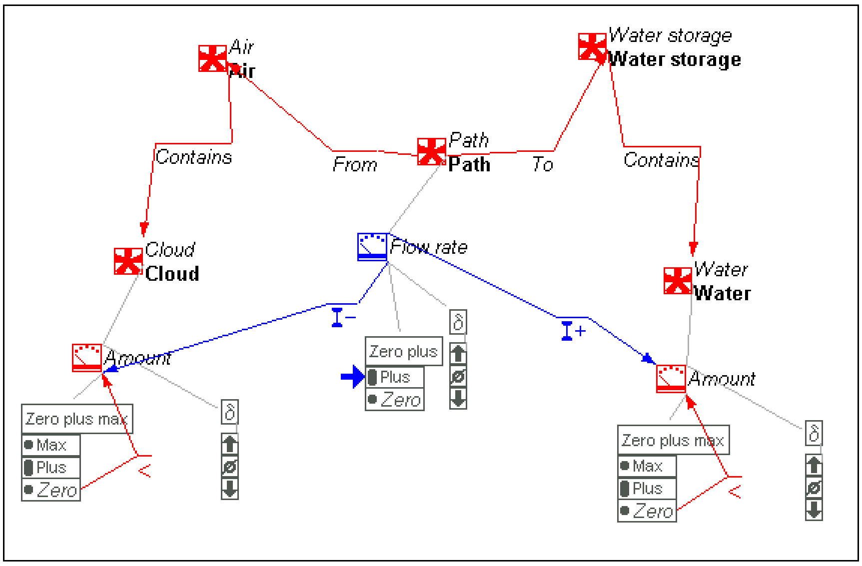

Figure 6.10. Precipitation.

The simple model of the water cycle leaves out quite some detail. Next to leaving out many of the energy exchanges that occur between various substances, some other features have not been included. For example, rivers usually flow to the sea because there is a certain vertical difference between the sea and river, which triggers a downward stream. Also the *vertical* differences in temperature in the atmosphere when modelled, add more detail to the model. Vertical differences are partly responsible for energy exchanges between substances and their context, for example the atmosphere. In general, the behaviour of air layers and the various substances contained by it can be modelled in more detail as well. More detail can also be added by making explicit the interdependencies that hold between various processes. In Model 1, the conditions of processes do not assume the existence and interaction with other parts of the system. The next model puts more focus on the integral functioning of the system

6.3.3 Model 2

Model 2 introduces more detail in describing the water cycle. It focuses on making explicit the functioning of processes in interaction with other processes. It also defines new types of processes that are left implicit or left out in model 1.

In the isa hierarchy of the model in figure 6.11, an initial division is made between physical object, heat-exchangeable object, status and assumptions. Status represents a mode of existence, like a phase of a substance. Subtypes of physical object are objects such as containers, substances and paths, are heat exchangeable entities. Attributes like *stiffness, size, openness* and *phase* are subtypes of status; *stiffness* is a measure to distinguish between pressure areas and surface storages (elastic or rigid), *phase* refers to the physical phase (liquid, gas or solid)

All substances have a common name and an attribute that determines the phase. Creating a piece of water is done by instantiating water from substance and liquid from phase. For instance we give the *entity* water the variable name seawater with an attribute *has_phase* "liquid". Using this approach it is the same as saying that for example the air we breathe is O_2 in gas phase.

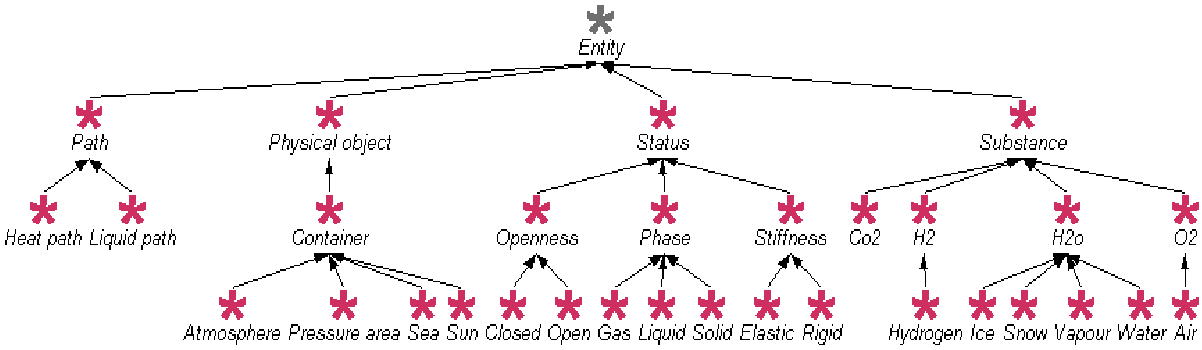

Figure 6.11. Entity hierarchy.

Several kinds of physical entities are distinguished. In the following, definitions on individuals such as substances, containers, contained substances, paths and portals will be discussed. When individualising objects or concepts, one of the criteria must be the spatio-temporal continuity of the objects (Hayes, 1978). For substances such as liquids the individualisation can be done in an assembly with containers that contain it, similar to the contained stuff ontology.

Substances and containers exist in separate views *as well* as in assemblies of both, the contained substances. This is in fact slightly different than the contained stuff ontology, where no liquids can be considered that are not contained in a container. The model in itself has no knowledge to reason about substances, it can only reason about the behaviour of contained substances. Containers are considered with respect to their *volume, heat, pressure, stiffness and openness*. In addition, containers may be equipped with a portal.

There is a substantial difference between containers that are modelled open or closed, this has to do with exposure to the atmosphere, see also (Collins & Forbus 1989, p16.). In case of a closed container, the exposure to the atmosphere doesn't influence the quantities *inside* the container, such as air pressure. In the current scope, we assume the existence of closed containers with elastic features, these mapping to for example a pressure area in the atmosphere. In principle this means that elastic containers are subject to exposure in the atmosphere and as a consequence, the pressure inside the container may be influenced as well (reaction force). In the contained stuff ontology, various properties of individuals, such as pressure or temperature exist when for example a container, a substance and its phase are assembled into a contained stuff. A contained substance is regarded as an individual when the following function applies:

contained stuffs –→ substance x phase x container.

Substances always have the quantity *heat* and *amoun*t. By integrating substance and phase in one view, we create the specific states of matter such as gas, liquid or solid, accompanied with necessary quantity conditions using the quantity space for substance-temperature: *above vapourpoint-between vapour and freezepoint-freezepoint-below freezepoint-absolute nil*. Table 6.1 gives an overview of the quantity conditions for different states of matter.

phase(substance):	**quantity condition:**
solid	temperature(substance) ≤ freezing-point(temperature)
liquid	temperature(substance) ≤ vapour-point(temperature), temperature(substance) ≥ freezepoint(temperature)
gas	temperature(substance) ≥ vapour-point(temperature)

Table 6.1. Quantity conditions for substances.

The energy *exchanges* in the system are modelled between substances. For instance in the model, the sea (open contained liquid) and a pressure area (closed elastic contained gas) are able to exchange heat. In order to create a flow rate, a path is introduced between heat connected substances. The quantity space for heat is limited to the interval *plus* for all entities.

An 'contained substance' or 'open contained substance' does not introduce the quantity volume. The rationale is that in the current perspective, the added value of introducing this quantity is neglectable in comparison to the impact that a 'closed contained gas' has on the quantity volume of a container.

The model fragment for 'closed contained gas', depicted in figure 6.12. It is a subtype of the more general 'contained substance, and has as condition the existence of a closed container and a gas. A 'closed contained gas' introduces the quantities volume and pressure for the container, and the following dependencies:

Amount	α_{Q+}	Pressure
Heat	α_{Q+}	Pressure
Pressure	α_{Q+}	Temperature
Volume	α_{Q-}	Pressure

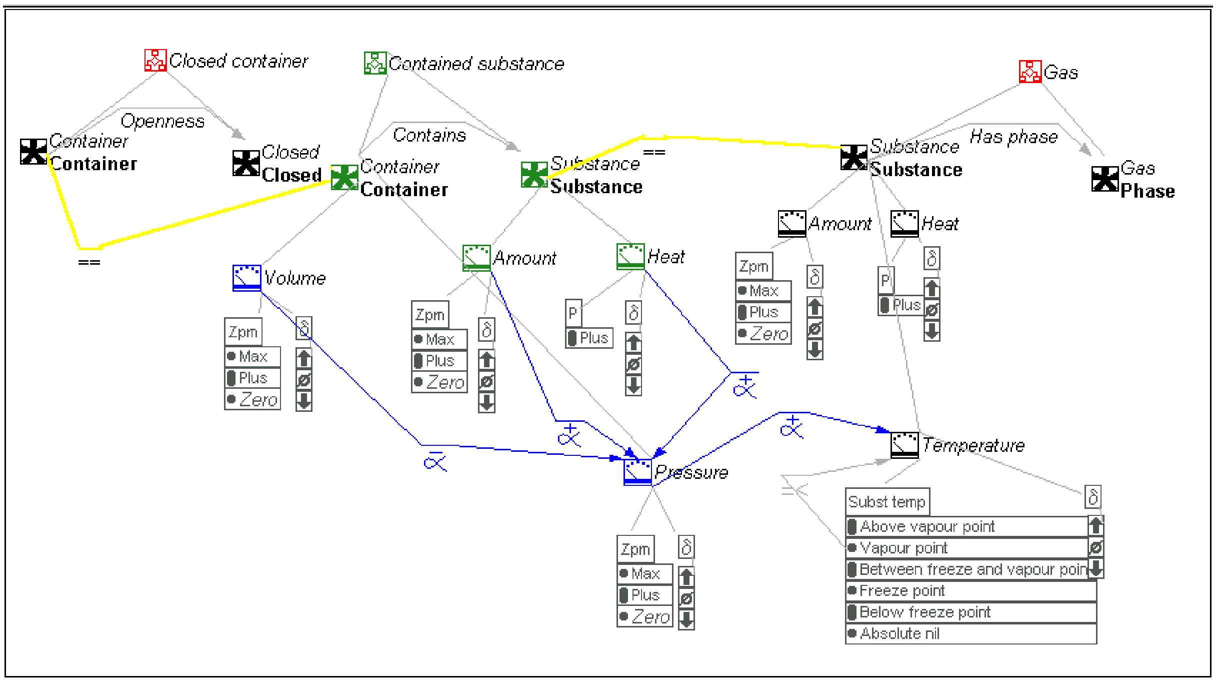

Figure 6.12. Model fragment of "closed contained gas".

The dependencies for closed contained gasses follow the usual statements in physics textbooks, see also (Forbus, 1984). The quantity spaces for these parameters are all of the type *zero-plus-max*.

A subtype model fragment of the 'closed contained gas' fragment controls the relations between the amount of substance inside the container and the volume and pressure of the container itself. The fragment 'contained gas volume pressure details' says that when the amount of substance is greater than *zero*, the following undirected qualitative correspondences exist:

Amount Q_{corr} Volume

Pressure Q_{corr} Volume

6.3.3.1 Multiple gasses in a container

Following standard definitions of containers and contained spaces, the former is normally a rigid object and the latter is in a relation to the container and should include a 3D-space with contiguous rigid boundaries surrounding it (Hayes, 1978). In our model decisions were made that are somewhat contrary to these definitions and therefore must be discussed in more detail. The core of the discussion lies in the definition of a *pressure area*. A pressure area should form a contained space, distinguishing it from other contained spaces such as other pressure areas in a bigger contained space, the atmosphere. But there are of course no visible boundaries between pressure area in the sky, let alone they are rigid and physical. The reason why there does exist some correspondence between a pressure area and a container is that the behaviour manifested by certain volumes of stuffs in the atmosphere is resembled well by a balloon filled with the same stuff in the atmosphere. As a formal equivalent the choice is made to distinguish between elastic containers and rigid containers for stuffs contained in the atmosphere and surface respectively. A pressure area is a closed elastic container containing multiple substances, and is itself contained in the atmosphere.

Until this point we have considered only separately contained substances. When considering what is thus called a *pressure area* we must describe how different substances can be jointly contained in the same container, thus describing the causal dependencies between shared parameters of the substances in the container such as *pressure, volume* and *heat*. The first problem is how to derive the value for pressure. Let's take the analogy with a balloon again. There are two decisive distinctions between a pressure area and a balloon. First of all, a balloon has actual physical boundaries where a pressure area has none. Secondly, although it's boundaries are elastic there exists a limit to the amount of 3D-space a balloon can fill and a limit to the pressure when the balloon has expanded to its maximum. A pressure area has no physical boundaries and is therefore virtually unconstrained in space. In the model the behaviour of only one or two pressure areas is considered at a time. This means that other pressure area's in the atmosphere will not be able to sufficiently constrain the volume of the area. Consequently, the pressure will not be able to increase significantly within the area. The only way to find a constraint mechanism for pressure is to assign a fixed value to the volume for the pressure area.

Therefore an agent model is introduced, which constrains the volume of a pressure area to *plus* and the derivative to *zero*.

The fragment 'assembly pressure area' defines that a pressure area contains two types of closed contained gas, and one closed contained liquid: air pressure area, vapour and water pressure area. The overall pressure of the assembly is influenced by changes in *amount* of substances. The quantity *pressure* in its turn has a positive qualitative proportionality with the *temperature* of the substances. This makes the circle complete: any increase of amount of a substance leads to increasing pressure in the assembly and this leads to an increase in temperature of the remaining substances in the pressure area. In the meanwhile, the substances that are contained in the pressure area will exchange energy through pre-defined heat paths.

The fragment 'assembly atmosphere' is a closed contained gas that contains another assembly, the pressure area. Because of its containment in the atmosphere, the vertical position of the pressure area is added by introducing the quantity *altitude*. It uses the quantity space atmosphere levels with values *high-middle-low*. In figure 6.13, the structure (entities and quantities) of the model fragment "assembly atmosphere" is depicted as it is instantiated in VisiGarp. All relations and dependencies are left out of the picture.

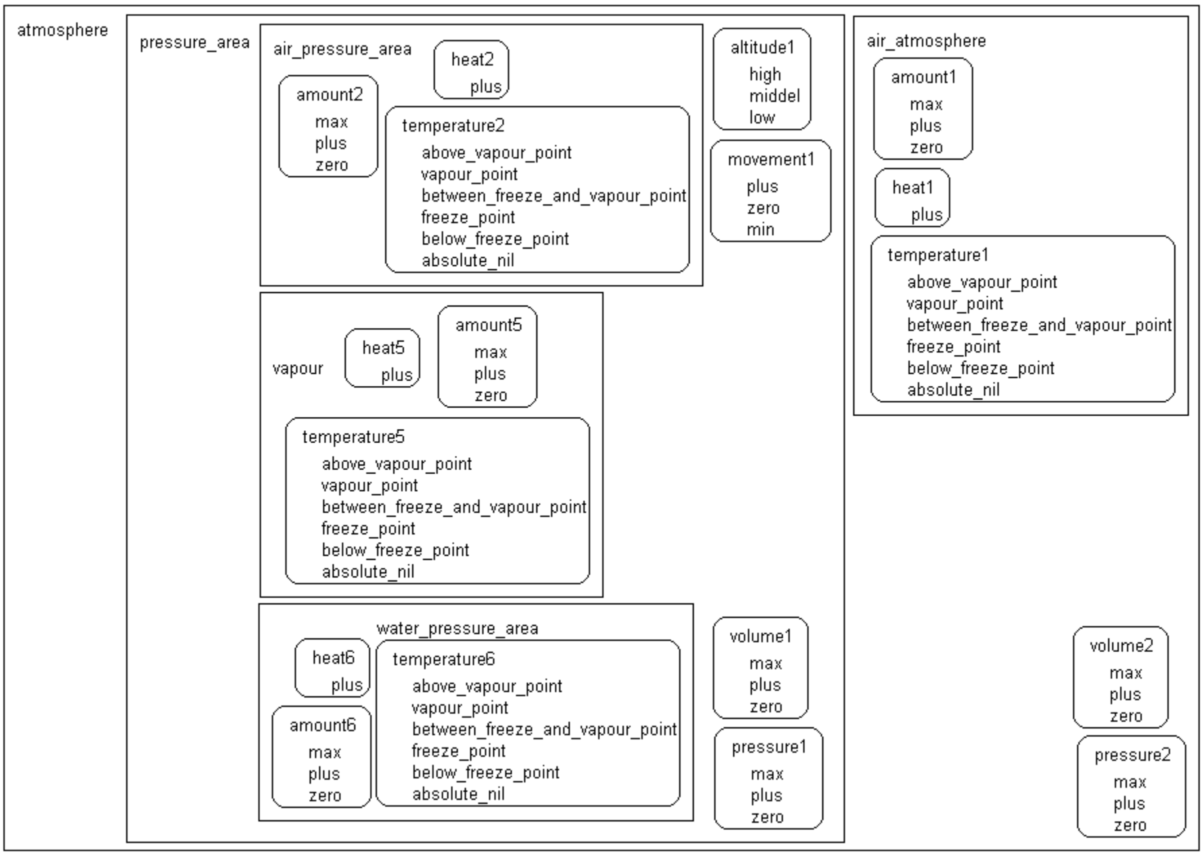

Figure 6.13. Entities and quantities in "assembly atmosphere".

By specifying identity relations in Homer, the system find that the containers in which the substances of 'assembly pressure area' are contained are all referring to the same instance of one container. In the figure this can be seen by noticing that there exist only two quantities volume (1 and 2) and pressure (1 and 2). The 'assembly atmosphere' thus consists of two containers and four substances.

6.3.3.2 vertical differences on the surface

In the implementation, surface layers are represented as open contained stuffs. These can be rivers, lakes or oceans. Although they are in constant flux, we will thus consider them as individuals. The container refers to the 3-dimensional space, which can have a portal at a certain position. The purpose of this representation is to reason about vertical differences of liquids that propagate to pressure differences on each side of a path that is connected to portal of containers. The different portal positions require different quantity spaces to be assigned to the level and amount of substance in a container, see figure 6.12. Assembling different types of contained stuffs makes it possible to simulate water features such as a river (which typically runs above sea level) emptying in the ocean.

In the approach taken here, the pressure values are assigned for every possible configuration of portal and level. With the idea outlined above we can assume a container geometry resembling the one in figure 6.14.

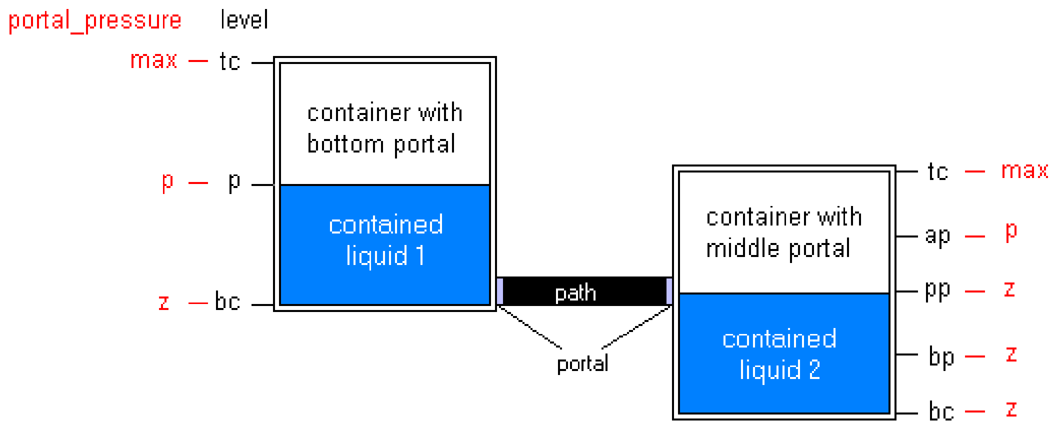

Figure 6.14. Container geometry for surfaces.

Before processes involving multiple objects can be described, the connectivity of the objects involved must be discussed, yielding a structural description of the situation at hand. The structural description should provide a set of constraints that allow the simulator to make certain inference about the difference in pressure on both portals.

The critical factor in modelling and simulating the flows that occur between different surfaces on land will be the level of the column of water above a path that connects one container to another. Paths are connected to containers through portals and portals can be placed either on the bottom, the middle or the top of a container. The level of the liquid relative to the position of the portal propagates to pressure on the portal. For example in a container with a portal placed in the middle and a level equal to max, the pressure on the portal must be plus. In the approach taken here, the pressure values are assigned for every possible configuration of portal and level, see also figure 6.14, which depicts one of the nine possible configurations. The two contained liquids in the picture have the same level, or more precise, the same amount of liquid when the two containers are assumed to have equal sizes. The quantity spaces level liquid and amount describe the various levels and amounts of liquid relative to the portal, which itself can thus have variable height. Open contained liquids with a portal at the top or bottom of the container use different quantity spaces for level and amount than open contained liquids with a portal at the middle (table 6.2).

Structure	Substance level quantity space	Substance amount quantity space
Open contained liquid With top portal	*bottom container – plus – top container*	*zero – plus – max*
Open contained liquid with bottom portal	*bottom container – plus – top container*	*zero – plus – max*
Open contained liquid with middle portal	*bottom container – below portal – portal place – above portal – top container*	*zero – below portal – portal place – above portal – max*

Table 6.2. Possible quantity spaces for Open contained liquids.

The portal pressure in a open contained liquid with a top portal can never be positive, since the substance cannot form a column above the top of the container. The quantities amount and level of substance are qualitatively proportional and correspond. For open contained liquids with a bottom portal all three quantities, substance level, substance amount and portal pressure are qualitatively proportional. Figure 6.15 shows a container with a portal in the *middle*.

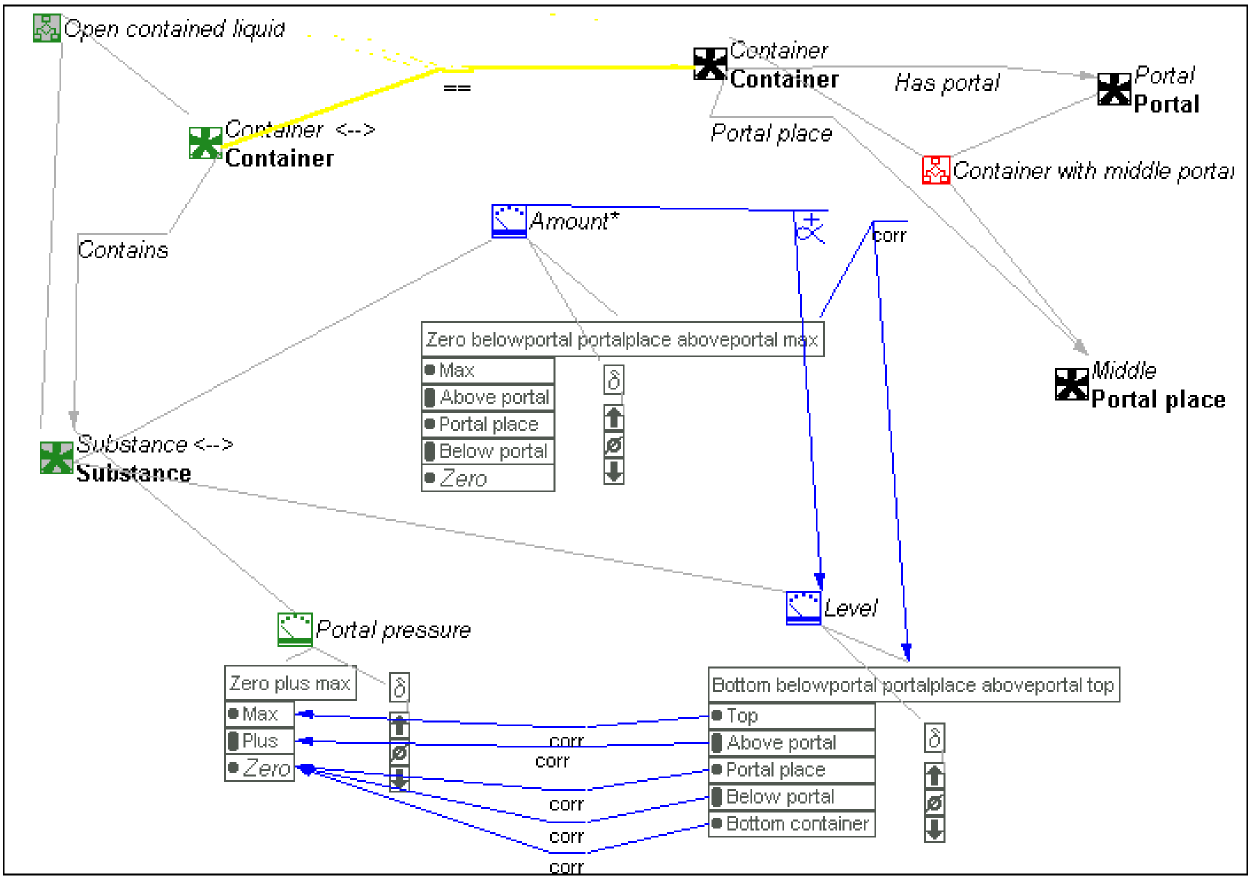

Figure 6.15. An open contained liquid with portal in the middle.

In the figure 6.15, all possible values for level have a corresponding value with portal pressure. The dependencies for the quantity portal pressure can be made more general when more information is available. For example when we know that the level is above the position of the portal, we can add information by saying that the pressure on the portal increases as the level rises. Conversely, when the level drops below the position of the portal, the pressure on the portal will always be zero. These issues are defined in two subtype model fragments of 'open contained liquid middle portal'.
The idea is that when two containers are connected by a path, and the level in one of the containers increases, then so will the portal pressure of the container and flow can occur. This flow has to restore the equilibrium in pressure on both portals. The use of portals with contained liquids and other issues concerning possible configurations of fluid flows are reflected upon in (Collins & Forbus, 1987). Somewhat different from the purpose of using portals by Collins and Forbus, who use portals for resolving ambiguity with causality within fluid paths, here portals are used mainly to produce constraints that account for vertical distinctions between surfaces. Several types of paths can exist in connections. We distinguish path, fluid path, gas path and heat path, where the first is an unspecified super type of the others. Paths may connect only two distinct containers. In specific cases, like the surface flow, where specific position of a container is relevant and thus the direction of the flow, specific attributes such as left hand side or right hand side are added to the paths. Figure 6.16 shows a qualitative structural description of the connection of surface containers.

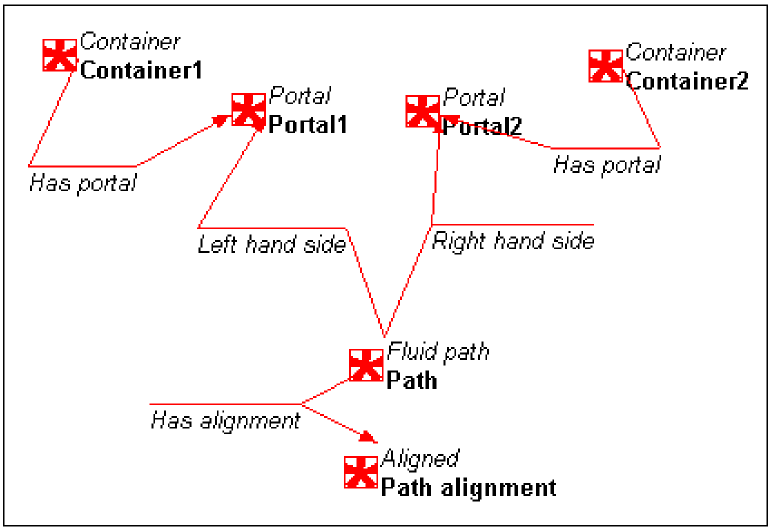

Figure 6.16. Generic definition of a portal connection.

The figure shows container A with portal A and container B with portal B being connected with a fluid path which has portal A at its left side and portal B at its right side. The description is generic in the sense that no information is needed concerning the positions of the portals. This information is needed when finally in figure 6.16, a specific portal connection is made which requires two distinctly named contained stuffs to participate.

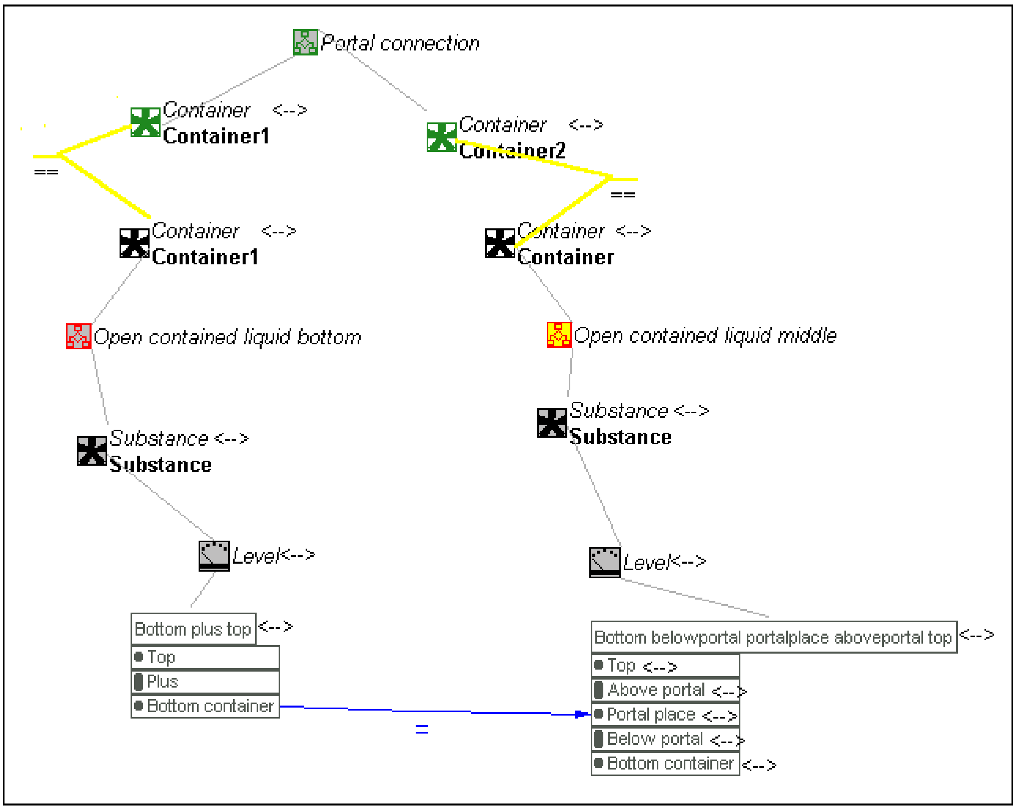

Figure 6.17. Portal connection: bottom to middle.

The quantities *level* of two substances always have a relation describing how the level of one substance is relative to the level of the second substance. In figure 6.17, the consequence of a open container with bottom portal being connected to and open container with middle portal is that the values *bottom container* (levelA) and *portal place* (levelB) are equal. The result of this method is that the simulator gets nearly all the information it needs from the structural description and does not have to calculate for example the pressure by inferring the difference between the level and the portal position. The current approach results in a structural description of every possible configuration of containers and portal positions. All nine possible configurations and their specific equality relations for *level* are given in table 6.3.

Portal connection	Relation
1. top to top	equal(top_container(LevelA), top_container(LevelB))
2. top to middle	equal(top_container(LevelA), portal_place(LevelB))
3. top to bottom	equal(top_container(LevelA), bottom_container(LevelB))
4. middle to top	equal(portal_place(LevelA), top_container(LevelB))
5. middle to middle	equal(portal_place(LevelA), portal_place(LevelB))
6. middle to bottom	equal(portal_place(LevelA), bottom_container(LevelB))
7. bottom to top	equal(bottom_container(LevelA), top_container(LevelB))
8. bottom to middle	equal(bottom_container(LevelA), portal_place(LevelB))
9. bottom to bottom	equal(bottom_container(LevelA), bottom_container(LevelB)

Table 6.3. Relative position of level for two contained substances.

In order to create a less abstract representation of surface water flows, the model can be elaborated with for example the notion of permeability of surface containers. With this idea, the boundaries of the containers must be assumed to be impermeable, otherwise portals should be assigned. This serves as a distinction between permeable and impermeable ground layers. Since soil itself may hold liquid between its pieces of stuff, a container with no portals suits the idea, hence it allows no water to flow in or out. The level of the liquid in the container resembles the groundwater table. Similarly the space above the water table compares to the zone of percolation, which is the (non-) permeable layer.
Consequently, for the water that reaches soil surfaces as a result of precipitation, three alternative kinds of behaviour are possible. In the first case it can infiltrate the soil given that the soil layer is permeable, e.g. a portal and a path exist. In the second case, it is possible that the soil is permeable but the level of the water table is maximal, which means that any further infiltration will result in flooding, runoff overland to a river. Third, it is possible that the soil surface is impermeable, which means that it runs over the surface as well. A quite nice representation to this in terms of QR was thought of during a course in model based reasoning about this particular domain. It is possible to model some kind of intermediate storage containers, resembling puddles. Puddles can be modelled relatively straightforward as open contained stuffs. This elaboration would allow a specification in the model between land and rivers or seas.

6.3.3.3 Processes

As mentioned before, energy exchanges are modelled between substances in the model. With a difference in temperature as condition, heat is exchanged with a rate that is equal to the difference in pressure. The “heat flow” fragment has a general top level and three specialisations, which model the direction of the flow. Because the flow rate has a quantity space containing *min-zero-plus*, the influences specified in the general fragment apply to each direction of heat flow. In figure 6.18, the subtype “heat flow negative” is depicted. Because the flow rate is *min*, the amount of heat of the source will increase and the amount of heat in the destination will decrease. The sign of the influence relation between quantities is thus opposite to its actual influence when the value of the influencing quantity is below *zero*.

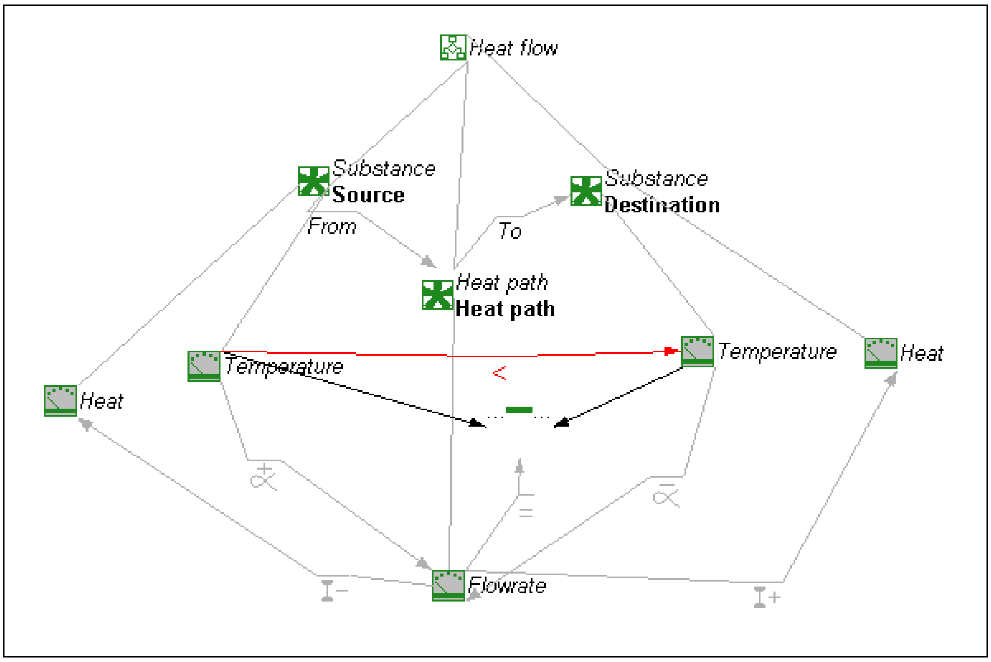

Figure 6.18. Heat flow negative.

Only substances that are connected to another substance via a pre-specified heat path can engage in energy exchange. The temperature of the source is positively proportional to the flow rate, and the temperature of the destination is negatively proportional to the flow rate. Changes in temperature thus may affect the intensity of energy exchange.

Conditional on the existence of a heat flow between the sun and the seawater, water may start to evaporate when the temperature of the water is at vapour point and its derivative is greater or equal than plus. Different than for example the model of evaporation in Model I, the process is dependent on the occurrence of the process of heat flow. The flow rate between the heat-exchanging entities also specifies the flow rate of evaporation. As you can see in figure 6.19, the model fragment “evaporation” also has consequences for the quantity heat of both substances. When the amount of a substance changes, the heat of the substances changes in the same direction. The model is specific for a heat flow between at least one designated substance, because there must exist a positive heat flow between *seawater* and another substance.

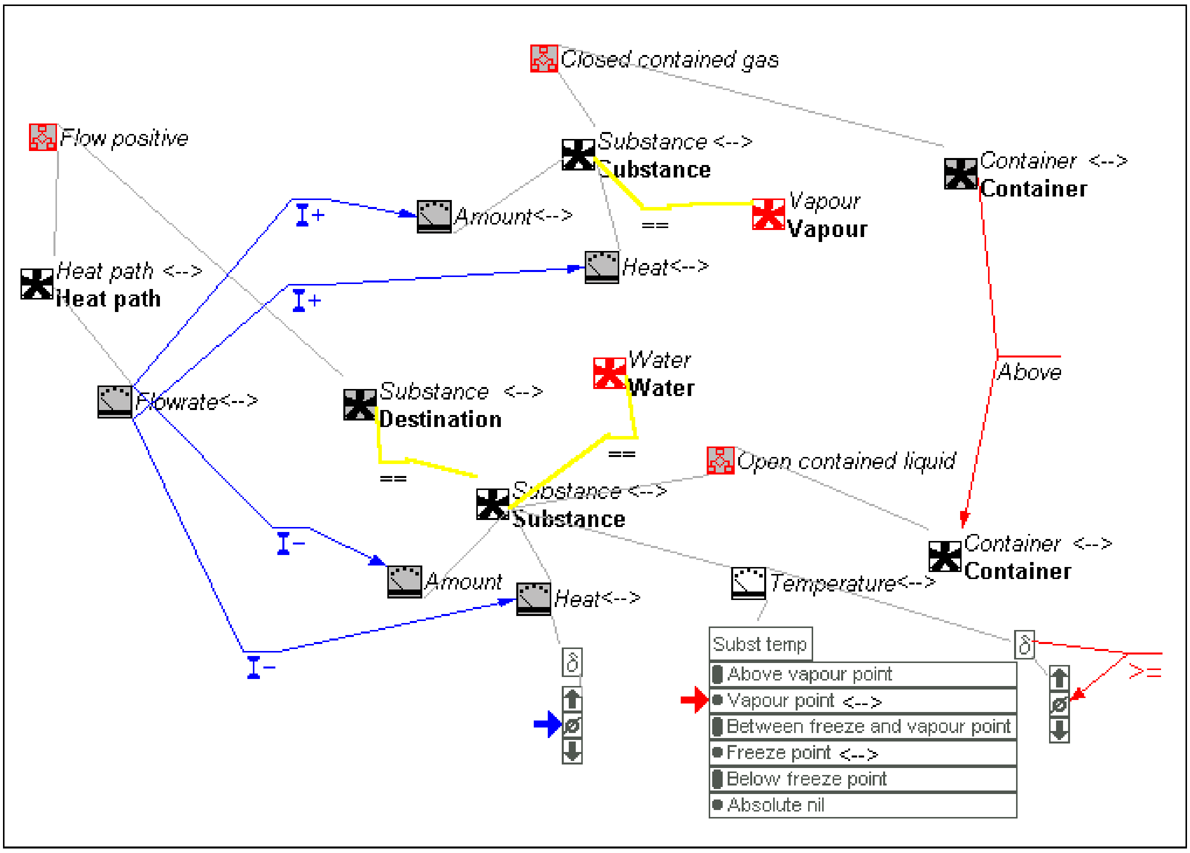

Figure 6.19. Evaporation occurs when there is heat flow.

The atmosphere and a pressure area can exchange heat by a flow rate that triggers on a difference in temperature between the air of the atmosphere and the air of the pressure area, and the existance of a heath path connecting both. A consequence of the energy exchange is that, given this heat flow and a pressure difference between the two, the pressure area may engage a vertical movement. Three types of movement are possible:

1. Pressure-Pressure area > Pressure Atmosphere: *upward movement*
2. Pressure-Pressure area = Pressure Atmosphere: *no movement*
3. Pressure-Pressure area < Pressure Atmosphere: *downward movement*

Because the pressure decreases in the atmosphere at higher altitudes, the differences in pressure between the atmosphere and the pressure area will change depending on the altitude of the pressure area. The pressure of the atmosphere decreases at higher altitudes. In order to calculate the difference between the pressure of the atmosphere, which should be specific to altitude, and the pressure of the pressure area, it would be necessary to define three different quantities for pressure in the atmosphere, namely one quantity per possible value for altitude. This would result in a qualitative representation of an equation of the type Δ(PressurePA – Δ PressureATM).

Adding this representation implies a thorough specialisation of the more general "closed contained gas" and most of the process fragments in the model.
Instead, when any pressure movement occurs, a quantity vertical pressure gradient is introduced. Figure 6.20 depicts the process of pressure area movement. The idea is that depending on the movement of the pressure area, the atmosphere influences the pressure of the pressure area in opposite direction. For example upward movement causes a negative influence on the pressure of the pressure area, and vice versa. Because the influence corresponds to the movement of the pressure area, the energy exchange and its relation to altitude is left implicit.

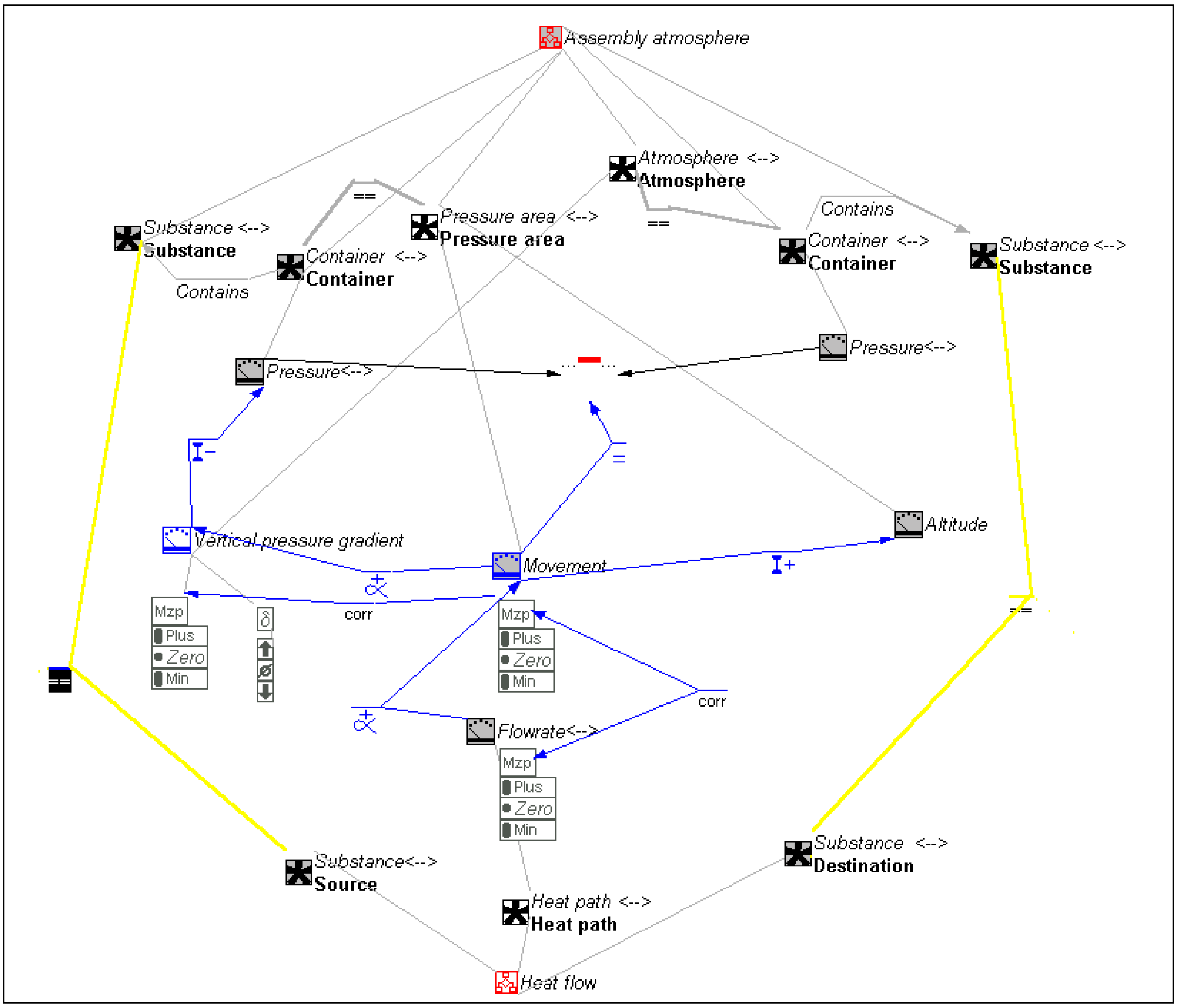

Figure 6.20. Vertical movement of a pressure area.

The assumption discussed that the volume of a pressure area always remains unchanged has the effect that the pressure area moves upward and continues to exchange energy with the atmosphere. In the meantime, the substances in the pressure area exchange heat by the same type of process. Vapour for example will start to exchange energy with the air of the pressure area once the latter cools down. As a consequence, the temperature of vapour will decrease to the lowest threshold for a substance to be in gas phase. When the temperature of vapour decreases to vapour point, and its derivative is smaller than zero, condensation occurs. Figure 6.21 depicts this process. It has largely the same structure as the model fragment “evaporation”. Again, the process is explicitly dependent on the occurrence of a heat exchange, here between air and water in a pressure area. Also the amount of energy of the substances is changed according to the changes in amount of substances.

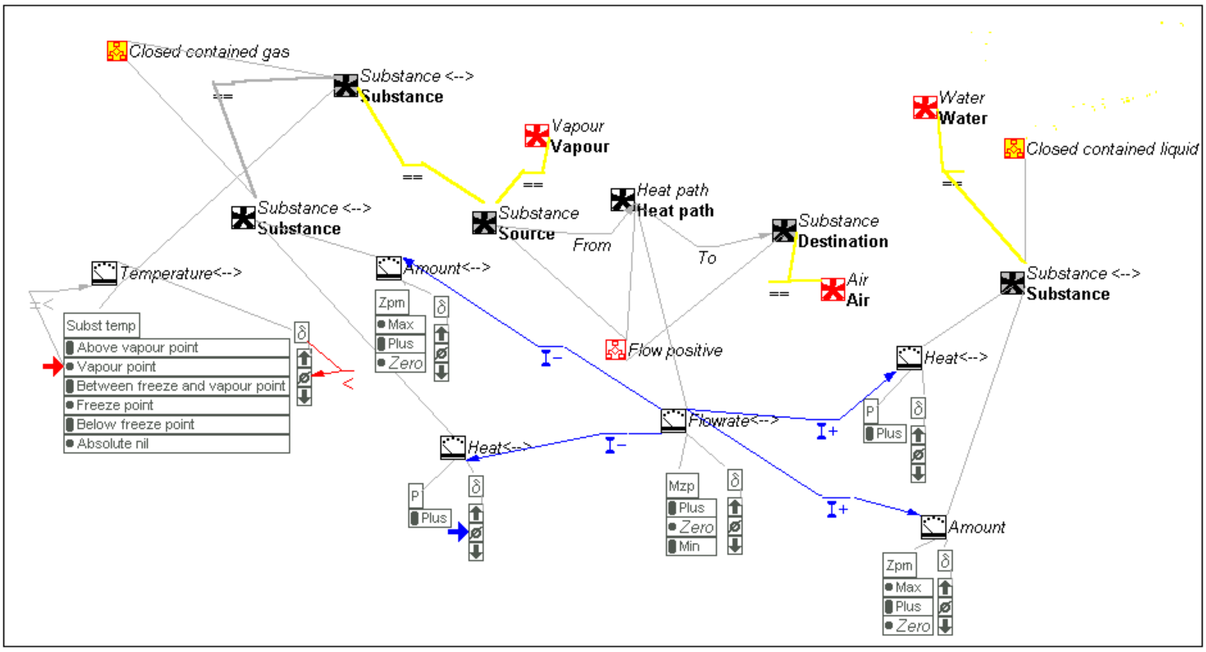

Figure 6.21. Condensation.

Only a certain amount of water can be kept in a pressure area. When the amount of water reaches *max*, the air is saturated with water. The model fragment “precipitation” in figure 6.22, is modelled as being dependent on the occurrence of the process condensation. When the amount of water is *max*, and the amount increases as a consequence of condensation, the flow rate through the liquid path corresponds to the flow rate of condensation. Note that in this model, the quantity heat of the seawater is not influenced by the increase of the amount the water.

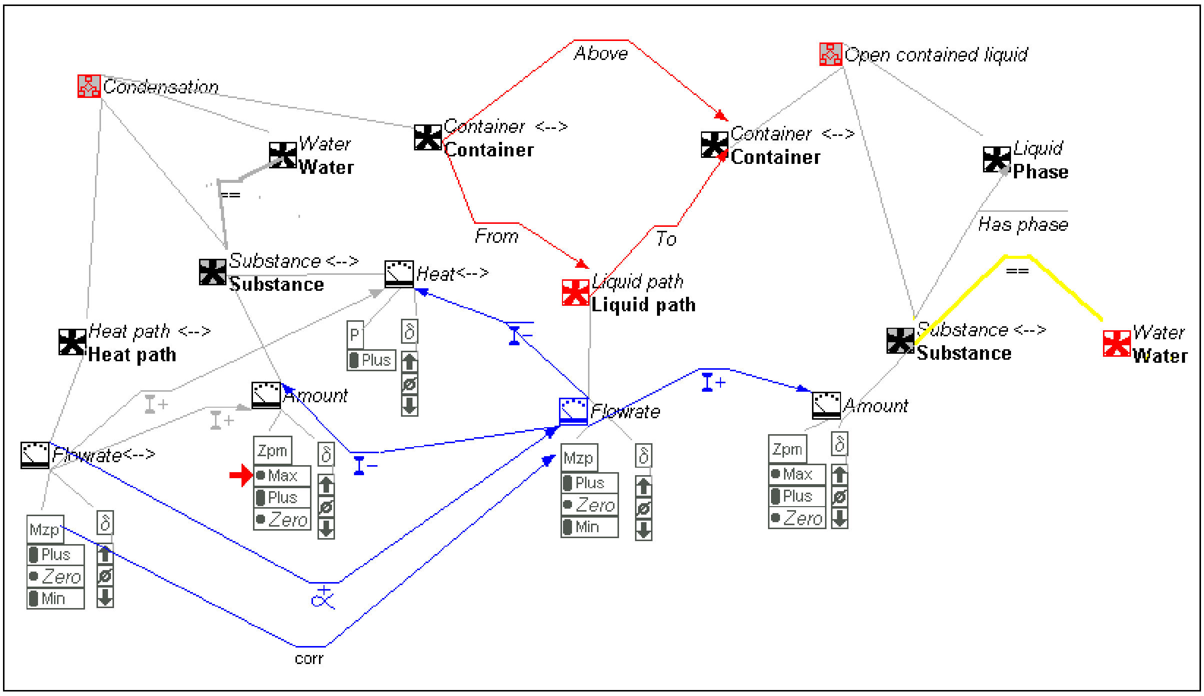

Figure 6.22. The model fragment "precipitation".

By modelling processes as being explicitly interdependent on the occurrence of some other process a rigid and complex causal model is constructed. The core of the causal model is the energy exchange between substances. The scenario used for the model defines several heat paths, listed in table 6.4:

Source substance	*Heat path*	*Destination substance*
Hydrogen	*from Sun to Sea*	Water(sea)
Vapour	*from Vapour to Air(Pressure area)*	Air(Pressure area)
Vapour	*from Vapour to Water(Pressure area)*	Water(Pressure area)
Water(Pressure area)	*from Water(Pressure area) to Air(Pressure area)*	Air(Pressure area)
Air(Pressure area)	*from Air(Pressure area) to Air(Atmosphere)*	Air(Atmosphere)

Table 6.4. Possible heat paths between substances.

The processes in Model 2 all have an (indirect) effect on the energy balance between substances. The consequence of which is that the heat flow occurs continuously when the model is simulated. In Model 1, there are no explicit interdependencies modelled for processes. The occurrence of (conditional) processes is left implicit in Model 1. However when simulated, the resulting simulation will follow a similar causal path of behaviour, because the conditions of the processes in model 1 cannot be satisfied without the occurrence of other processes.

7. Simulation of the water cycle

In this chapter, the current status of the qualitative simulation of the water cycle is described. Currently there exist three runnable models. Water cycle 1 (Model 1), Water cycle 2 (Model 2), and a running model of vertical differences of contained substances. As of yet the different models have not been combined into an overall simulation model, which could for example support the idea of model progression by means of different scenario's that vary in their focus, perspective and detail. Each single simulation will be reflected upon next.

7.1 Simulating vertical differences

The simulation will be illustrated by an example simulation of two containers, one with a top portal (left side), and one with a middle portal (right side). The scenario is depicted in figure 7.1.

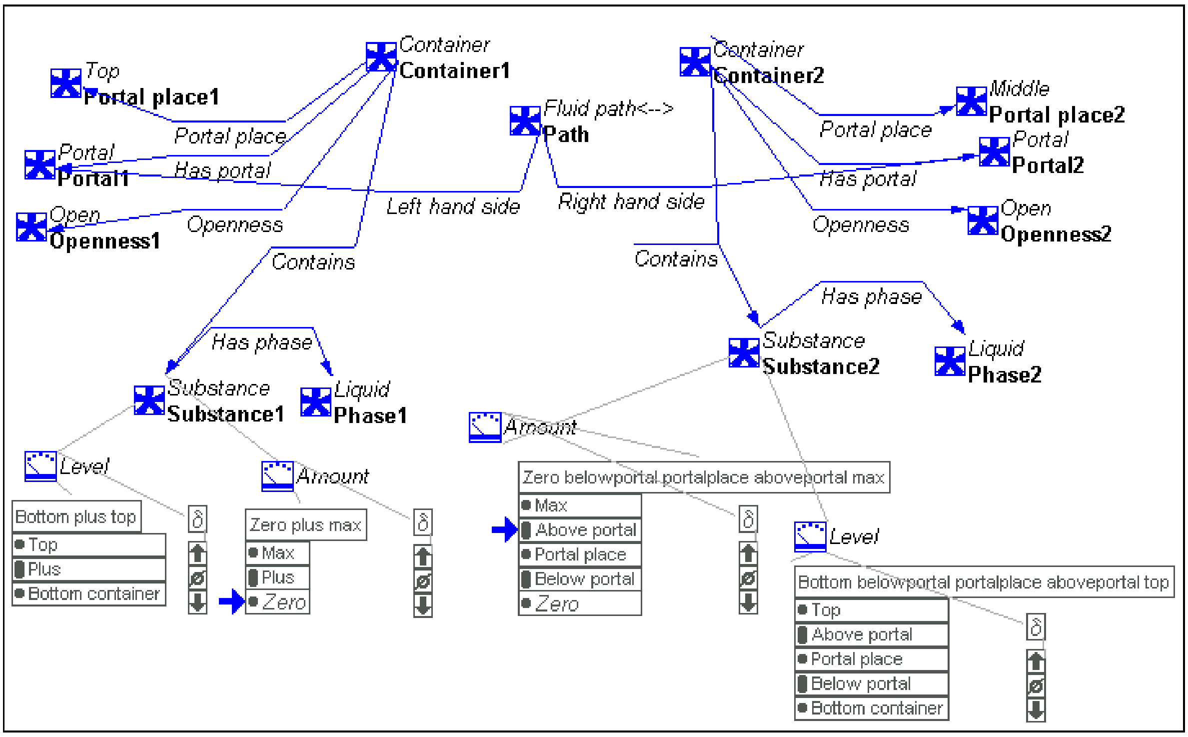

Figure 7.1. Scenario for top-middle containers.

The amount on the left-hand side is zero and the portal pressure of a container with a top portal is zero by definition. Any value above *Portal place* for the amount in the container on the right-hand side would render an inequality between both portal pressures. The simulator finds this in the first state.

The inequality triggers a liquid flow process by instantiating the fragment “flow from right-hand-side to left-hand-side”. The model fragment flow from right-hand-side to left-hand-side is depicted below in figure 7.2, generated using VISIGARP. Because the model fragment is a subtype of the more general ‘liquid flow’, only the inequality is highlighted. The dependencies between level and pressure are instantiated by the model fragments for containers with a specific portal, described in paragraph 6.4.3.2.

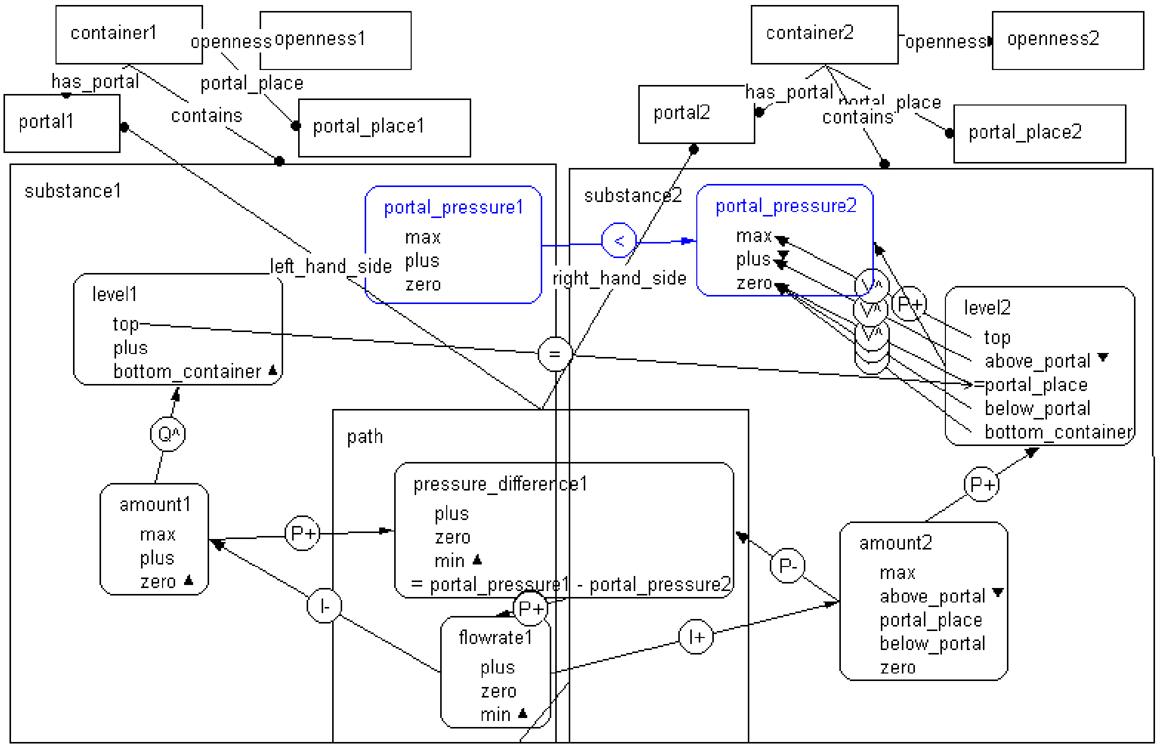

Figure 7.2. Flow from right-hand-side to left-hand-side.

Moving on to Figure 7.3, the green circles are the possible states resulting from the predecessor(s). Black circles are terminated states with no successors. In state 1, an inequality is found and the liquid flow fragment is triggered. The simulator finds the same inequality discussed above in state two, and after that only in state 5 and not in states 3 and 4(figure 6.24a). In figure 6.24b, we see that in fact state five leads to state 3, which is already computed. This illustrates the ambiguity in the qualitative calculus. Because the length of the interval above the portal on the left side is not known, both states 5 and 3 are valid successors of state 2. This can be seen in figure 7.4, which depicts a value history diagram for al five states in this simulation. Either amount1 becomes max while ‘amount 2’ reaches portal place (state 3) or amount 1 becomes *max* while amount 2 is still above portal place (state 5). In the end, state 5 is also a valid predecessor of state 3, which terminates (figure 7.3b).

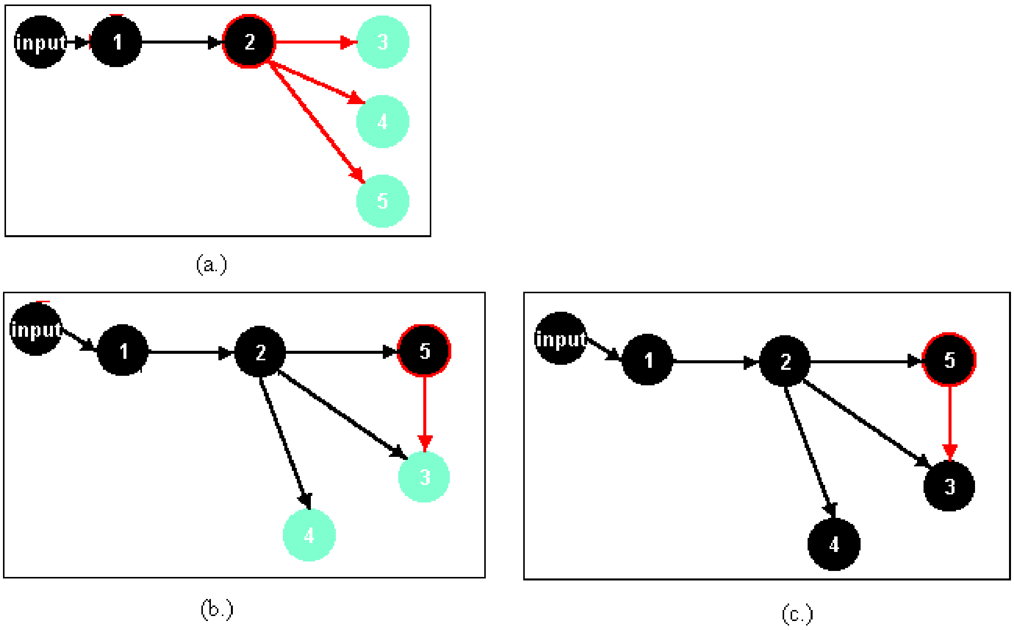

Figure 7.3. state-transition graphs in VisiGarp.

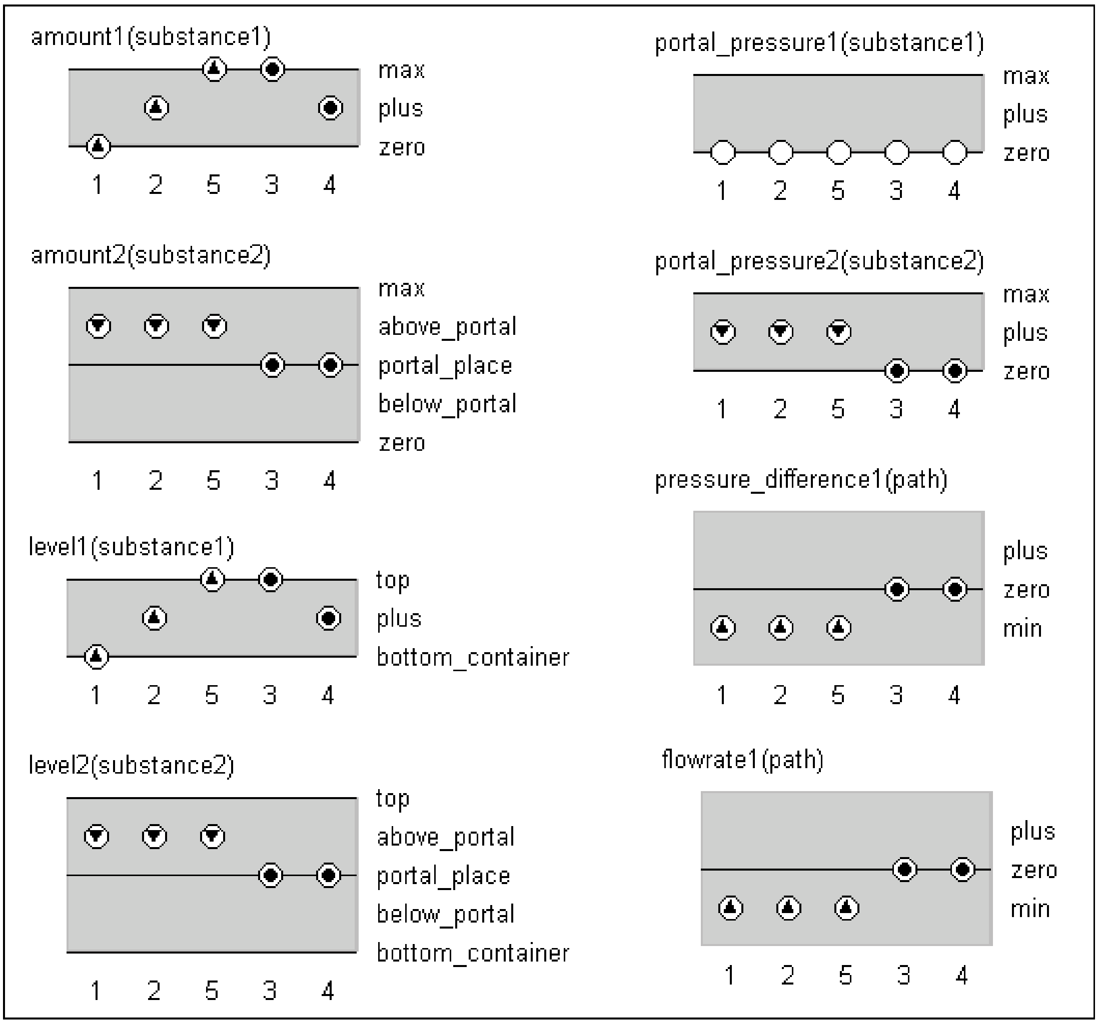

Figure 7.4. Quantity value history.

For the simulation model of vertical differences of contained substances, many scenarios' can be constructed for all possible configurations of containers and levels of liquid. Some of these scenarios are suitable to simulating water flows as they occur for example between rivers and seas.

7.2 Simulating Model 1

The input scenario for Model 1 in figure 7.5 introduces all the entities existent in the model: there are two water storages containing water and two air-layers containing vapour. Air-layer 2 also contains the entity cloud, the equivalent of water contained in the air. The value for the amount of water 1 is set to *max* and the value for amount of water 2 is set to *plus*, all other substances have the value *zero* for amount. The quantities pressure for both air-layers are set to *plus*, thus being equal and in balance. Both controllers account for the continuity of values for the amount of cloud and air-pressure of air 2 throughout the states where there exist no influences on these quantities.

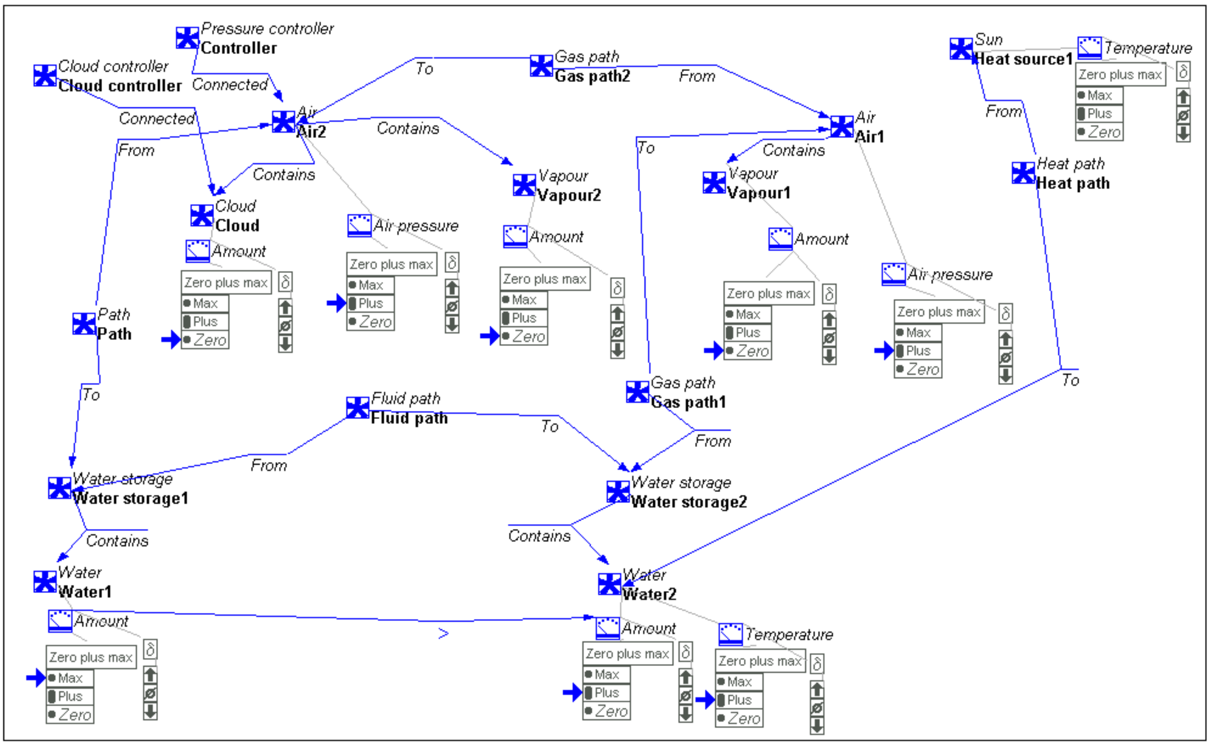

Figure 7.5. Scenario for Model 1.

The simulation of Model 1 is able to produce a state-transition-graph that activates the main processes of the water cycle within eight successive states. The model starts with a liquid flow between to water storages on the surface and a heat source heating one of them. The simulation continues to find a new process each successive state and stops when precipitation occurs. Figure 7.6 shows an example simulation of Model 1. The states in the transition graph are annotated with the active process fragment of each state. Note that each process remains active throughout the simulation once it is instantiated. The process of precipitation in state 61 increases the amount of water in the storage that is the source of the initial liquid flow in state 1. In between these states, the processes evaporation, transportation and condensation occur. From this perspective, the simulation is able to communicate a causal model that is of cyclic nature.

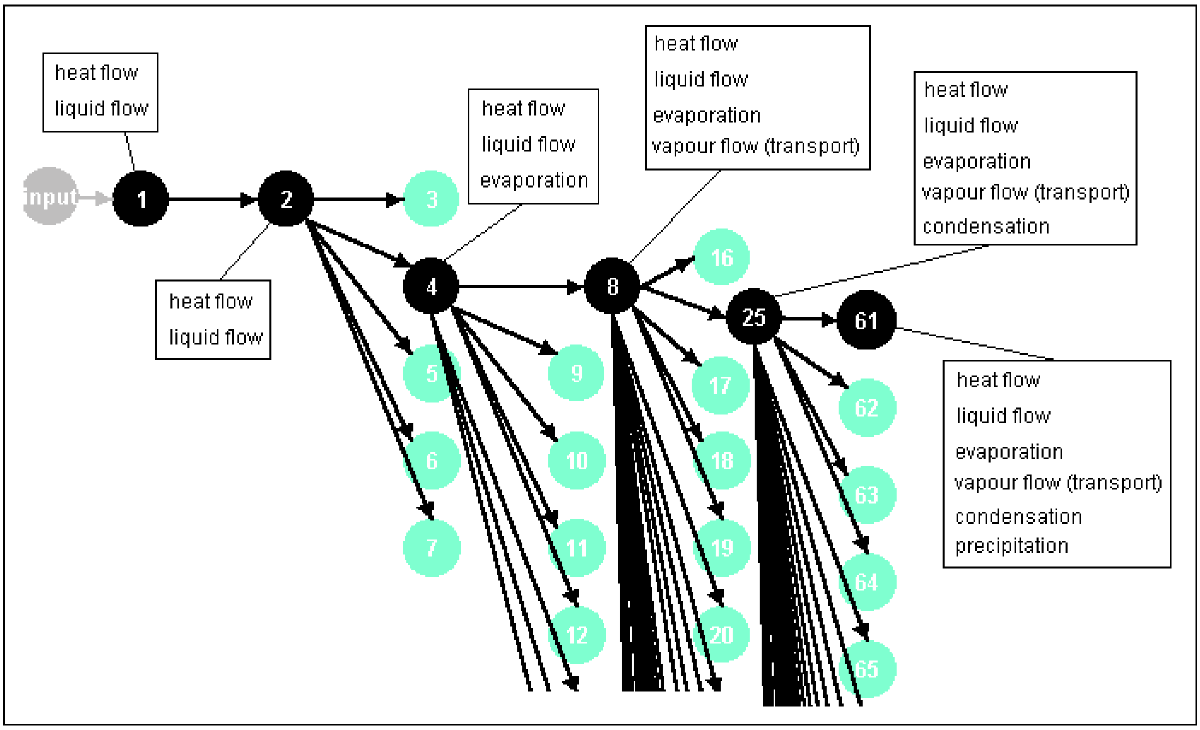

Figure 7.6. Example simulation of Model 1.

Except for state 1, which has a single successor state, the states after state two have a fairly big amount of successors each. Typically in the simulation is that each successive state introduces a new process, which adds more ambiguity by for example instantiating new quantities (e.g. flow rates) with various possible values. This means that the ambiguity created by other processes that remain active as well is sometimes multiplied by the newly added ambiguity.

The value history diagram of the simulation (figure 7.7) offers a closer look to the values of the quantities of interest in the simulation. In state 1 and 2, two processes are active; liquid flow and heat flow. Water flows from water storage 1 to water storage 2, and the sun heats the latter. In state 4, the temperature of water 2 reaches max and the model fragment 'evaporation' increases the amount of vapour 1 and decreases the amount of water 2. Because of the difference in pressure between air 1 and air 2, the fragment 'transport' in state 8, exchanges vapour between air 1 and air 2. In state the amount of vapour 2 is at *plus*, and its temperature is below *max*. Therefore, in state 25, the model fragment 'condensation' forms a cloud, which stands for water in the air. Finally, in state 61, the amount of clouds becomes plus and the fragment precipitation becomes active, which increases the amount of water 1. Theoretically the causal chain starts over again, when the amount of water 1 becomes greater than the amount of water 2, similar to state 1.

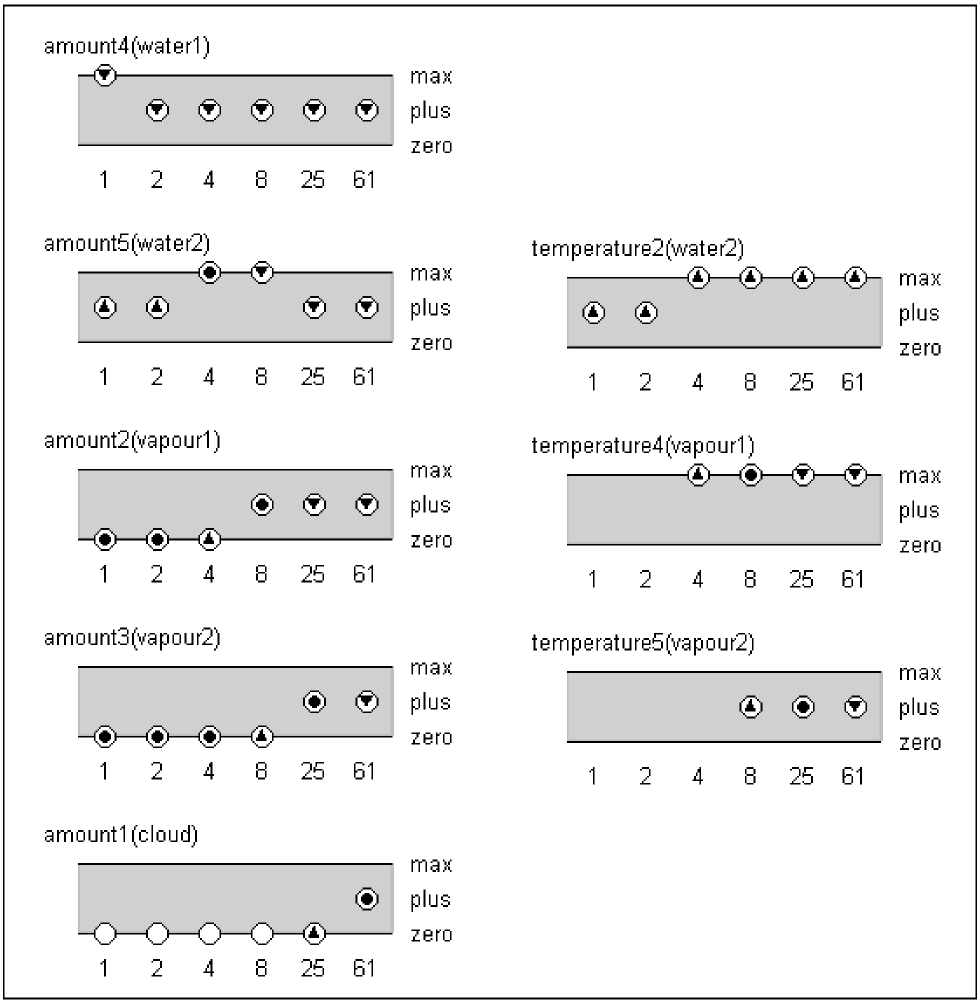

Figure 7.7. State transition graph in Model 1.

Generally speaking, the simulation introduces ambiguous behaviour on the basis of unspecified or unknown values for quantities. It therefore assumes multiple values for the quantities. This forms a drawback in the sense that the not all simulation results are as intended given the model as it is constructed. The simulation model produces redundant instantiation of new quantities of the same type and function, each for a different value of one or more conditional quantities in a model fragment. Although this is a well-known effect of the definition of the model as it is, the ambiguity should be reduced to that which is implied purely by the knowledge in the model and leaving out the ambiguity that is generated by undesirable interpretations by the algorithm.

However, all resulting states are *valid* descriptions of possible behaviour as can be anticipated from the manner in which the system is modelled. The model doesn't assume values for quantities that are not appropriate, which would result in erroneous behaviour. For example in figure 7.7, the overall amount of substances never increases or decreases, there is always an opposite direction of change in one of the quantities amount (except state 61, termination-state in this simulation). The model can be qualified as being constructed with the purpose to reason about the behaviour of a water cycle in a very superficial and abstract way. The model is constructed focusing on the *occurrence* and *sequence* of certain processes, leaving their exact *functioning* implicit, so as their interdependencies with other processes.

7.3 Simulating Model 2

Currently the simulation model that is used only reasons about liquid flows, heat exchange, evaporation and vertical movement in the atmosphere. The processes condensation and precipitation have been discussed but are not included in the simulation discussed here. The process of transportation is not included in the model. The simulation model takes as input a scenario of the water cycle in which the structures *sun, seawater*, *assembly pressure area* and *assembly atmosphere* are active. The sun and sea engage in a process of heat flow because the temperature of hydrogen is greater than that the temperature of the sea water. All four other possible heat flows are assumed to be non-existent, their values being equal to each other. Also the movement of the pressure area is assumed to be steady, with the pressure of both assemblies being equal. The scenario is depicted in figure 7.8.

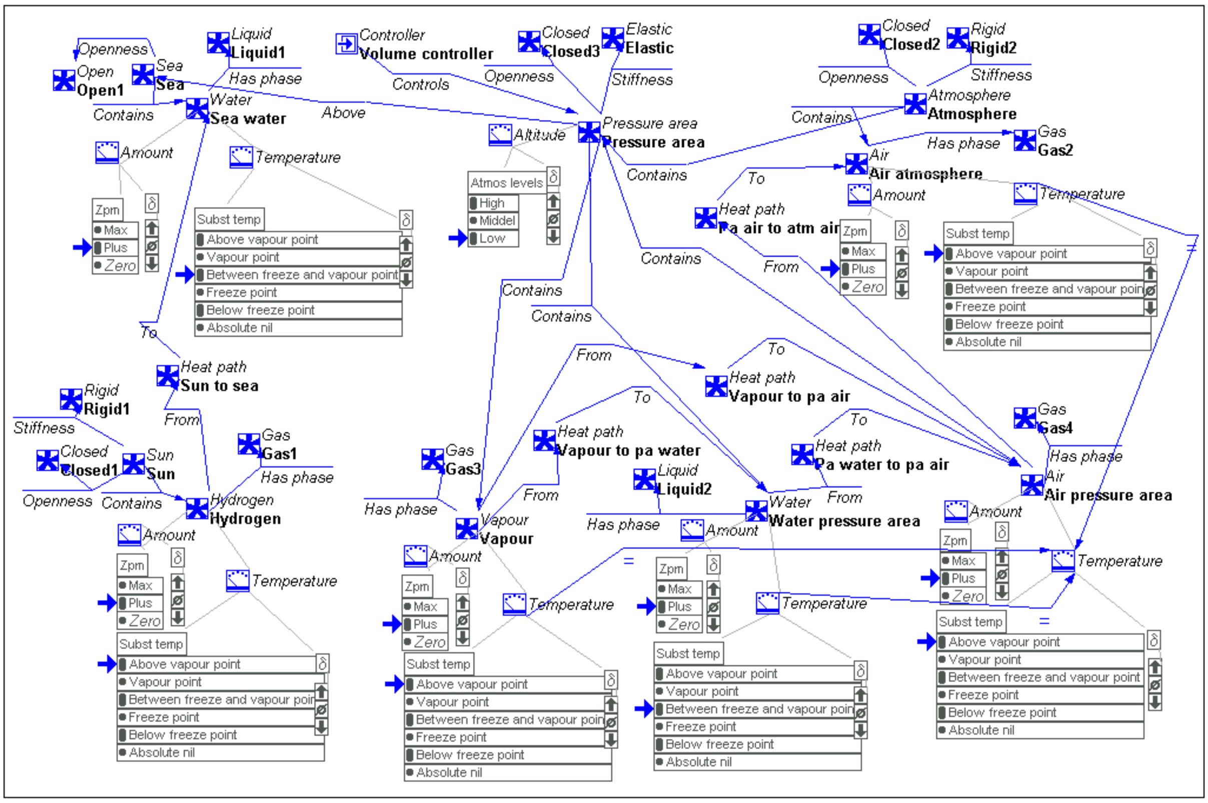

Figure. 7.8. Scenario for water cycle model 2.

In fact the simulation starts with three possible initial states from the input, because it assumes all three possibilities with respect to the temperature difference between seawater and hydrogen: *smaller*, *equal* and *greater*. The remaining four heat flow processes between substances are also active, be it that the heat flow is steady (zero). The simulator finds the process of evaporation in the next annotated state after state "1". In the same state the process of "pressure area movement" changes from steady to rising. This is the effect of the inequality between air pressure area and air atmosphere, which is caused by the increase of amount of vapour. Recall that the overall pressure of the pressure area assembly is affected by this influence. The causal model associated with this behaviour is shown in figure 7.10. There are two processes active between the pressure area and the atmosphere, a energy exchange as a consequence of an inequality in temperature of air and a vertical movement on the basis of a difference in pressure of air. When the process of evaporation increases the amount of vapour in the air, the systems energy balance start to change: the substances contained in the pressure area all exchange heat with each other and their net result forms the joint influences on the quantity pressure of the pressure area. The successive states in the simulation are all characterised by the exchange of energy between substances and the movement of the pressure area as its consequence. After seven subsequent states the pressure area reaches the altitude *high*. In figure 7.9, a value history diagram is depicted that shows the behaviour of several quantities of interest. The value history shows that the amount of water decreases in favour of the amount of vapour. The temperature of vapour changes through continuous energy exchange with other substances. The movement of the pressure area corresponds to flow rate 1, thus the processes of heat flow and movement are always changing in the same direction. The altitude has a single influence from the quantity movement and increases in the course of the simulation. The flow rates depicted in the figure show the effect of the incoming vapour and the resulting energy exchanges.

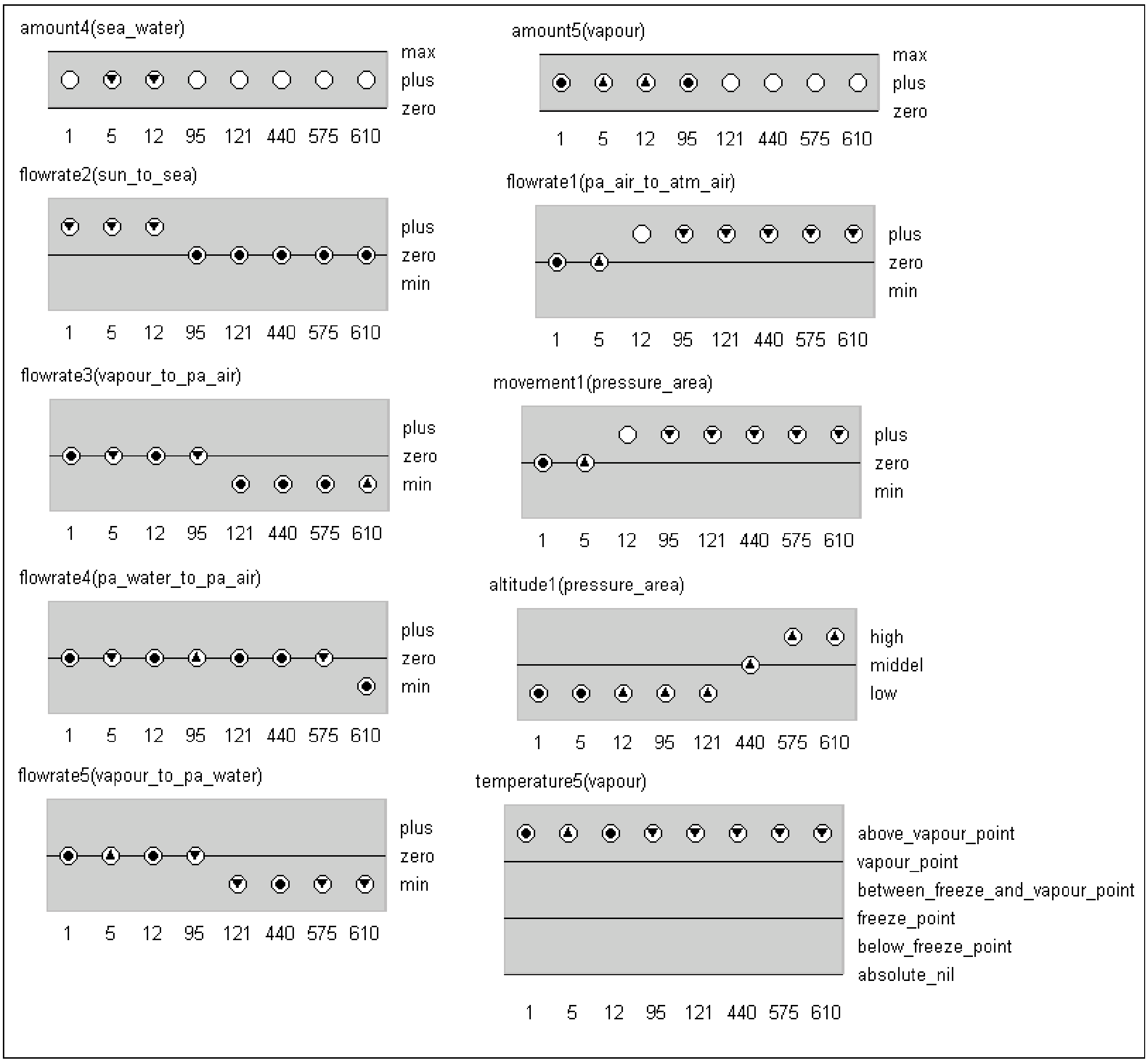

Figure 7.9. Value history diagram

Model 2 of the water cycle is much more specific in terms of dependencies between quantities throughout the whole system. It is also accurate in the prediction of possible qualitative values and derivatives for all quantities of interest in subsequent states. This is the result of well-defined interdependencies between processes and these processes being generic at the same time. In the model, quite a few entities in the model have shared quantities, so that changes in such shared quantities propagate throughout big parts of the system. An example of this propagation is the behaviour associated with contained gasses in a pressure area. Here, three different gasses share one quantity pressure. Figure 7.10 shows the causal model in state 5 of the simulation, in which the active influences between the entities are depicted.

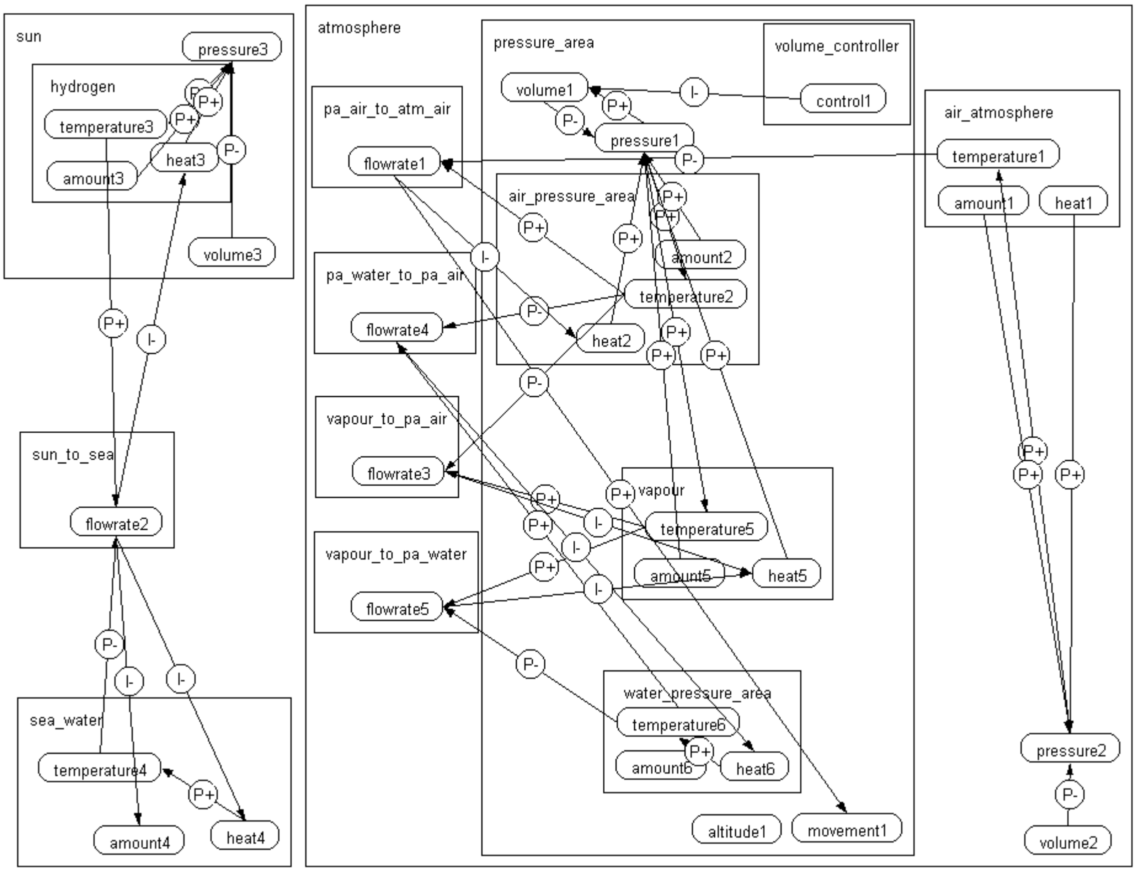

Figure 7.10. Causal model of state "5", generated using VisiGarp.

The generic model fragment "heat flow" is always active between substances that are connected by a heat path, thus resulting in a complex causal model of the energy exchange between the substances. When a difference in temperature can be assumed by the simulation, either the subtypes "heat flow positive" "no flow"or "heat flow negative" become active

When the process of heat flow occurs between any two substances, the amount of possible qualitative states as a result becomes large and increases throughout subsequent states. The point can be illustrated by examining the derivatives of the quantities 'flow rate' that belong to the five heat paths that are defined between the substances and shown in figure 7.11 In state 1, the flow rate *sun to sea* influences the temperature of the water. The same flow rate is also mentioned in the model fragment "Evaporation" where it has an influence on the derivative of the quantity heat. Through the defined dependencies for a closed contained gas, the influence propagates to the derivative of the flow rate. The quantity temperature also propagates this influence to the flow rates of the other heat paths it is connected to.

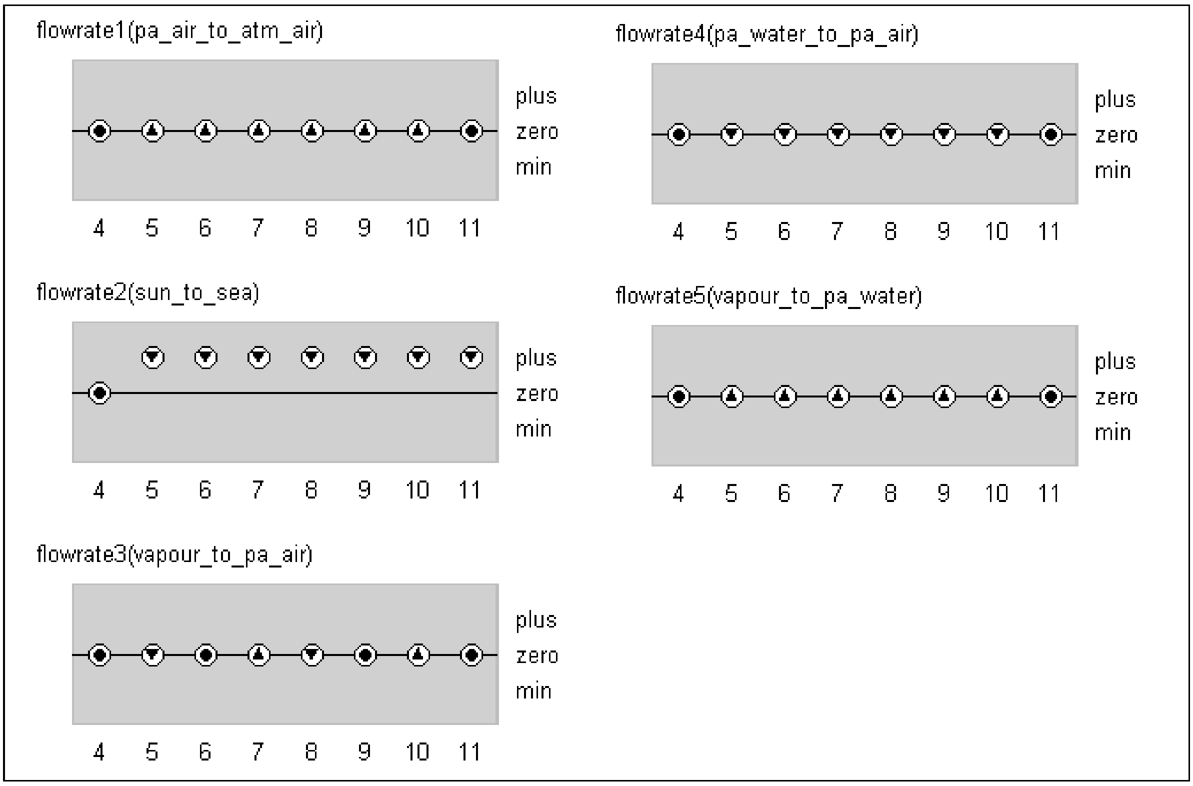

Figure 7.11. Value history for flow rates after state "1".

The qualitative ambiguity produced here is disputable in the sense that the simulator infers new behaviour of a more global system scope, as a consequence of a change that is modelled with local scope. Apart from the validity of this behaviour, the reason for it to occur in the model lies in the high generalisation in the models of the processes. With such a high level of generalisation, alterations in the model itself have far-reaching consequences for the overall behaviour in the model.

The model is thus capable of reasoning quite detailed about the processes in the water cycle that are highly interrelated per definition. The causal order of the paths in the simulation follow the intention of the model, thus not introducing illogic behaviour given the functioning of the system. The simulation however produces a highly ambiguous causal path, for the reasons that are discussed briefly above.

The model is thus currently not suitable for simulating the global and interrelated functioning of the system and keeping the amount of generated states within reasonable borders at the same time. In order to create manageable simulations, the specification of multiple modelling assumptions is an alternative. Such assumption can constrain the amount of states produced, but can exclude important behaviour.

Analysing the result of large (qualitative) simulations remains a complex task, which can interfere for example with the effectiveness of a particular teaching strategy. An improvement of this drawback is that qualitative models can be arranged to structure the knowledge into sets of smaller simulation models (clusters[3]), which can support a progressive (learning) route through the subjects of (educational) interest. Various scenarios that apply to different clusters can be defined which typically simulate just local parts of the water cycle. Although this idea of *curriculum design* has been researched earlier (White & Frederiksen 1990, Winkels & Breuker 1993), an integrated approach on these ideas specialised for qualitative models is proposed by Salles & Bredeweg (2001), by describing how to construct progressive learning routes through qualitative simulations in ecology. In the paper article they combine ideas from research mentioned above in order to define a set of dimensions on which partial models can be classified. The classification relies on the hierarchical implementation of the library of model fragments, and a set of scenario's that represents a route of increasing complexity through the knowledge contained in the library.

[3] Clusters contain model fragments of particular types, e.g. the first cluster may contain only single description views, whereas more complex clusters may contain description views composition views and process views.

8. Conclusion and discussion.

The domain of the water cycle forms a collection of physical processes that involve various components and functioning. Two models of the water cycle have been developed, each forming a qualitative ontology of the domain of the water cycle. The models vary in their ontology with respect to the interrelation and generalisation of concepts. Model 1 gives a high level view on the system and it uses model fragments that are specific for physical situations. Model 2 inhibits a more in-depth specification of dependencies that exist within the water cycle. In addition, a separate model is developed for reasoning about vertical differences on the surface and corresponding liquid flows. In terms of knowledge articulation, all models add to a multi-level representation of the water cycle. It is clear that each model focuses on various aspects and different levels of detail, and from the perspective of multiple scopes of human mental models, the qualitative models are complementary

The simulations that each model produces also reflect the different nature of the models. Model 1 results in a simulation where the *global* behaviour is simulated in a couple of successive states, but it is far from accurate and complete about the *underlying* behaviour, which results in ambiguous prediction of behaviour. The model is constructed with the purpose of generating a simulation of a particular type, namely a sequence of the processes of the water cycle, which also includes their general behaviour. The content of the model is therefore adapted to produce the type of simulation. Model 2 is more generic and complete in its description of concepts. It results in a very detailed simulation, with a high density of dependencies. The simulation illustrates the approach of building a qualitative model that focuses on a complete representation of functioning within the domain. As such the simulation has the purpose of showing how the system evolves given its represented functioning. The result is a causal representation of the complex interactions of the water cycle at each point in time. Multiple processes influence a small set of entities and the simulation predicts valid paths of behaviour. But the simulation is also highly ambiguous in its prediction of behaviour. The reason for this ambiguity is not inaccuracy or incompleteness, but in this simulation, the ambiguity is the consequence of the high density of dependencies introduced by the relations. On the one hand, single quantities have many active dependencies that result in ambiguous influences. On the other hand changes in a single quantity sometimes propagate and produce variations in the system outside the scope of the process in which the quantity participates.

The development of large-scale qualitative models confronts the developer with tradeoffs between the constraints of qualitative simulation algorithms and the correct or accurate representation of the physical situation at hand. Danger exists in making alterations in the domain knowledge contained by the model for the sake of constructing efficient and more insightful simulations. Large qualitative models are sometimes not effective in their capability of showing system behaviour by simulation, by creating complex and ambiguous causal paths. At least for large and generic models like Model 2, involving various different interrelated processes, the simulation models can be divided into pieces that simulate just parts of the system. Decomposition on the basis of a curriculum for didactic use and the use of modelling assumptions also make the simulation of such models more insightful to the observer.

Throughout this research, issues have been raised about the relation between qualitative models and their purpose in educational contexts. Whereas research has shown that there exist reasons to assume that the use of qualitative models and simulations has important connections to human reasoning, there is no sound evidence that the approach facilitates knowledge acquisition per se. From a didactic perspective, the research on teaching and human learning offers knowledge about styles and methods of knowledge communication and knowledge acquisition. Much of this knowledge is still to be researched with respect to implementation in automated teaching devices. The models in this research are aimed at communicating conceptual and causal knowledge of an ecological domain. They form a basis from which a curriculum may be produced that is able to guide learners through the domain of the water cycle while successively addressing deeper levels and higher complexity. Given an explicit definition of the didactic purpose that should be covered by the qualitative models, an appropriate means of interacting with the knowledge contained by the models needs to be developed. Such an interaction can for example take the form of constructivism, where subjects engage in a process of knowledge articulation and learning by doing.

The qualitative models here form a multi-level knowledge representation that can be expanded with additional A.I. techniques in order to engage in teaching activities. Examples of these techniques are (automatic) question generation and explanation generation. Another role of the discussed models in this context is that they can serve as norm models in support of learners model building activities. Feedback and questions should be generated on the basis of comparison of models to the norm model.

The future scope of the current work lies in the integration of qualitative water cycle models from different perspectives into simulation models, using multiple scenarios for each perspective on the system. Specific knowledge in terms of curriculum design for the domain of the water cycle can help classifying the knowledge into educationally relevant knowledge chunks or dimensions. The resulting classification can be mapped to scenarios with explicit didactic purposes. The possibility of integrating multiple levels of analysis and exploring different causal paths of physical systems is what makes qualitative models promising with respect to *knowledge communication*. The possibility of using these models in an automated environment that is able to support didactic methods by including specific types of interaction (e.g. curriculum planning, automated feedback, explanation) makes the use of qualitative models promising with respect to *instruction*.

In order to assess the facilitating effect on learning of interaction with qualitative models, various types of evaluation can be conducted. These evaluations are usually aimed at investigating the type of interaction with qualitative models and relate this to subsequent increase of knowledge of learners. Such an evaluation would be appropriate when additional aspects are included in the qualitative models and simulations, such as subject matter sequencing and providing feedback and explanation to the learners. Purely concentrating on qualitative model building and simulations, performed by either domain experts or learners, a logic next step is to integrate model building environments with (visual) simulation (inspection) tools. The testing of models and therefore also the development cycle of qualitative models for simulation purposes can be supported to a better extent. A benchmark in which both models can be defined and simulated, for example should allow to document, compare, and edit different versions of models and their simulation histories in an integrated manner.

9. Acknowledgements

This study would not exist without the intensive co-operation with Dr. Bert Bredeweg at the department of Social Science Informatics of the University of Amsterdam. His ideas and contribution in modelling activities have been of great support to this work. Furthermore the exchange of ideas and co-operation with Barbara Dubbeldam, Maarten van Hoof, Roland Groen, and Anders Bouwer were of great value.

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