Appendix A: Qualitative Reasoning Vocabulary

Learning about qualitative reasoning requires the acquisition of a certain vocabulary. This appendix provides a short definition for each item in the vocabulary and can be used as a reference. An overview of the available modelling ingredients is shown in Figure A.1.

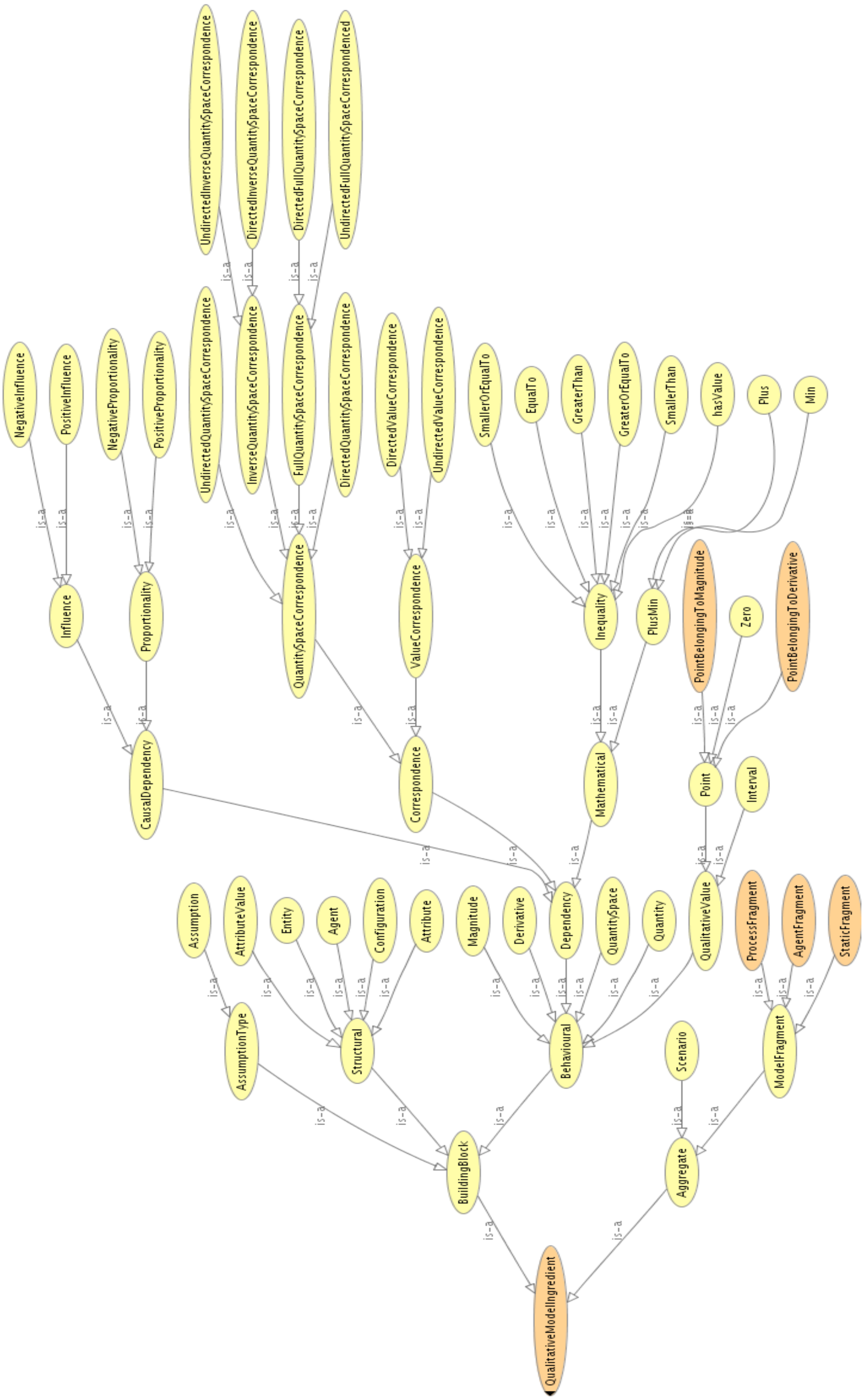

Figure A.1: QR modelling ingredients hierarchy

A.1: The notion of Model

A central concept to Qualitative Reasoning and Modelling is the 'model': A model is an abstract representation of a system that enables users to make testable predictions about what happens to a system in different situations.

A.2: Structural Building Blocks

Structural modelling ingredients describe the organisation of the concepts within a system and the static features of those concepts.

A.2.1 Entities

Entities are the physical objects or abstract concepts that play a role within the system. These entities are arranged in a subtype hierarchy.

Examples:
- An Animal is an Entity
- A Vertebrate is an Animal
- A Mammal is a Vertebrate
- A Zebra is a Mammal

Remarks:
The organisation of entities in a subtype hierarchy allows more general entities higher in the hierarchy to be used in model fragments instead of more specific entities below them. This allows for more efficient modelling, as there is no need to - for example - create a model fragment describing flow for every occurrence of an entity. Instead, just one model fragment is needed to describe the characteristics of the whole class.

A.2.2 Configurations

Configurations are used to model relations between instances of entities and agents; they are sometimes referred to as structural relations.

Examples:
- Lion preys on Zebra.
- Container contains Water.
- Container is connected to Tube.

Remarks:
Entities and agents cannot exist within a model fragment without a configuration connecting them; they have to be structurally related.

A.2.3 Attributes

Attributes are properties of entities that remain static during simulation (i.e. do not change). They have an associated set of attribute values, which are the possible values of the attributes.

Examples:
- The colour of the animal is black.
- The openness attribute of a pan filled with boiling water can be either open or closed.
- The status of a lock can be either unlocked of locked.
- The status of a device can be turned on or turned off.

Remarks:
Attributes are often used as conditions in model fragments to indicate that a specific process is only active when certain attributes have certain values.

A.2.4 Agents

Agents are used to model entities outside of the modelled system. Agents can have quantities influencing the rest of the system, which are sometimes called exogenous or external influences.

Examples:
- James fishing in a pond, decreasing the number of fish within that ecosystem.
- John filling one of the tubes in the communicating vessels system
- A manager setting a Brazilian Cerrado forest on fire.

A.2.5 Assumptions

Assumptions are labels that are used to indicate that certain conditions are presumed to be true. They are often used to constrain the possible behaviour of a model. Because they describe neither structural nor behavioural aspects of a system, they belong to neither the structural building blocks nor the behavioural building blocks categories.

Examples:
- The height of water in each of the fluid containers in the communicating vessels system is greater than zero.
- The populations within an ecological system are closed (no migration).
- Adhesion and cohesion are assumed to have no effect on the height of a fluid in a container.

Remarks:
Assumptions can only be used as a condition and are often combined with an inequality relation as a consequence.

A.3: Behavioural Building Blocks: Features

The behavioural modelling ingredients are further distinguished into features and dependencies. The behavioural features describe the variable aspects of entities of a system.

A.3.1 Quantities

Quantities represent changeable features of entities and agents. Each quantity has two associated quantity spaces: a definable one for the magnitude, and the default quantity space {Min, Zero, Plus} for the derivative of the quantity.

Examples:
- A contained liquid has the quantities of: volume, height and pressure.
- The temperature of an object.
- The size of a population.

A.3.2 Magnitude

The magnitude indicates the current value of a quantity.

Example:
- The magnitude of the temperature of the water is its boiling-point.

A.3.3 Derivative

The derivative indicates the current value of the first derivative of a quantity, and indicates whether the magnitude is increasing, decreasing or stable.

Example:

- The derivative of the temperature of the water is steady.

A.3.4 Quantity Spaces

A quantity space specifies a range of qualitative values a quantity magnitude or derivative can have. The qualitative values in a quantity space form a total order. Each qualitative value is either a point or an interval, and within the quantity spaces these two types consecutively alternate.

Examples:

- The quantity space for the height of contained liquid is {zero, positive, full}.
- The quantity space for the temperature of a material could be: {absolute zero, solid phase, freezing point, liquid phase, boiling point, gas phase}.
- The quantity space for the size of a population could be: {zero, positive} if there is no maximum size for a population. Otherwise, {zero, positive, maximum} could be used.

A.3.5 Qualitative Value

A qualitative value is either a point or interval that can become the current magnitude or current derivative of a quantity. Qualitative values are contained by quantity spaces.

Examples:

- Zero, minimum, negative, positive, high, full, maximum, medium.

Remarks:

Qualitative values having the same name do not necessarily represent the same value. For example, two contained liquids with their height quantities equal to the value positive do not necessarily have the same height, as one could be smaller than the other. The one exception is the value zero, which specifies the turning point between positive and negative. Zero is universally equal among quantity spaces.

A.3.6 Current Value and Quantity Value

The current value refers to either the value of the magnitude or the value of the derivative of a quantity in a specific situation. The quantity value is the combination of the current value of the magnitude and the current value of the derivative of a quantity. Quantity values are often written down as: <magnitude, derivative>.

Examples:

- <full, decreasing>
- <zero, stable>
- <positive, increasing>

Remarks:

The changes in quantity values are visualised in the value history.

A.4: Behavioural Building Blocks: Causal Dependencies

Behavioural dependencies describe relations between behavioural features. There are three kinds of dependencies: causal dependencies, mathematical dependencies and correspondences. Causal dependencies are used to model how processes induce changes, either directly or indirectly. These dependencies are represented as influences and proportionalities.

A.4.1 Influences

Influences are directed relations between two quantities, and are either positive or negative. Influences are the cause of change within a model, and are therefore said to model processes. Depending on the magnitude of the source quantity and the type of influence, the derivative of the target quantity either increases or decreases. An influence I+(Q2,Q1) causes the quantity Q2 to increase if Q1 is positive, decrease if it is negative, and remain stable when it is zero (assuming there are no other causal dependencies on Q2). For an influence I- this is just the opposite. Influences are also referred to as direct influences.

Examples:

- I+(Size, Natality) – Population *Size* increases if population *Natality* is above zero, decreases if it is below zero, and remains stable if it is zero.
- I-(Size, Mortality) – Population *Size* decreases if population *Mortality* is above zero, increases if it is below zero, and remains stable if it is zero.
- I+(Height, Growth rate) – Plant *Height* increases if plant *Growth rate* is above zero, decreases if it is below zero, and remains stable if it is zero.

Remarks:
Influences should be used when the following relation has to be modelled: 'If the source quantity has a non-zero value, the target quantity will change'.

A.4.2 Proportionalities

Proportionalities are directed relations between two quantities. They propagate the effects of a process, (i.e. they set the derivative of the target quantity depending on the derivative of the source quantity). For this reason, they are also referred to as indirect influences. Like influences, proportionalities are either positive or negative. A proportionality P+(Q2,Q1) causes Q2 to increase if Q1 increases, decrease if Q1 decreases, and remain stable if Q1 remains stable (given that there are no other causal influences on Q2). For a proportionality P- the opposite applies.

Examples:

- P+(Height,Amount) – Fluid *Height* increases if fluid *Amount* increases, decreases if fluid *Amount* decreases, and remains stable if fluid *Amount* remains stable.
- P-(Height,Width) – Fluid *Height* decreases if container *Width* increases, increases if container *Width* decreases, and remains stable if container *Width* remains stable.
- P+(Birth,Size) – Population *Birth* increases if population *Size* increases, decreases if population *Size* decreases, and remains stable if population *Size* remains stable.)

Remarks:
Proportionalities should be used when the following relation has to be modelled: If the source quantity changes, the target quantity will change too.

A.5: Behavioural Building Blocks: Mathematical Dependencies

Mathematical dependencies describe relations between behavioural features.

A.5.1 In/equalitities

In/equalities (<,≤,=,≥,>) specify an ordinal relation between two items, (i.e. that one item is different from, or equal to, the other item). Because inequalities specify an order between items, they are sometimes referred to as ordinal relations. There are eleven ways to use inequalities, depending on the type of the two items related by it. Table 1 shows the possible inequalities between magnitude items, while Table 2 shows them for derivative items. Note that the type of an inequality from A to B is considered the same type (i.e. has the same number) as an inequality from B to A.

1. From a magnitude to another magnitude.
2. From a point belonging to the quantity space of a magnitude, to a point belonging to the quantity space of another magnitude.
3. From a plus/min relation between magnitude items, to another plus/min relation between magnitude items.
4. From a magnitude to a point belonging to the quantity space of a magnitude. The reverse is impossible.
5. Between a magnitude and a plus/min relation between magnitude items.
6. Between a point belonging to the quantity space of a magnitude and a plus/min relation between magnitude items.
7. From a derivative to another derivative.
8. Between a plus/min relation between derivative items and another plus/min relation between derivative items.
9. From a derivative to a point belonging the quantity space of a derivative (i.e. zero). Note that the reverse is impossible.
10. Between a derivative and a plus/min relation between derivative items.
11. Between a point belonging to the quantity space of a derivative (i.e. zero) and a plus/min relation between derivative items.

Table 1: The possible inequalities between magnitude items

To From	Magnitude	Point (Magnitude)	Plus/Min (Magnitude)
Magnitude	1	4	5
Point (Magnitude)	Impossible	2	6
Plus/Min (Magnitude)	5	6	3

Table 2: The possible inequalities between derivative items

To From	Derivative	Point (Derivative)	Plus/Min (Derivative)
Derivative	7	9	10
Point (Derivative)	Impossible	Impossible	11
Plus/Min (Derivative)	10	11	8

Examples:

1. The magnitude of the number of predators is greater than the magnitude of the number of prey.
2. The value max of the height of the water container is equal to the value max of the height of the other water container.
3. The magnitude of the population natality minus the magnitude of the population natality is smaller than the difference between the magnitude of immigration and emigration.
4. The magnitude of the amount of fluid in the container is greater than zero.
5. The difference between the pressure in the left water container and the pressure in the right water container is equal to the flow.
6. *No example given*.
7. *No example given*.
8. *No example given*.
9. *No example given*.
10. *No example given*.
11. *No example given*.

A.5.2 Plus/Min relations

Using plus/min relations more complex expressions can be created than is possible with only inequalities. They are used to calculate the sum of difference between two items. Plus/min relations can be the target or source of an inequality relation. There are nine different ways plus/min relations can be used, depending on the type of the two items related by it. Table 3 shows the possible uses of plus/min relations between magnitude items, while Table 4 shows the possibilities between derivative items. Note that the type of a plus/min relation from A to B is considered the same type (i.e. has the same number) as an inequality from B to A.

1. From a magnitude to another magnitude.
2. From a point belonging to the quantity space of a magnitude, to a point belonging to the quantity space of another magnitude.
3. From a plus/min relation between magnitude items, to another plus/min relation between magnitude items.
4. From a magnitude to a point belonging to the quantity space of a magnitude.
5. Between a magnitude and a plus/min relation between magnitude items.
6. Between a point belonging to the quantity space of a magnitude and a plus/min relation between magnitude items.
7. From a derivative to another derivative.
8. Between a plus/min relation between derivative items and another plus/min relation between derivative items.
9. Between a derivative and a plus/min relation between derivative items.

Table 3: The possible plus/min relations between magnitude items

To From	Magnitude	Point (Magnitude)	Plus/Min (Magnitude)
Magnitude	1	4	5
Point (Magnitude)	4	2	6
Plus/Min (Magnitude)	5	6	3

Table 4: The possible plus/min relations between derivative items

To From	Derivative	Point (Derivative)	Plus/Min (Derivative)
Derivative	7	Impossible	9
Point (Derivative)	Impossible	Impossible	Impossible
Plus/Min (Derivative)	9	Impossible	8

Examples:

1. The magnitude of the predation of the hunters is equal to their food need minus the amount of prey.
2. *No example given*.
3. The sum of birth and immigration minus the sum of death and immigration is equal to the magnitude of population growth.
4. *No example given*.
5. The intensity of the light plus the concentration of carbon dioxide plus the surface area of the leaves is equal to the rate of photosynthesis.
6. *No example given*.
7. *No example given*.
8. *No example given*.
9. *No example given*.

A.6: Behavioural Building Blocks: Correspondences

Correspondences are used to indicate that qualitative values of different quantity spaces occur at the same time.

A.6.1 Value Correspondences

Value Correspondences are relations between qualitative values of quantity spaces belonging to different quantities, and can be either directed or undirected. Directed means that when value A of quantity space X corresponds to value B of quantity space Y, the simulator derives that quantity space Y has value B when quantity space X has value A. If the correspondence is undirected, it also derives the value A of quantity space X when quantity space Y has value B.

A.6.2 Quantity Space Correspondences

Quantity Space Correspondences exist between two quantity spaces, indicating that each of the values of the quantity spaces of those quantities correspond to each other. Like value correspondences these can also be either directed or undirected.

A.6.3 Inverse Quantity Space Correspondences

Quantity space correspondences can also be inversed, indicating that the first value of the first quantity space corresponds to the last value of the second quantity space; the second value corresponds to the penultimate value, etc. Inverse correspondences can also be either directed or undirected.

A.6.4 Full Quantity Space Correspondences

Full Quantity Space Correspondences indicate that there is both a quantity space correspondence between the quantity spaces of the magnitudes, as well as a quantity space correspondence between the quantity spaces of the derivatives. Full correspondences can be either directed or undirected.

A.7: Aggregates

There are two kinds of aggregates, namely model fragments and scenarios. Aggregates are complex model constituents, as they consist of multiple model ingredients.

A.7.1 Model Fragments

Model fragments describe part of the structure and behaviour of a system in a general way. They are partial models which are composed of multiple ingredients. Model fragments have the form of a rule. This means that model ingredients are incorporated as either conditions or consequences. Table 3 shows the abilities of ingredients to be used as a condition or consequence. As can be seen from the table, model fragments themselves can be reused within other model fragments as conditions. Furthermore, sub-classes of model fragments can be made, which augment the parent model fragment with new ingredients. The consequence ingredients of model fragments that match on the actual system situation, will be added to the scenario. In that case, the scenario fulfils the conditions specified in the model fragment (which describes a general situation). There are three different kinds of model fragments: static fragments, process fragments, and agent fragments.

Condition

The conditions in a model fragment indicate what things should be true within a scenario (or state) in order for the consequences to be true. The model ingredients that can be used as conditions within a model fragment are shown in Table 5.

Table 5: Condition and consequence abilities of QRM ingredients

Possible conditions	**Impossible conditions**
Entities Configurations Agents Attributes Quantities Inequalities Min/Plus Assumptions Model Fragments	Correspondences Proportionalities Influences
Possible consequences	**Impossible consequences**
Entities (except in static MF) Configurations (except in static MF) Attributes Quantities Inequalities Min/Plus Correspondences Proportionalities Influences	Agents Assumptions Model Fragments

Consequence

Consequences within a model fragment capture the information that is added to a scenario when the conditions of the model fragment are fulfilled. The model ingredients that can be used as consequences within a model fragment are shown in Table 5.

Model Fragment Types

Static Fragments

In static fragments all ingredients may occur except agents and influences. Static fragments are used to describe parts of the structure of the system, and the proportionalities that exist between the quantities.

Process Fragments

Process fragments contain at least one influence, but no agents. These model fragments are used to describe processes that take place within the system.

Agent Fragments

Agent fragments contain an agent and may contain one or more influences. Agent fragments are used to describe the influences agents (exogenous entities) have on the system.

A.7.2 Scenarios

Scenarios describe the actual state of a system, and can consist of all the ingredients that can be used as conditions in model fragments, except for other model fragments (see table 1). The use of ingredients in scenarios differs from their use in model fragments, as in scenarios ingredients are incorporated as facts instead of as conditions or consequences. Obviously, this allows model fragments to match with scenarios. Scenarios are used as input for the qualitative simulator and function as the starting state from which the rest of the behavioural graphs are generated.

A.7.3 Identity

Identity relations are used to specify that two model ingredients in different imported model fragments are the same. There are two possible applications. Firstly, they can be used to indicate that two entities in different imported model fragments are actually the same one. Secondly, they can be used to specialise entities in child model fragments. For example, the fish entity in a parent model fragment can be specialised to a salmon entity in the child model fragment.

A.8: Simulation Vocabulary

A.8.1 Simulation

The word simulation is ambiguous, as it is used to refer to two things. Firstly, it is used as a synonym for the output generated by the qualitative simulator in the simulation environment. Secondly, it is used to designate the process of qualitative reasoning itself, which is used to generate the simulation output. The simulation environment in the Garp3 software provides control to the reasoning process to be able to follow each step of the simulation, therefore distinguishing the concepts of full simulation, which refers to the complete simulation with the resulting state-graph, from that of partial simulation, which is an incomplete simulation and state-graph.

A.8.2 Simulation Output

Simulation output refers to the state-graph generated by the qualitative reasoning engine as a result of simulating a qualitative model by providing a scenario as input.

A.8.3 The notion of State

State

A state describes a particular situation of a modelled system. A state contains information about the structural organisation, the current values of quantities, inequalities, and the active model fragments. A state can be interpreted, terminated, ordered, or closed.

Interpreted State

An interpreted state is either a scenario, or a new state generated during the closing of a state, and all the applicable model fragments.

Terminated State

A state is referred to as terminated if all the possible ways a state can end, due to changes of magnitudes of derivatives of quantities, are identified.

Ordered State

A state is referred to as ordered, when transitions overruled by other transitions with higher priority have been pruned, and terminations that occur simultaneously due to correspondences have been merged.

Closed State

A state is referred to as closed when the successive states and transitions are generated from its pruned and merged terminations.

A.8.4 The notion of State-graph and Behaviour

Behaviour

Within the context of qualitative reasoning and modelling the behaviour of a system refers to the changes of quantity values (and in/equality statements) as the result of processes that are active within the modelled system.

Transition

A transition describes the change between two different states. The transition information describes the transition conditions that are fulfilled by the source state, and the results of the change (i.e. the next state).

State-graph

A state-graph is a set of states, and the possible transitions between those states, which represents the behaviour of modelled system. State-graphs are generated by simulating a qualitative model.

Behaviour-graph

See state-graph.

Behaviour Path

A behaviour path is a sequence of successive states within a state-graph. The path describes the evolution of the quantity values and ordinal relations as time progresses.

A.8.5 The notion of History

Value History

The value history describes how quantity values change through a sequence of states (usually a behaviour path).

Transition History

The transition history shows the transitions that cause the changes from one state to the other for a sequence of states.

Equation History

The equation history describes how the ordinal relations change through a sequence of states (usually a behaviour path).

A.9: Inequalities and Values as Conditions or Consequences

A.9.1 Value Assignment

Values are abbreviations for inequalities between a quantity, or a derivative, and qualitative values in its quantity space. The qualitative simulator converts these values to (possibly multiple) inequality relations. For example, a magnitude set to an interval between two points using a value is mapped to the inequality relations smaller than (with respect to the higher point), and small than (with respect to the lower point). A value assignment to a point is equivalent to an equality relation to that point.

Remarks:
When value assignments (and/or inequalities) are used as a condition, and the value (and/or inequality) cannot be derived, the reasoning engine tries to assume the value (and/or inequality). If the resulting state is not inconsistent, it will appear in the state-graph. Value assignments (and/or in/equalities) as consequences should be used conservatively, because if two model fragments with opposing consequence value assignments (and/or in/equalities) become active, the resulting state is inconsistent and will be removed. It is good practice to only use these types of ingredients in combination with an assumption.