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Using exogenous quantities in qualitative models about environmental sustainability

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Abstract. Representing the impact of external factors on the behaviour of a system is a challenge for modellers, particularly when these factors are dynamic and may change during the simulation. This article presents mechanisms implemented in the qualitative reasoning engine Garp3 for modelling quantities that exhibit exogenously defined behaviours. Exogenous quantities are those that influence the system but are not influenced by quantities represented in the system. Seven types of mechanisms for handling exogenous quantities are implemented: "constant", "generate all values", "increasing", "decreasing", "steady", "sinusoidal", and "random". Examples drawn from models of environmental sustainability (related to Millennium Development Goal 7) are used to illustrate the functioning of these primitives. Individually or combined, the mechanisms provide many options for modellers to represent cycles, oscillations, and regions of local stability.

Keywords: Exogenous quantities, qualitative reasoning and modelling (QRM), ecological informatics

1. Introduction

Defining the boundaries of a system is an important step in modelling. This definition is influenced by the goals and intended uses of the model. Often a system is influenced by exogenous factors – those that affect the behaviour of the system but which are not affected by the system behaviour [5,9]. Exogenous factors are thus outside the system boundary, but need to be considered in the model. For instance solar radiation is an influential factor on ecological systems but we usually do not include a description of how such radiation is produced in an ecological model.

There is a need for modelling environments that allow inclusion of such factors without changing the system structure in order to explain such non-focal details. Considering previous work on building qualitative models in ecology [11], we identified requirements for a modelling environment that would provide good support for qualitative ecological modelling. Such modelling environments should allow for exogenously influenced behaviour to appear either within or at the beginning of the causal chain. In other words, they should be useful to either constrain behaviours to conform to some "given" behaviour or to initiate change in a system. Furthermore, given the large number of influences normally important in ecological systems, when using a compositional modelling approach [3], it would be convenient to have a set of behaviour patterns (e.g., oscillating, constant, increasing) that could be applied to a quantity so that the propagation of that behaviour through a causal chain could be understood before simulating a model composed of multiple processes and causal chains. Such a feature would facilitate the modelling of pieces of domain knowledge, reserving the details of composing them together for later.

This article discusses a new functionality implemented in the qualitative reasoning (QR) engine Garp3 (http://hcs.science.uva.nl/QRM/) [1] that allows for the integration of external influences by assigning specific behaviour patterns to quantities, the exogenous quantities. We explore the use of exogenous quantities in the context of environmental sustainability, as de-

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fined by Millennium Development Goal 7 [6]. Implemented models involving indicators related to MDG7 are described to illustrate how Garp3 handles externally defined behaviours. These models aim at supporting communication with stakeholders about sustainability issues. This is a good test bed for modelling exogenous quantities, because sustainability requires the combination of a number of influences and complex interactions among quantities to be represented in the models. By treating some processes exogenously, we can reduce the complexity of the modelled system to facilitate communication about a given process, without considering the full complexity of its implementation in a "full" model of the system.

2. Including external factors

In a qualitative model, values of entities that are relevant to the model are expressed using quantities, whose values represent possible qualitative states the quantity may assume within the scope of the model. For example an entity climate may be characterised by the quantity rainfall. As we are interested in dynamic aspects of systems, the qualitative value of a quantity is actually a tupple of two values: $< magnitude, derivative >$, representing amount and direction of change, respectively. Possible values of a quantity are presented in a Quantity Space (QS) as a sequence of alternating points and intervals.

Exogenous quantities can be simulated in Garp3 by selecting the option within a scenario to automatically generate magnitudes and derivates for a given quantity. The following options exist:

– Magnitude: Generate all values
– Derivative: Increase, Steady, Decrease, Sinusoidal, Random
– Magnitudes and/or Derivative: Constant

To further illustrate the behaviour of these exogenous quantities, we use a simple model consisting of only one quantity rainfall. We assign rainfall the QS {below, average, above}, where average is a point value, below is an interval less than average, and above is an interval greater than average. Typical examples are shown in Table 1 and discussed below. The first column of the table introduces a unique identifier that is used in the text below. The magnitude and derivate columns show the initial settings in the scenario. The state graph column shows the behaviour of the model after a full simulation. The numbered circles refer to qualitatively distinct states of the system behaviour: each state is a unique combination of qualitative magnitudes, derivatives and (in)equality statements for all modelled quantities. The single circle without a number in each state graph depicts the scenario, which specifies the starting conditions of the simulation. Arising from the scenario is a set of states, indicated by grey lines leading to numbered circles. If the causal structure of the model indicates that a transition to another qualitatively distinct state is possible, new states are generated and an arrow connects the starting state to the next state. A behavioural path refers to all states connected in a chain of circles and arrows. Note that branching of behaviours is possible if more than one transition is possible from a given state. Qualitative values for the quantity rainfall are enumerated in the value history (rightmost column). Numbers in the value history refer to the number in the state graph (note that the order of states in the histories for #7 and #8 do not correspond to a particular behavioural path). For each numbered state, the small white circles designate the magnitude of rainfall. When known, the derivative corresponding to that magnitude is indicated as increasing (up arrow), decreasing (down arrow), or steady (black dot). If the value of the derivative is not known, the white circle is empty (as in #1).

2.1. Magnitude: generate all values

This option tries to generate all possible magnitudes for a quantity and can, for instance, be used to assume different values when the modeller is not sure about which solution is adequate for each possible state. Table 1 (#1) shows the state graph and value history produced when using only this facility. Thus, the initial scenario has just the quantity rainfall, without an initial magnitude or derivative defined. On the basis of this scenario the simulator generates three states, one for each value of the rainfall. Notice that this option does not set the derivatives, hence they are not shown in the value history, and no transitions between the three states are found.

The idea of "generating all values" was inspired by observing modellers creating model fragments for all possible values of a quantity. Being able to automatically generate all values for a quantity simplifies the approach of specifying all qualitative behaviours. Importantly, the algorithm used in Garp3 generates all values while obeying other constraints (e.g., a model fragment may specify that only certain values are to be considered, or that certain quantities must always correspond in value). It may thus happen that not all magnitudes are generated for a quantity when additional constraints prevent this.

2.2. *Derivative values*

The idea of automatically generating certain values for derivatives comes from observing modellers trying to specify different exogenous influences on a system, which is not supported well by traditional QR engines. Particularly, the idea of moving from equilibrium to disequilibrium caused by factors outside of the system being simulated requires new reasoning capabilities. Consider a stable ecosystem that moves to an unstable situation because new individuals start immigrating [12]. How to represent a situation in which immigration is $< 0, 0 >$ (non-existing and steady) that changes to a situation in which immigration is building up as an exogenous influence on the system? For instance: $[< 0, 0 > \rightarrow < 0, + > \rightarrow < +, + >]$. To accommodate such situations, we have developed five mechanisms to automatically derive derivative values while obeying crucial QR principles such as the "continuity"[1] and "epsilon ordering"[2] rules [2].

2.2.1. *Exogenous decrease, steady, and increase*

Take the example of "generating all values" (Table 1, #1). We now specify that rainfall is "exogenous increasing" (#2). This results in the reasoning engine trying to add a positive derivative to each of the value statements of rainfall in each state. As there is no other information in the model that conflicts with that, rainfall is increasing and transitions between the states are found, leading to the path $[1 \rightarrow 2 \rightarrow 3]$. Alternatively we can specify "exogenous decreasing" and "exogenous steady". In the case of the former, rainfall is decreasing and a path will be found from magnitude above to below: $[3 \rightarrow 2 \rightarrow 1]$. In the case of steady, all derivatives become 0, and no transitions will be found.

It is also possible to abandon the "generate all values", and start with a specific value for rainfall, while keeping the option of exogenous decreasing (#4), steady (not shown), or increasing (#3). Notice the subtle difference in the resulting state graphs. The scenario now links only to one specific initial state (to state 1 in the case of #3), and not to all possible states. In other words, the simulation produces only one initial state, but the same overall system behaviour.

[1] Magnitudes and derivatives cannot jump across values. Instead they move continuously towards adjacent values in their quantity spaces.

[2] Changes from a point (into an interval) precede changes towards a point (from an interval).

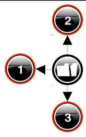
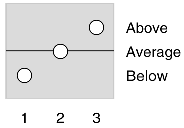
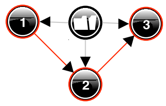
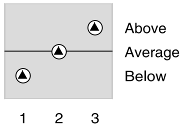
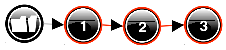
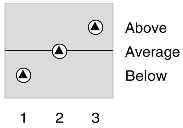
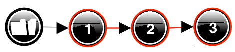
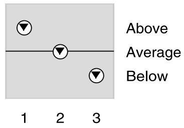
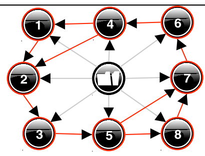
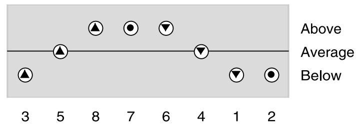
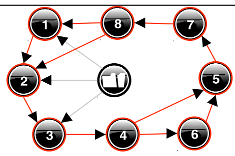
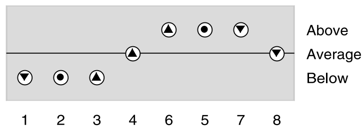
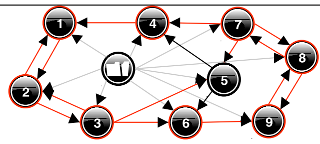
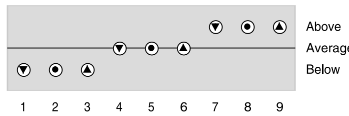
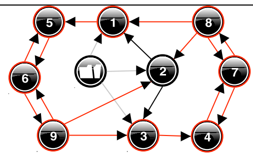
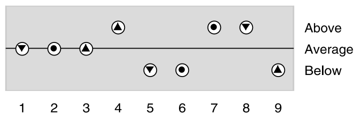
2.2.2. *Exogenous sinusoidal and random*

A very common pattern observed in ecological systems is cyclic behaviour, where the quantity regularly increases and decreases within certain bounds. This can be achieved using the option "exogenous sinusoidal". The derivative of the exogenous quantity keeps going in one direction until the maximum magnitude is reached. Then the derivative changes to zero, and starts moving in the opposite direction until the minimum magnitude is reached and the derivative value changes to zero, and starts moving in the opposite direction again, and so on. As this behaviour is repeated it results in cycles, for example, daily cycles (night and day), monthly cycles (tides) or annual cycles (daylength, precipitation). Table 1, (#5), shows a simulation in which generate all values and sinusoidal are assigned to rainfall. The main behaviour has the following sequence of states: $[1 \rightarrow 2 \rightarrow 3 \rightarrow 5 \rightarrow 8 \rightarrow 7 \rightarrow 6 \rightarrow 4 \rightarrow 1]$. In addition, state 4 can directly go to state 2 (ignoring state 1) and state 5 to state 7 (ignoring state 8). Also notice that the system behaviour does not become steady at point average. The sinusoidal continuously changes from its lowest value to its highest value, and the other way around. Stabilising at an intermediate value does not fit that idea. If we replace the "generate all values" by assigning a specific initial value, the ultimate system behaviour remains the same. However, only three initial states are now generated when starting at an interval (#6), and two when starting at a point.

Exogenous random may also produce cycles. However, instead of continuously moving towards the extreme values, random can assume any derivative value (albeit obeying continuity) and move in any direction. The idea is that some quantities may unexpectedly change direction, giving them a random behaviour. #7 presents a simulation in which rainfall is assigned the combination of "generated all values" and "random". In this simulation many behaviour paths are possible. For example, the sequence $[1 \rightarrow 2 \rightarrow 3 \rightarrow 6 \rightarrow 9 \rightarrow 8 \rightarrow 7 \rightarrow 4 \rightarrow 1]$ reflects a cyclic behaviour. Also notice that the system behaviour may oscillate within an interval, e.g., $[1 \rightarrow 2 \rightarrow 1]$, or $[3 \rightarrow 2 \rightarrow 3]$, etc. The behaviour cannot oscillate at a point, because while being at a point any change in the quantity necessarily leads to the magnitude moving to one of the adjacent intervals. Finally, notice that with "exogenous random", it is possible to become stable at an intermediate value. #8 shows a simulation in which rainfall is assigned a specific initial value, namely average, and "exogenous random". The behaviour is the same as for

Table 1

Examples of exogenous quantity behaviours in Garp3

#	Magnitude	Derivative	State graph	Value history
1	Generate all	Unknown		
2	Generate all	Increase		
3	Start at: *below*	Increase		
4	Start at: *above*	Decrease		
5	Generate all	Sinusoidal		
6	Start at: *below*	Sinusoidal		
7	Generate all	Random		
8	Start at: *average*	Random		

#7 except that from the scenario only three initial states are found.

There is a subtle issue concerning the notion of the “epsilon ordering rule” [2] and the behaviour of exogenous quantities. By using the derivatives for implementing exogenous behaviour these quantities can be treated as regular quantities during the reasoning process. This is an advantage over having a dedicated mechanism controlling all exogenous behaviour, including their value changes. However, an exception has to made for the ordering/transition inference and a specific ordering procedure is implemented for this. Firstly, combination constraints are generated for mutually exclusive terminations: a random exogenous quantity cannot start to move up and down simultaneously. Secondly, Garp3 features derivative correspondences [1]. These are used in determining combination constraints on exogenous terminations of different ex-

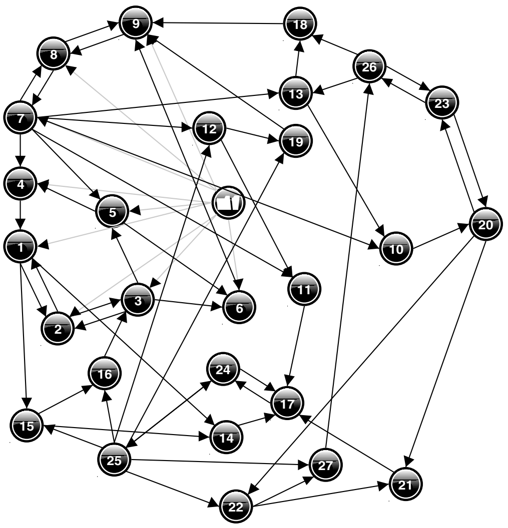


Fig. 1. State graph: "generate all values" for rainfall, "random" for soil humidity, and soil humidity proportional to rainfall.

ogenous quantities. This inference is similar to the one using value correspondences to order value terminations already implemented in Garp3. The epsilon type of the terminations that determine the derivatives of exogenous quantities is treated as non-immediate. These terminations do not have a specific reason for happening and therefore should not have precedence over others [7].

2.3. *Exogenous constant*

One of the most useful features for simplifying a simulation, or to provide different perspectives to a model, is to assign a constant value to a quantity. In Garp3, this can be done with an exogenous quantity. To illustrate this we present two simulations involving a model that consists of two quantities, rainfall and soil humidity. These two quantities are related by a qualitative proportionality, $P+(\textit{soil humidity}, \textit{rainfall})$, so that when rainfall changes, humidity changes in the same direction. Initially, let us consider that rainfall is exogenously influenced and assigned "generate all values" and "exogenous random". Soil humidity is not under external influences. A simulation starting with the following initial values: $\textit{rainfall} = <?, ?>$ and $\textit{humidity} = < wet, ? >$ is shown in Fig. 1. The simulation produces nine initial states, including all the possible combinations between the three values of each quantity. The full simulation results in 27 states, with all the combinations between the two quantities magnitudes and derivatives.

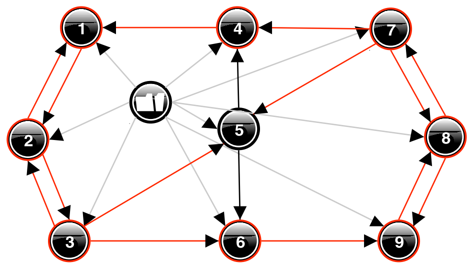


Fig. 2. Details as in Fig. 1 but now "steady" for soil humidity.

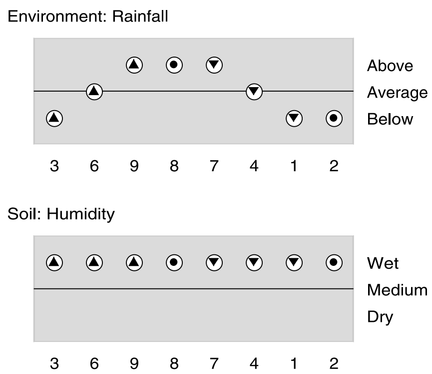


Fig. 3. Value history for the state graph shown in Fig. 2.

Consider now a simulation in which soil humidity is still exogenous but held constant at the interval Wet, while rainfall has the same conditions as in the previous simulation. The resulting state graph is shown in Fig. 2. It produces again nine initial states, but now these are the only states produced in the full simulation. In fact, only the states with the quantity with the constant value Wet are possible, as shown in the value history (Fig. 3). Having a quantity with the magnitude constant due to external influences clearly reduces the number of possible behaviours and simplifies the simulation. This function is useful if the value of a certain quantity is known and it is desired to know what other quantity values and system behaviours are consistent with that.

3. Qualitative models of sustainable development

We now discuss applications of exogenous quantities for models related to environmental sustainability. These models are related to the seventh Millennium Development Goal (MDG7), to "ensure environmental sustainability". The MDG were defined in The Millennium Declaration, signed in 2000 at the United Nations (UN), and consist of 8 goals and 18 targets on poverty, hunger, education, gender, health, environment and co-operation, to be achieved mostly until 2015. There are 48 indicators to monitor progress of countries towards achieving the goals. National governments are expected to periodically report on the situation of the MDG. Among the MDG, the MDG7 is probably the most difficult to understand and to achieve on time. In fact, most national reports published so far mentioned difficulties with MDG7 [6]. Reasons for that include conceptual problems in defining sustainability and problems to select (or create) suitable indicators to monitor MDG7 (Table 2 shows indicators proposed by the UN to monitor MDG7). Basically, for experts there are hypotheses and commonsense knowledge about environmental sustainability. In developing countries, despite the efforts of UN agencies and national governments, data about indicators of environmental sustainability often do not exist or are incomplete, based on poor-quality statistics, expressed in qualitative terms. Finally, there are problems in communication with the public: environmental issues are poorly understood and the indicators, to make things worse, are often presented as mere lists of data. Available data is left out of context and unrelated to data provided by other indicators in this format. Explanations and predictions can hardly be drawn directly from the data because causal relations are not made explicit.

In our work, we focus on building qualitative models and simulations of external influences to indicators of MDG7, pointing out the importance of Garp3's new functionality for dealing exogenous quantities. Environmental sustainability is a good domain to explore exogenous influences, because it lies at the intersection of domains such as ecology, sociology, and economics. Exogenous quantities can therefore be useful to investigate the consequences for a system whose causality is fairly well understood (e.g., pair wise ecological interactions) of behaviour in a system whose causality is poorly understood (e.g., market fluctuations). In this case, the less-well understood system can be treated as an exogenous quantity, and assumed to behave in a certain way. Furthermore, the Pressure-State-Response (PSR) framework adopted by the UN and the European Environmental Agency [13] to monitor and manage indicators and targets for the MDG is highly adaptable to the ontology provided under Qualitative Process Theory (QPT; [4]), where pressures from PSR can be considered rates in QPT and states in PSR are states in QPT (response, aimed at reducing negative undesirable pressures or states in PSR, can be modelled either as rates or influenced quantities).

Based on QPT, we use two types of relations between quantities to drive the computation of quantity values and to implement causal relations: direct influences, posed by processes, which directly add to or take away from the influenced quantities, and qualitative proportionalities (or indirect influences), which propagate changes initiated by processes in one quantity to other quantities. Direct influences, modelled by I+ and I-, mean that the influencing quantity (a rate) is used to calculate the influenced quantity's derivate value. For example, if I+(X,A) and this is the only influence on X, the derivative of X takes the value of the rate A. If rate A has a positive value, X increases. Similarly, if I-(X,B), this is the only influence on X and the rate B has a positive value, then X decreases by an amount equal to B's value.

Qualitative proportionalities are modelled by P+ and P- and establish a relation between two quantities in a way that the influenced quantity gets the same derivative sign as the influencing quantity. For instance, if P+(C,X) and this is the only influence on C, then this quantity will change in the same direction as X. Thus, if X is increasing, C will also increase. Similarly, if P-(D,X) and this is the only influence on D, then D will change in the opposite direction.

We implemented models involving the indicators of MDG7 (Table 2). They are discussed below.

3.1. Energy consumption and air pollution

This model considers how changes in the global oil market propagate to indicators of MDG7. Changes in oil market are caused by complex interactions among economic, environmental, and social factors; these interact to create cycles of shortage and abundance of petroleum. Hence, we model change in the oil market as an exogenous quantity, and its behaviour assumes generate all values and exogenous sinusoidal options. This model shows how changes in supply and demand of available energy due to market oscillations may affect the use of petroleum in industry, transport and domestic activities, which in turn are causally related to atmospheric pollution, including CO_2 emissions, ozone depleting substances production and global warming gases (indicator 28). The model also includes indoor air pollution, caused by smoke produced by use of solid fuel such as wood and charcoal (indicator 29). The model shows the consequences of atmospheric pollution on the incidence of respiratory diseases and on atmospheric temperature, a condition related to global warming.

Table 2
Targets and indicators associated to the MDG7

Goal 7: Ensure environmental sustainability	
Targets	Indicators
Target 9 – Integrate the principles of sustainable development into country policies and programmes and reverse the loss of environmental resources	25 – Proportion of land area covered by forest 26 – Land area protected to maintain biological diversity 27 – Use of energy per unit of GDP (energy efficiency) 28 – Carbon dioxide emissions (per capita) [Plus two figures of global atmospheric pollution: ozone depletion and the accumulation of global warming gases] 29 – Proportion of population that use solid fuel
Target 10 – Halve, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation	30 – Proportion of population without sustainable access to an improved water source
Target 11 – By 2020, to have achieved a significant improvement in the lives of at least 100 million slum dwellers	31 – Proportion of people without access to improved sanitation 32 – Proportion of people with access to secure tenure

The model distinguishes two types of respiratory diseases: general diseases, due to atmospheric pollution that affects the whole population, and chronic respiratory diseases (crd), due to household air pollution. This latter type of pollution affects mostly people living in poor households, with high densities and bad ventilation, who use solid fuel for cooking. Data available support the hypothesis that the use of solid fuel is an alternative for petroleum as an energy source for a large number of poor Brazilian households, where stoves of the two types are available. It was shown that the use of solid fuel increased during a recent petroleum shortage and decreased again after the crisis [10].

Exogenous sinusoidal behaviour is assigned to the quantity market change rate, which has QS {demand, zero, offer} to represent situations where demand for petroleum is greater than, equal to, or less than supply, respectively. The model consists of 15 model fragments involving 6 entities (human, economy, energy, atmosphere, industry, transport) and 11 quantities. The exogenous quantity market change rate puts a direct influence on the quantity available petroleum, and this quantity influences the use of petroleum in the industry and in the transport sectors, major producers of atmospheric pollutants in many countries. These are indirect positive influences, so that when available petroleum is decreasing (because there is a shortage and demand increases over the supply), so are the quantities use of petroleum in industry and transport, and the quantities pollutant gases and O_3 depleting substances are also decreasing.

There is a negative indirect influence of available petroleum on the quantity use of solid fuel so that it increases when available petroleum is decreasing (and the prices increase). As a consequence, the amount of smoke inside households is increasing and so is the population with crd. The two quantities representing atmospheric pollution affect the population with respiratory diseases (in general) and atmospheric temperature. This last quantity has QS {below, alert point, global warming} to capture the idea that there is an alert point and above that there is an interval that corresponds to the global warming phenomenon. Figure 4 shows the causal model.

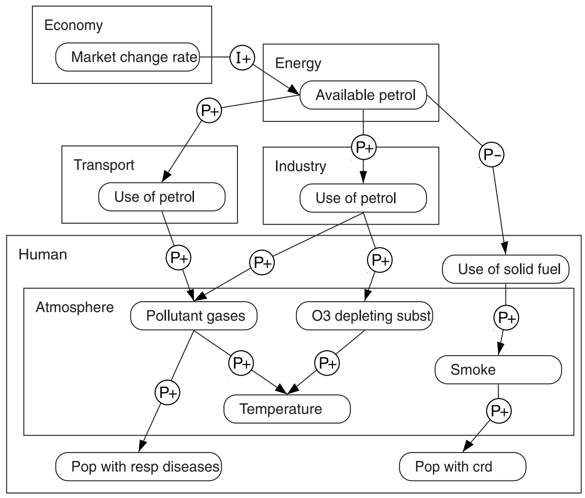


Fig. 4. Causal model “Energy consumption and air pollution”.

One of the possible simulations with this model starts with temperature in the $< \mathit{alert\,point}, ? >$, available petroleum with value $< \mathit{plus}, ? >$ and the other quantities with intermediate values and un-

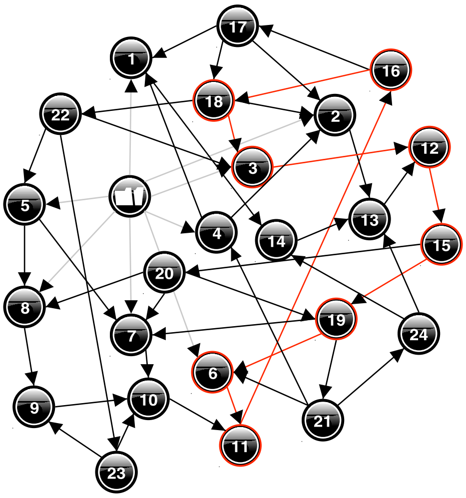


Fig. 5. Behaviour graph based on the model in Fig. 4.

defined derivatives. The exogenous quantity market change rate may oscillate and 8 initial states are produced, in which this quantity assumes values demand (demand greater than supply), zero (or equilibrium, demand equals supply) and offer (supply greater than demand), with derivative increasing, stable and decreasing. This full simulation produces 24 states as shown in the Fig. 5. Table 3 shows some of the quantity values exhibiting cyclic behaviours. Interestingly, global warming is likely to happen when petroleum offer is increasing and domestic crd follows an opposite pattern.

3.2. Deforestation model

Because there is a multitude of social, economic, and environmental factors that influence the decision to remove forest from an area, we treat deforestation rate as an exogenous quantity in a model to assess the consequences of deforestation on indicators of MDG7. Specifically, we explore the consequences of exogenously increasing deforestation rate on area covered by natural vegetation (indicator 25) and, therefore, loss of biodiversity (indicator 26). In countries like Brazil that have potentially vast unexplored resources in terms of technological products derived from this biodiversity, this situation could decrease gross domestic product (GDP), which features in other indicators of the MDG (including MDG7).

Deforestation also increases the area without natural cover of vegetation. This situation speeds up the erosion process, which increases the removed soil. Two outcomes of erosion are reduction of water reservoirs and of agricultural production. The former influences the use of water, that is, almost all biological and economic activities, including human supply. Hence, increased deforestation is expected to increase the proportion of population without access to a safe water supply (indicator 30). In the model, GDP is influenced by three quantities: technological products agricultural production, and uses of water. A feedback loop (P-) establishes the link between GDP and deforestation rate, so that the rate of the process increases when GDP decreases, reinforcing the destructive process. Conversely, when GDP increases, it is expected that deforestation decreases.

As an example, we run a simulation starting with an initial scenario in which the area covered with natural vegetation has value large and derivative undefined, and GDP has its maximum value. This simulation produces four states, in which the consequences of exogenously increasing rate of deforestation clearly reduce the area covered by natural vegetation, reduce biodiversity, increase removed soil by erosion, reduce agricultural production and the uses of water, and increase the amount of population without safe water. In these conditions, the value of GDP reaches its minimum value.

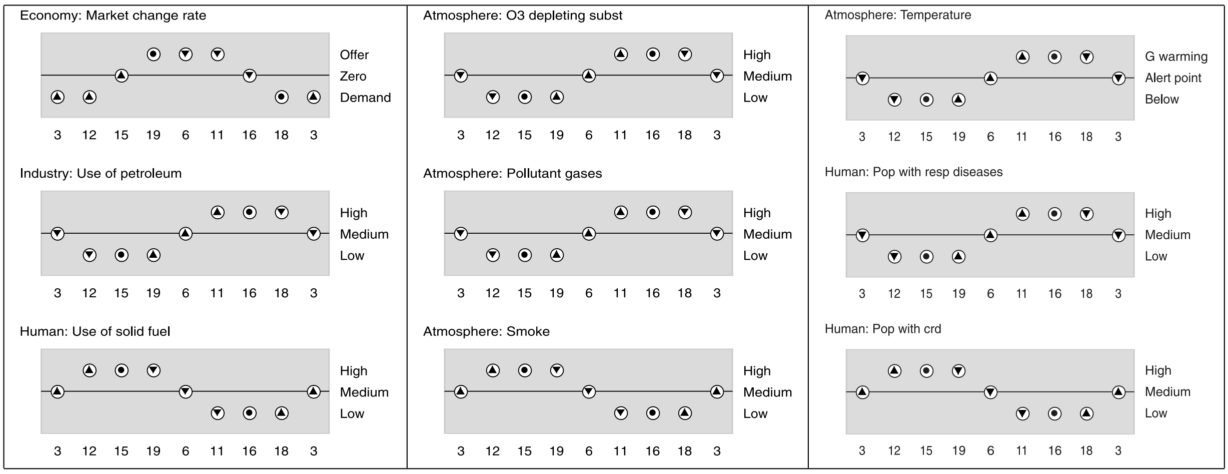
3.3. Energetic efficiency model

Energetic efficiency (indicator 27) is defined as the ratio between the amount of energy consumed during a certain time and the GDP produced during that period. The idea is that the country is more efficient in the use of energy when either more wealth is produced with the same amount of (or less) energy, or the same amount of wealth is produced with less energy. It may not be intuitive, but increased efficiency results in smaller numerical values of the indicator. However, often both energy consumption and GDP are increasing, what makes the situation more complex. The problem is now to figure out which quantity increases faster. Here, we consider two uses of exogenous quantities. First, we use generate all values and exogenous increasing for the quantity economic activity. Second, we use the constant to reduce complexity in the simulation so that the results can be better understood.

In the implemented model, the economic growth process is represented by a rate that puts a direct influence (I+) on the quantity economic activity. This quantity influences the use of energy (represented by the quantity petroleum in four main activities: agriculture, industry, transport and services). In each of these sec-

Table 3

Value histories for 9 quantities in a behaviour path of 9 states present in the full simulation of "Energy and air pollution"



tors the quantity use of petroleum has an indirect influence (P+) on the quantity sectoral GDP. Taking into account all the economic sectors, both quantities, use of petroleum and sectoral GDP, have indirect influences (P+) respectively on total use of petroleum and total GDP. The former puts a positive (P+) and the latter a negative (P-) indirect influence on the quantity energetic efficiency.

Simulations with a model that encodes so many competing influences results in a large behaviour graph, with a large number of states. In fact, in a scenario with economic activity is as exogenous quantity with the generate all values and exogenously increasing derivative, 214 states are produced (with other initial values of all sectoral use of petroleum and sectoral GDP set to value low using QS {low, medium, high} and energetic efficiency in equilibrium using QS {decreasing, equilibrium, increasing}). However, if we also use exogenous constant constraints on use of petroleum and sectoral GDP in agriculture, the simulation produces 65 states. This reduced complexity allows us to more easily examine the behaviour of those quantities that are not held constant.

4. Discussion

This article presents the use of exogenous quantities in qualitative models. Exogenous quantities influence the behaviour of a system, without being affected by that behaviour themselves. Our approach differs from previous work in that it allows modellers to define exogenous quantities and assign specific behaviours to them.

Seven mechanisms have been established and implemented in the qualitative reasoning engine Garp3. The examples used to illustrate the exogenously determined behaviours are relatively simple, but representative of phenomena typically addressed in ecology and sustainability sciences, such as oscillations, cycles, randomness and uncertainty. In fact, the mechanisms seem of particular interest for ecological modelling, as is shown by the models presented on environmental sustainability addressing the seventh Millennium Development Goal.

Using exogenous quantities enhances the potential of qualitative reasoning for handling uncertainty in dynamic models. Three of the mechanisms are directly related to uncertain conditions: generate all values, sinusoidal, and random. These can be used to model the kind of uncertainty referred to as "aleatory" uncertainty [8], where all the values (of both magnitudes and derivatives) are equally likely to happen, given our knowledge of the system, and the level of uncertainty cannot be reduced (e.g., through better measurement). However, it remains interesting and useful to develop models to understand the effects on other quantities, given the uncertain values and behaviour of the uncertain quantities.

Exogenous quantities enrich the representational potential of qualitative models while maintaining the simulator's capabilities of deriving behaviour from the structural description of the system. The exogenous behaviours, as presented in this article, can be placed either at the beginning of a causal chain or within a causal chain, among non-exogenous quantities. Thus, any type of quantity (directly and indirectly influenced) can be considered an exogenous quantity.

Our ongoing work seeks to evaluate the effectiveness of exogenous quantities in a broader set of ecological models as well as the effectiveness of qualitative models to improve the "average citizen's" understanding of factors related to environmental sustainability.

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