Using qualitative reasoning to model wind power production in coastal zone

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Abstract

Knowledge about the natural dynamics of wind resources and the advantages of its exploration as energy source has a high value for implementing sustainable and integrated environmental management. The present work aims to explain the mechanism of wind formation in coastal zone, its capacity to produce energy, and the conversion of wind power in to energy for domestic use by human activities. The model shows changes of the wind direction in the coast zone due to changes of the air temperature caused by differences of water and land specific heat, leading to variations of air pressure. The result is a sea-land breezes that creates an adequate scenario to place wind farms for energy production. The model was built using Qualitative Reasoning techniques, and implemented in the DynaLearn workbench (www.dynalearn.eu), software which is being tested and evaluated.

1 Introduction

Wind is an indirect form of solar power and has emerged as a preeminent option of energy sources, in part because it is considered for many experts to be ecologically sustainable [Welch and Venkateswaran, 2009]. In fact, applications of wind to generate electrical power grew during the second half of the 20th century as the oil price increased during the 1970s, promoting intense interest in its value as a fuel-free, renewable energy source [Tavner, 2008].

Worldwide energy supply insecurity, high oil prices and increasing levels of greenhouse gases (GHG) emission have prompted researchers to look for alternative energy sources to replace existing non-renewable energy sources such as fossil fuels [Lee *et al*., 2010]. Wind has a number of advantages over most other energy sources. Wind farms require much less effort and time for planning and building than fossil fuel or nuclear power plants. Because the wind is free, clean and renewable it constitutes a good choice in energy independence [Cunningham and Cunningham, 2007].

Based on that, the knowledge about the natural dynamics of this resource and the advantages of its exploration as energy source has a high value for making decisions in sustainable and integrate environmental management. In that way, Qualitative Reasoning (QR) offers a modelling paradigm which allows the explicit representation of the main process operating in atmosphere that causes the Wind dynamics providing a renewable supply of energy. Furthermore, the ontology provided by QR facilitates education about these processes, which will be useful for explanation to decision makers and stakeholders—those people who have a vested interest in the outcome of sustainable decisions [Nakova *et al*., 2007].

For this modeling effort, we chose the Qualitative Process Theory (QPT) approach proposed by [Forbus, 1984]. This is a process centered approach that defines systems consisting of objects which properties are described as quantities and the system behavior is determined by process leading to changes in the states of the objects.

Once we are dealing with a conceptual representation of an applicable alternative of power production, this qualitative modeling approach should provide an easy and friendly way for learning about the atmospheric dynamics in order to promote a better understanding of how wind power systems works. This approach will facilitate a whole view of the system, its structure and behaviour by stakeholders (mainly who is responsible for public administration) in order to make better decisions about energy and resources management. These features are offered by DynaLearn, an interactive learning system that integrates techniques developed in three areas: qualitative conceptual modeling, semantic technology and virtual pedagogical agents [Bredeweg. *et al.*, 2009a]

The presented work aims to describe the wind formation in coastal zone, its capacity to produce energy, the wind power conversion into energy for domestic use by human activities.

2 Model system

The use of qualitative modeling to the evaluation of the functioning conditions of a system becomes a valuable tool, which allows real conditions simulations, from the knowledge of the behavior of the processes involved that can happen in an uncertainty line, bound to the technical-scientific knowledge [Tucci, 1998].

The key issues and concepts for explaining how wind energy is produced are the following:

- Sun is the primary source of energy whose radiation reaches the Earth's atmosphere.
- An important mechanism that produces a very frequent air movement occurs along the shoreline of continents and islands caused by the difference in specific heat of the land and sea water.
- Sea water has a higher specific heat than the land, ie the amount of energy required to raise the water temperature is greater than the energy required to increase the soil temperature.
- The atmospheric air pressure difference causes wind movement (air flow) from regions of higher pressure into regions of lower pressure. This way the wind mainly flows from the land into the sea during the night or from sea into the land during the day.
- Part of the kinetic energy of wind (wind power) can be transformed into rotational mechanical energy using wind turbines, which in turn convert this mechanical energy into electrical energy.

This model can be used as a reference model for other people to use as source of inspiration to create other representations in which wind energy is part of the model. The main objective of this model is to represent the process of obtaining electric power using wind energy as a renewable source, namely the kinetic energy contained in wind, showing how this form of energy production is sustainable.

This model aims to answer the following question: *How the conversion of energy from the sun in wind power is performed?*

In order to answer this question, 2 other questions should be answerer: *How air movement is produced? How kinetic energy of the wind is transformed into electric energy in the wind plant?*

3 Model implementation

Relevant information for building this model about the wind formation dynamics and functioning of wind power engines were obtained from specialized literature [Herbert *et al.*, 2007; Tavner, 2008; Welch and Venkateswaran, 2009; Lee *et al.*, 2010] The model was built with Qualitative Reasoning techniques, which has been successfully used to model ecological systems (see the special issue of Ecological Informatics on Qualitative Reasoning, volume 4, issues 5-6, pages 261-412, November-December 2009). The ontology provided by the Qualitative Process Theory [Forbus, 1984] was used to describe processes as a mechanism that drives the dynamics of the system. Accordingly, direct influences (I+ and I-) capture how the processes work, and qualitative proportionalities (P+ and P-) propagate the effects of processes throughout the system.

The model was implemented in the DynaLearn workbench (www.dynalearn.eu), software which is already in testing and evaluation phases. DynaLearn provides 6 *learning spaces* (LS) of increasing complexity: in LS1, the user creates concept maps and may organize vague ideas about the domain knowledge to create a graph where main concepts are nodes and the arcs represent the relations among them. In LS2, a basic representation of the causal relations is created in a directed signed graph (directed arrows with + and – signs between influencing and influenced quantities). The objects that constitute the system and the relations between them are captured respectively as entities and configurations. Quantities are used to model continuous properties of the objects, but at this LS only their derivatives are represented. Simulations can therefore show tendencies of change (increasing, decreasing and stable), ambiguities and inconsistencies in the model.

LS3 allows for introducing the magnitude value of one or more quantities, which produces simulations with states and state transitions, showing the change of the values of the quantities along time. Differentiation of causal primitives in direct influences (I+ and I–) and proportionalities (P+ and P–) can be used in LS4, allowing for representation of feedback loops. LS5 is similar to LS4 except for the possibility of representing conditional knowledge. Finally, very much like Garp3 [Bredeweg *et al.*, 2009b], LS6 introduces the concepts of reusable knowledge captured in *model fragments*, hierarchical relations between entities, agents and assumptions, and adopts the compositional modelling approach [Falkenhainer and Forbus, 1991].

The wind energy model was developed step by step, starting with a concept map (LS1), followed by a basic causal model (LS2), which was further improved with the basic causal model enriched by the specification of magnitude values for the quantities. A model expression in LS4 was also developed, establishing a differentiated causal model in which the processes were defined, and finally, the model was implemented in LS6. A more detailed discussion can be found in [Salles *et al.*, 2010]. Some of these model expressions will be presented in the following sections.

3.1 Wind energy concept map and basic causal model

The main ideas involved in explaining how wind energy can be transformed into electric energy and supply domestic and industrial needs are captured in the LS1 model expression, shown in Figure 1.

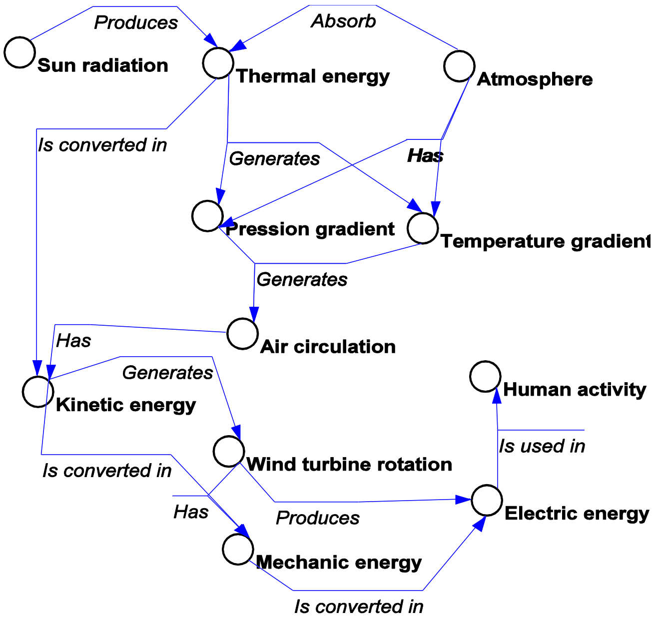

Figure 1. Model expression in LS1, a concept map showing key concepts involved in the wind energy generation.

The ideas presented in LS1 are refined in the model expression presented in LS2. Entities (objects) are the main components of the system of interest. The system structure is represented by entities, related among themselves by configurations. Model expression in LS2 also requires the identification of quantities, continuous properties of the objects included in the model. One version of the basic causal obtained is presented in Figure 2.

Note that in the LS1 model expression (Figure 1), 11 concepts were pointed out as relevant to summarize the basis for explaining how wind energy is produced.

Abstracting these concepts to create the LS2 model expression, six entities were created, and nine quantities were defined. In the next sections, the most developed model (LS6) is presented.

3.2 Entities and Configurations in LS6 model of wind energy

The proposed model considerates the following entities: 'Land' and 'Sea' as representatives of a complex environment, 'Wind turbine' and 'Human activity' representing the human intervention in the environment and 'Atmosphere' as an environmental compartment, from where some relations are established (Figure 3).

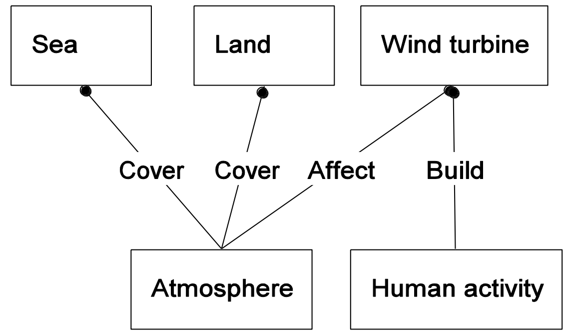

Figure 3. System structure showing all entities and configurations included in the model.

3.3 Quantities and Quantity Spaces

Some of the properties which values are considered relevant to the system behavior are included in the model as quantities. Those are associated to qualitative states, important to the understanding of the system behaviour. These qualitative states assumed by quantities are represented in the model as quantity values, organized in an ordered set, the quantity space. The quantities and their respective magnitude qualitative values are presented in Table 1.

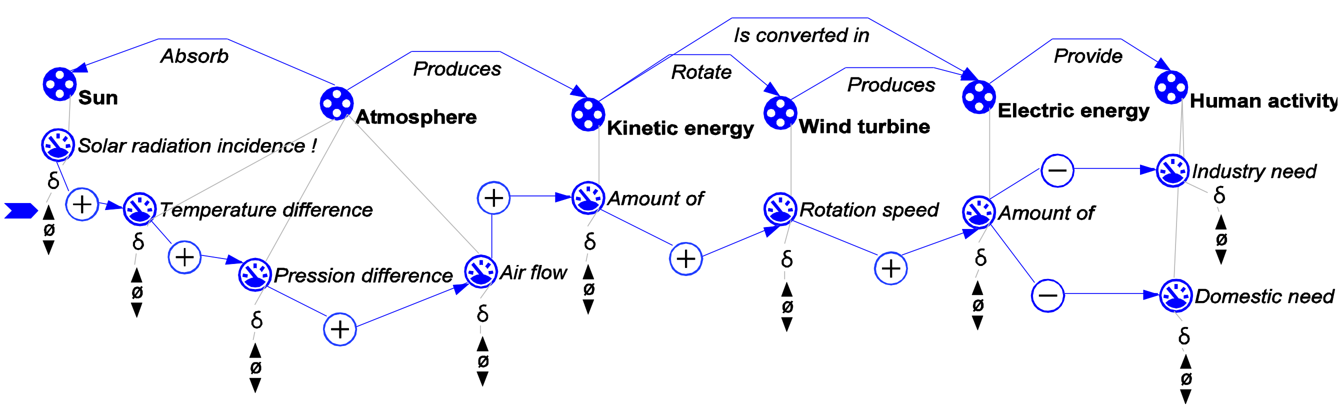

Figure 2. Model expression in LS2, a basic causal map resulting from abstracting generic concepts into entities and quantities involved in the wind energy generation model.

Table 1. Entities, quantities and quantity spaces involved in the Wind Power model.

Entity	Quantity	Quantity Space
Atmosphere	Kinetic energy	*{Zero, Low, Medium, High}*
	Air flow	*{Minus, Zero, Plus}*
	Solar incidence	*{Zero, Plus, Max}*
	Heat dissipate	*{Zero, Plus}*
Wind turbine	Rotation speed	*{Zero, Low, Medium, High}*
	Energy production	*{Zero, Low, Medium, High}*
	Energy supply	*{Minus, Zero, Plus}*
Sea	Press atm surf	*{Lowest, Low, Medium, High, Highest}*
	Temp atm surf	*{Low, Medium, High}*
Human activity	Energy consumption	*{Zero, Low, Medium, High}*
Land	Press atm surf	*{Lowest, Low, Medium, High, Highest}*
	Temp atm surf	*{Lowest, Low, Medium, High, Highest}*

3.4 Model Fragments

The equilibrium between the amount of energy emitted by the Sun and absorbed by the Earth surface, and then irradiated again to the atmosphere, is represented in this model by direct positive (I+) and negative (I-) influences and seen as one factor of the thermal balance of the Earth. The difference in the thermal capacity, regarding the contrasting densities of land and sea environments, is represented from correspondences and qualitative spaces defined in MF02 (Figure 4).

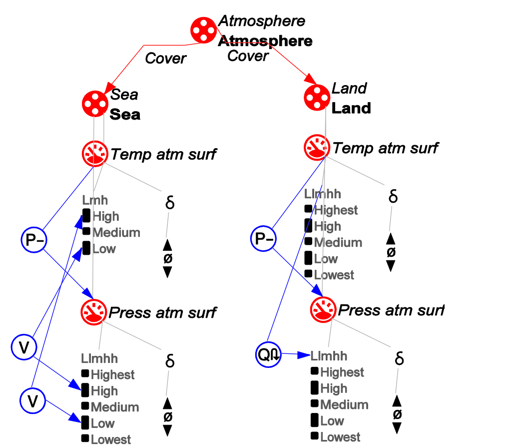

Figure 4. Model fragment with a representation of the influences of temperature in the air pressure.

The temperatures propagate through negative proportionalities (P-) to the atmospheric pressure of the surface of these environments. The difference between the atmospheric pressures is represented in MF03 (Figure 5) through calculations, inequalities and proportionalities (P+ and P-) as the responsible factor of the air masses movement, in the model represented as *Air flow*.

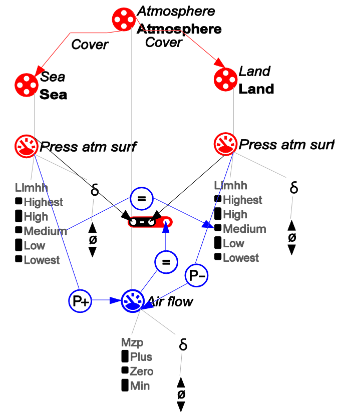

Figure 5. Model fragment with a representation of Air flow as a result of the difference in air pressure.

The force of the air flow, or wind, is source of kinetic energy. The variable *Air flow* with QS {minus, zero, plus} represent different directions and forces that the wind can assume, regarding the difference between land and sea atmosphere pressures along time. The model fragment shown in Figure 5 is of central importance for understanding the wind behavior. Considering the pressure differences at the surface of the land and the sea, three situations are possible:

(a) If 'Land' atmospheric pressure > 'Sea' atmospheric pressure, then Air flow > zero and the air flows from land to the sea;

(b) If 'Land' atmospheric pressure = 'Sea' atmospheric pressure, then Air flow = zero; and there is no (net) flow;

(c) If 'Land' atmospheric pressure < 'Sea' atmospheric pressure, then Air flow < zero; and the air flows from sea to the land.

Once the air flow is produced, then kinetic energy is also produced. After that, the transformation of the kinetic energy, obtained by the wind, in mechanic energy, through its passage by the wind turbine, represented in MF05, is implemented by P+ between these variables (Figure 6). So, increasing the speed of the air, wind turbine will receive more kinetic energy, finally producing more energy.

MF06 represents, by means the calculation of potential utilization of wind power as supply, human energy consumption, based on unequal quantities of *Energy production* and *Energy consumption* (Figure 7).

Interpretation of outcomes of this model fragment can be understood as follows. Considering the differences between energy production by the wind turbine and consumption by human activity, three situations are possible:

(a) if *Energy production* > *Energy consumption*, then *Energy supply* > zero and the turbine produces more than is consumed;

(b) if *Energy production* = *Energy consumption*, then *Energy supply* = zero and the turbine produces the same amount of energy that is consumed;

(c) if *Energy production* < *Energy consumption*, then *Energy supply* < zero and the turbine produces less energy than the amount of consumed energy.

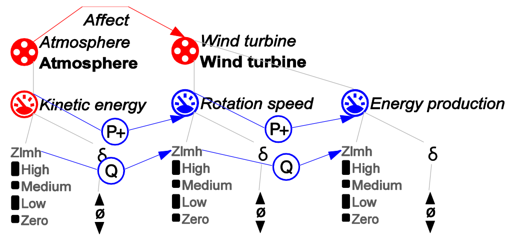

Figure 6. Model fragment with the propagation of the influence of Kinetic energy.

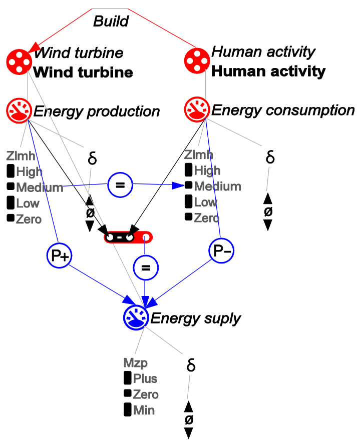

Figure 7. Model fragment with Energy supply as a result of the difference between Energy production and Energy consumption.

3.5 Scenarios

Scenarios represent initial situations, including configurations of the system of interest, and initial values of the quantities [Nakova *et al*., 2007]. The current version of the model has seven scenarios, starting with simple simulations that explore parts of the system, up to the more complex scenario, which is presented in Figure 8. In this scenario, exogenous behaviors [Bredeweg *et al*., 2007] are assigned to the variables *Solar incidence* and *Heat dissipate*, in order to represent respectively decrease and stability. This way, the simulation shows the transition from day to night. Initial values of the other quantities are also represented in Figure 8.

4 Simulation Results

The simulation with this scenario presented in Figure 8 produced a behaviour graph with 130 states. Overall, the simulation shows that wind is caused by differential heating by the sun of the Earth's surface, namely covered by land and by the sea [Herbert *et al.*, 2007]. For example, considering the coastal region during the day, it is easy to observe that the land absorbs more heat than the sea water. Land's temperature becomes higher than the water's. As the heat dissipates to the atmosphere, the air above land also becomes hotter and less dense. So the warmer air rises decreasing the surface air pressure over land.

This way the air pressure over land becomes smaller than it is over the sea, producing neighbour zones with high pressure difference. Given that the wind flows from regions with higher air pressure to regions with lower pressure, during the day wind flows from sea into land.

During the night the situation is the opposite, as the land loses heat faster than water, making the land temperature colder than the water temperature. This way the atmosphere above the land is denser than sea's and atmospheric pressure over the land becomes higher than the sea creating an air flow from the land to the sea. Therefore the wind flows from the land into the sea during the night. Fishermen with wind driven boats leave to the sea early morning, and come back in the afternoon.

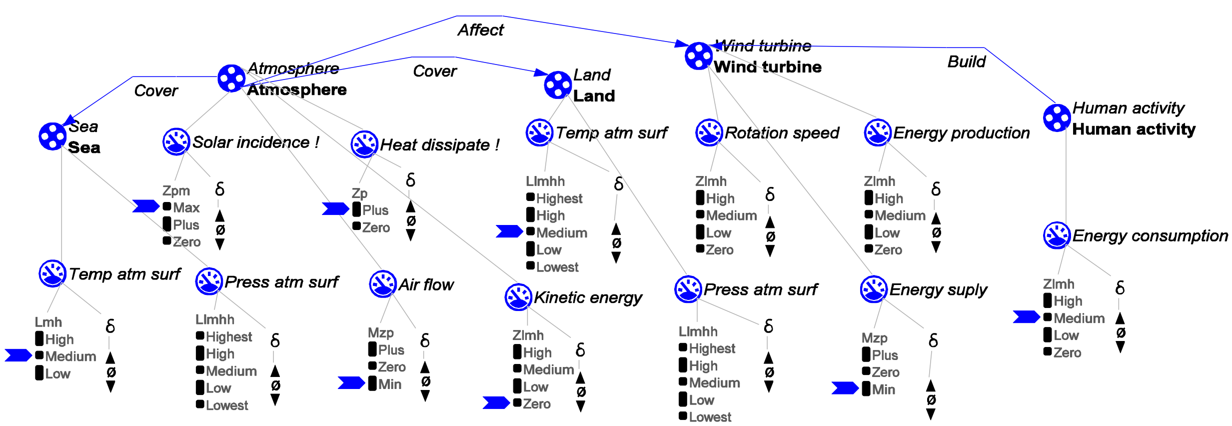

Figure 8. Scenario 7 All the active influences on wind power generation.

The causal model produced in state 14 of this simulation makes it easier to follow the changes (Figure 9).

Two competing processes (solar heating incidence and heating dissipation on the 'Land' and on the 'Sea') determine the atmospheric temperature on the surface of land and the sea. These quantities pose negative proportionalities on *Pressure of atmospheric at the surface*, again, both of the land and of the sea water. The values of these quantities are used to calculate the value of *Air flow*, which indicates the direction of the wind (see section 3.3, Figure 5). This process puts a direct influence on *Kinetic energy*, which effects in turn propagate to *Rotation speed* of the 'Wind Turbine', causing the turbine engine to work. To determine the values of *Energy supply*, was implemented a calculus were *Energy production* in the Turbine minus *Energy consumption* by 'Human activities' will be equal to *Energy supply*. The balance between these two quantities is used to calculate the Energy supply, setting the amount of energy available to supply human activities.

After runing the simulation, it was obtained a state graph with 130 states, each path was inspected and we choose that one which is more similar to the behaviour we want to show. The value history diagram of selected quantities confirms the reading that just finished (Figure 10). The behaviour path presented in this Figure passes through the following states: [12 → 14 → 33 → 36 → 46 → 51 → 66 → 72 → 100 → 106]. In this behaviour path, *Solar incidence* increases in *Maximum* during states 12 and 14, then gets the derivative zero and starts decreasing, while *Heat dissipate* starts decreasing, goes to zero and starts increasing again. Accordingly, the *Temperature at the surface* in 'Land' starts increasing, and it keeps this tendency until state 51. From this point *Temperature* starts decreasing. The values of the variable *Temperature at the surface* in 'Sea' start increasing, and keep this tendency until state 51. From this point *Temperature* starts decreasing. The values of the variable go to *low* in states 100 and 106. These results can be explained by the effect of heating on the density of the air. The air becomes less heavy and the air pressure starts increasing, stabilizes in state 51 and reduces the value, which in turn propagates to other quantities. Figure 11 presents the equation history of the same behaviour path, showing that in states 12 and 14, the pressure at the surface level at the sea is smaller than the pressure at the land surface, causing the wind to flow from land to the sea; next, in states from 33 to 72, the pressures are equivalent (equal) so there is no predominant flow; finally, in states100 and 106, the pressure at the surface level at the sea is greater than the pressure at the land surface, causing the wind to flow from the sea to land (bringing the fishermen back home).

For this simulation, we assumed a medium and stable magnitude value for the *Energy consumption* by the Human activity. When the *Air flow* has a negative value (*min*) the air is flowing from 'Sea' to 'Land', otherwise, when *Air flow* has a positive value, the wind is running from 'Land' to the 'Sea'. The selected path shows that change in the direction of wind, which also means a sort of fluctuation in the energy produced by the wind turbine (Figure 11). But assuming a stable value of *Energy consumption*, when the wind is running more and more lower to change its direction the energy production achieves low and zero values causing a negative value of energy supply. It occurs because in this point the energy consumption is higher than energy production by wind turbine, other sources of wind formation weren't considered in this model and other sources of energy or energy storage weren't considered as well.

[Voorspools and D'haeseleer, 2006] observed that whereas conventional power stations can be considered as binary units being either fully available or not at all, the fluctuating output of unpredictable power sources may vary between zero and full load.

5 Discussion and concluding remarks

This paper describes the development of a qualitative model to be used in learning about wind energy generation. The model successfully represented the wind dynamics in the coastal zone and how it can be used as a renewable source of energy. Initially, vague ideas were organized in a concept map (LS1, Figure 1) and set the conditions for the development of a basic causal model (LS2, Figure 2). Increasing the complexity makes it easier for the modeller, in particular if it is a person that is not familiar with models and modelling, to move into more complex representations. This way of building models has a good coincidence with the framework for building qualitative models, described in [Bredeweg *et al.* 2008]

The model shows the shift of wind direction in the coast zone, representing the phenomena of changing the air temperature caused by different specific heat of water and land leading to different variation of air pressure resulting in sea-land breezes a very useful scenario chosen by engineers and stakeholders to place wind farms for energy production. In most part of the states this simulation results in a scenario where the energy supply is positive i.e. has a plus magnitude value, what requires a high energy production. It is an advanced model, as it is simple enough to be used by novice learners, but still shows the basic mechanism underneath the functioning of a system.

Ongoing work includes a preparation of evaluation material for secondary school students in building models, and this model can be used as a reference model for other people to use as inspiration, or re-use it to create other representations in which wind energy is part of the model, or use the model for DynaLearn to provide automated feedback to improve or fix models built in activities of Learning by Modelling.

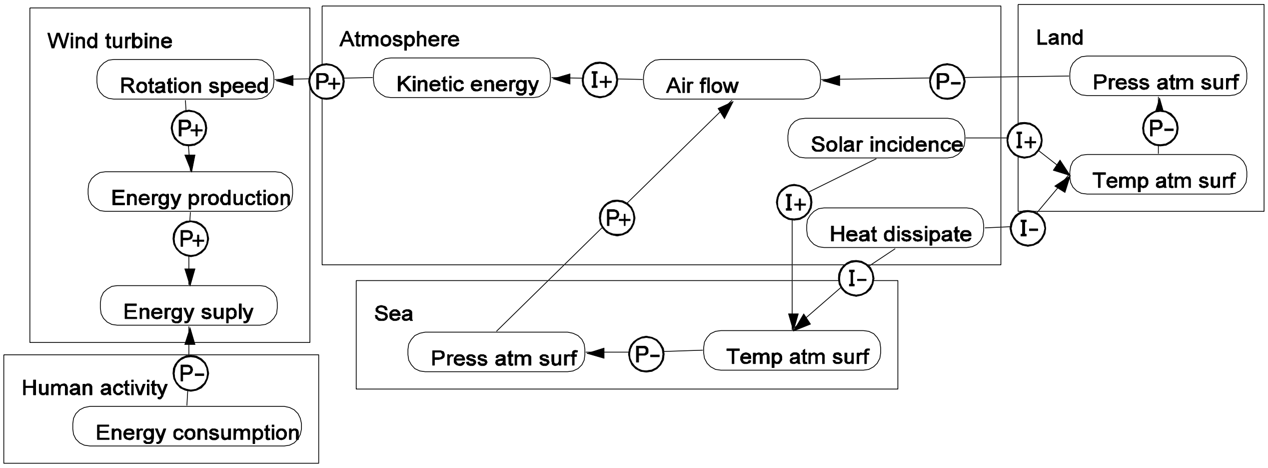

Figure 9. Causal model obtained in state 14 of the simulation starting with the scenario 7, 'All the active influences on wind power generation'.

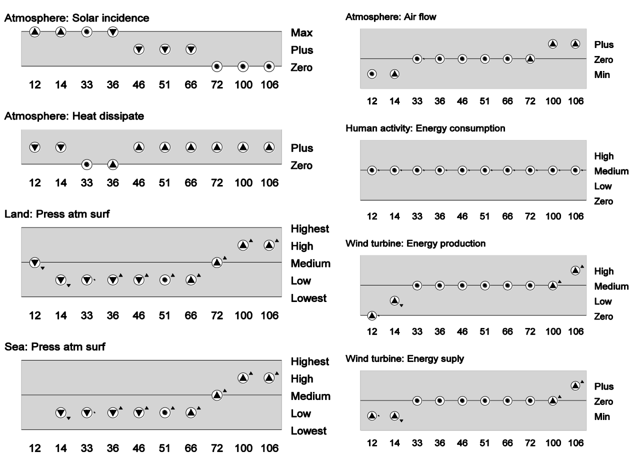

Figure 10. Value history diagram of the selected quantities in one of the behaviour path starting in state 2 of the simulation starting with the scenario "Scenario 7 All the active influences on wind power generation ".

Press atm surf (Land) ? Press atm surf (Sea)

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33 36 46 51 66 72

Press atm surf (Sea) ? Press atm surf (Land)

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12 14 100 106

Figure 11. Equation history of the chosen behaviour path.

Acknowledgments

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