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Object-oriented Modeling of Heat and Humidity Budgets of Biosphere 2 Using Bond Graphs

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Abstract

Biosphere 2 is a closed ecosystem located near Tucson, Arizona, designed for studying the interactions between different biological species among each other and with their materially closed controlled environment, taking into account the limited resources that such an environment provides. Energy considerations play a central role in how these interactions play out. To this end, bond graph models were designed that enable the researcher to better understand the nature of these interactions, hopefully offering some insight into the much larger ecosystem of planet Earth.

1. Introduction

Biosphere 2 was designed and built around 1990 as a materially closed ecosystem, in which eight humans were living during two years, producing their own food, regenerating the atmosphere using the plants, which needed to be cultivated as well. The plants required water and nutrients, which had to be constantly monitored and purified (regenerated). The control architecture necessary to keep this ecosystem balanced and functioning represents the most complex engineering project realized to date, involving 1800 sensors of different kinds, measuring the state of Biosphere 2 at 15 minute intervals, air handlers for temperature and humidity control, scrubbers for water regeneration, and hundreds of actuators, controlling "rain fall," fan speed, air handler power, heat exchanger temperature, etc.

The model described in this paper makes use of bond graphs for describing the energy flows associated with the thermodynamics of Biosphere 2, driven by sun shine and other weather conditions. For simplicity, the air conditioning systems were left out, i.e., no material flows are considered within Biosphere 2. The entire ecosystem is thereby reduced to a single biome of appropriate dimensions, and the influence of the surrounding weather conditions, including ambient temperature, solar radiation, wind velocity, cloud cover, and exterior humidity, was studied by analyzing the thermodynamics through the heat flows. Both sensible heat and latent heat were taken into account; i.e., the model not only accounted for heat conduction and radiation, but also for evaporation and condensation.

A first such model of Biosphere 2 was created by Luttmann as part of his Ph.D. dissertation (Luttmann, 1990). The model was coded in TRNSYS, a Fortran program designed for the thermal simulation of buildings. The code was totally monolithic, making it difficult to maintain and enhance, and indeed, the code contained a number of serious errors that were not discovered until much later.

The model was later converted to bond graphs, coded in an early version of Dymola, by Nebot during a postdoctoral stay at the University of Arizona (Nebot/Cellier/Mugica 1999). Due to the use of bond

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graphs, the model was no longer monolithic, and therefore much easier understandable and maintainable. A number of errors were corrected in the conversion. Yet, also this model was still coded in an alphanumerical fashion using the textual bond graph library presented in (Cellier, 1991).

The model was converted by Cellier to a graphical format using the newest version of Dymola with Modelica and a newly designed graphical bond graph library (Cellier/Nebot 2005). Graphical programming makes the code even better readable, because connections between modules can be visualized in a two-dimensional form, whereas a textual representation by its very nature must be one-dimensional. Also this conversion made it possible to correct a number of errors that had slipped through the earlier conversion.

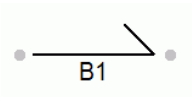
The paper presented here deals in particular with the models of evaporation and condensation, explaining, how bond graphs were used in modeling the transitions from sensible to latent heat, and vice versa. The paper then elaborates on the shortcomings of this approach to modeling the phenomena of evaporation and condensation, and proposes an improved model based on thermo-bond graphs (Cellier/Greifeneder 2003).

2. Bond Graphs and Power Flow

Bond graphs represent the power flow through a physical system. Originally designed by a mechanical engineer, Henry Paynter, a professor at M.I.T. for graphical representation of the dynamics of mechanical systems, they have meanwhile also become a common tool for the representation of electrical systems, mechatronic systems, as well as hydraulic and pneumatic systems. All of these systems have in common that power flow can be represented as the product of two adjugate variables, one extensive, the other intensive. In bond graph technology, these variables are called the effort, *e*, and the flow, *f*, respectively:

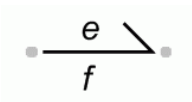
$$P = e \cdot f$$

A bond represents the flow of power from one location to another:

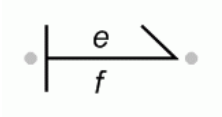


It is depicted graphically by a harpoon (semi-arrow). The direction of the harpoon denotes positive power flow. The harpoon always points to the left in the direction of positive power flow. The two grey dots at the two ends of the bond represent connectors that connect the bond to the emanating and receiving locations of the power flow.

The two adjugate variables, *e* and *f*, may be shown next to the bond. In that case, the effort, *e*, is shown on the side of the harpoon, whereas the flow, *f*, is shown on the opposite side:



In order to simulate a bond graph, it is necessary to find equations for the two adjugate variables. In all physical systems, it so happens that the two equations capturing the behavior of the two adjugate variables are always generated at the opposite connectors. The side, where the flow variable is being computed, can be graphically marked by a so-called causality stroke:



In the above example, the flow variable is computed at the emanating node, whereas the effort variable is computed at the receiving node of the bond.

The selection of the two adjugate variables follows quite naturally in electrical, mechanical, hydraulic, and pneumatic systems. In electrical systems, it has become customary to use voltages and potentials as effort variables, and currents as flow variables. In translational mechanical systems, it is customary to denote the forces as efforts and the velocities as flows. In rotational mechanical systems, the usual choice is to use torques as efforts and angular velocities as flows. In hydraulic and pneumatic systems, the common selection is to declare pressures as efforts and volumetric flows as flows. Yet, it is always possible to exchange the efforts and the flows. This is done in the so-called dual bond graphs (Cellier 1991).

We lack the space to repeat in this paper, how bond graphs are being constructed in general (Cellier 1991), and how they are being implemented in Dymola with Modelica. We refer to (Cellier/Nebot 2005) as a paper describing to the Modelica specialist, how bond graphs are being implemented using the graphical bond graph library, and to (Cellier/McBride 2003) as a paper describing to the bond graph specialist, how the graphical bond graph library has been implemented in Modelica.

3. Bond Graphs for the Description of Thermodynamics

Thermodynamic systems are different from the aforementioned systems, as they lack two *natural* adjugate variables, the product of which is power. Also thermodynamic systems require at least two variables for their description. Thermodynamic systems without moving masses, i.e., without convective flows, can e.g. be described by temperature and heat flow. Unfortunately, the product of these two variables does not represent power, as heat flow alone has already the dimension of power.

For this reason, some bond graph practitioners introduced the concept of a pseudo-bond graph, using temperature as effort variable and heat flow as flow variable, recognizing that the bonds carrying these two variables are no longer true bonds, which may cause difficulties, when thermodynamic models are coupled to other models (Thoma/Ould-Bouamama 2000).

Other researchers, including the authors of this paper, prefer to stick with real bond graphs. To this end, the heat flow is decomposed into the product of two variables: temperature and entropy flow, whereby temperature is used as the effort variable, and entropy flow is used as the flow variable (Cellier 1991). Entropy flow is a physical variable that, unfortunately, cannot be measured directly, whereas temperature can be measured easily, in spite of the fact that it is not a truly physical variable in a Newtonian sense.

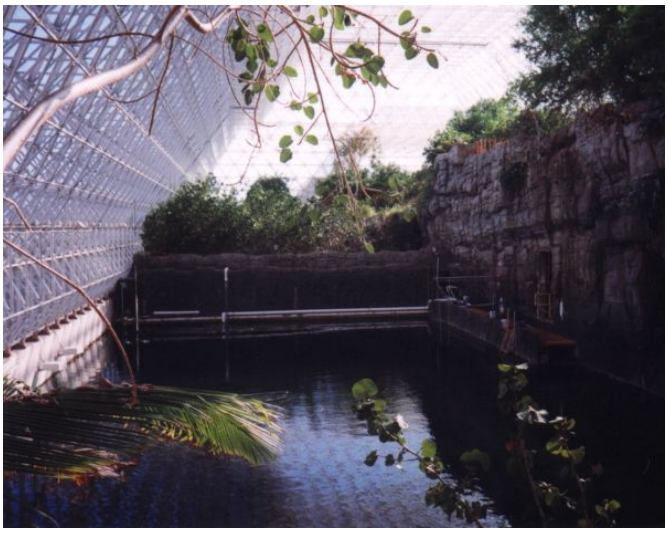
Pseudo-bond graphs have the advantage that many thermal resistors and capacitors are linear in terms of temperature and heat flow, whereas all thermal resistors and capacitors are non-linear in terms of temperature and entropy flow. True thermodynamic bond graphs have the advantage that they can be treated like all other bond graphs and can be more easily coupled to non-thermal subsystems.

The reader is reminded that both true bond graphs and pseudo-bond graphs break down in the presence of moving masses, i.e., convective flows. At least three variables are required to describe these systems, and the regular bond graphs must be replaced by thermo-bond graphs (Greifeneder/Cellier 2001a, 2001b, 2001c).

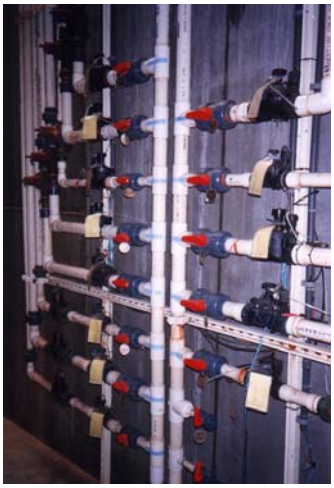
4. Biosphere 2

Biosphere 2 was built as a materially closed, but energetically open system for the purpose of studying, in a controlled setting, the interactions among biological species on the one hand, and their interaction with the environment on the other. Eight researchers lived in this environment during two years, producing their own food and regenerating the atmosphere.

Biosphere 2 was built as a glass-panel structure housing a number of different biomes. The pyramidal structure to the right houses a rain forest with plants from the Amazon basin in South-America. The area to the left houses the savannah, a salt water pond, salt water marshes, and a Sonoran desert area. The agricultural biome cannot be seen on this picture, as it is behind the building.

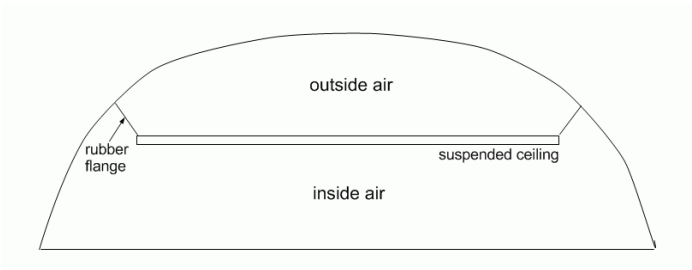


This inside view shows the pond, the high savannah (above the artificial rocks to the right), and the salt water marshes (mangroves) in the background. The glass panels let, on average, pass 60% of the solar radiation, whereas 20% are absorbed by the glass panels, and the remaining 20% are reflected. The pond is about 5m deep, and houses a variety of salt water fish and even a corral reef. Artificial tides were introduced to keep the mangroves healthy.

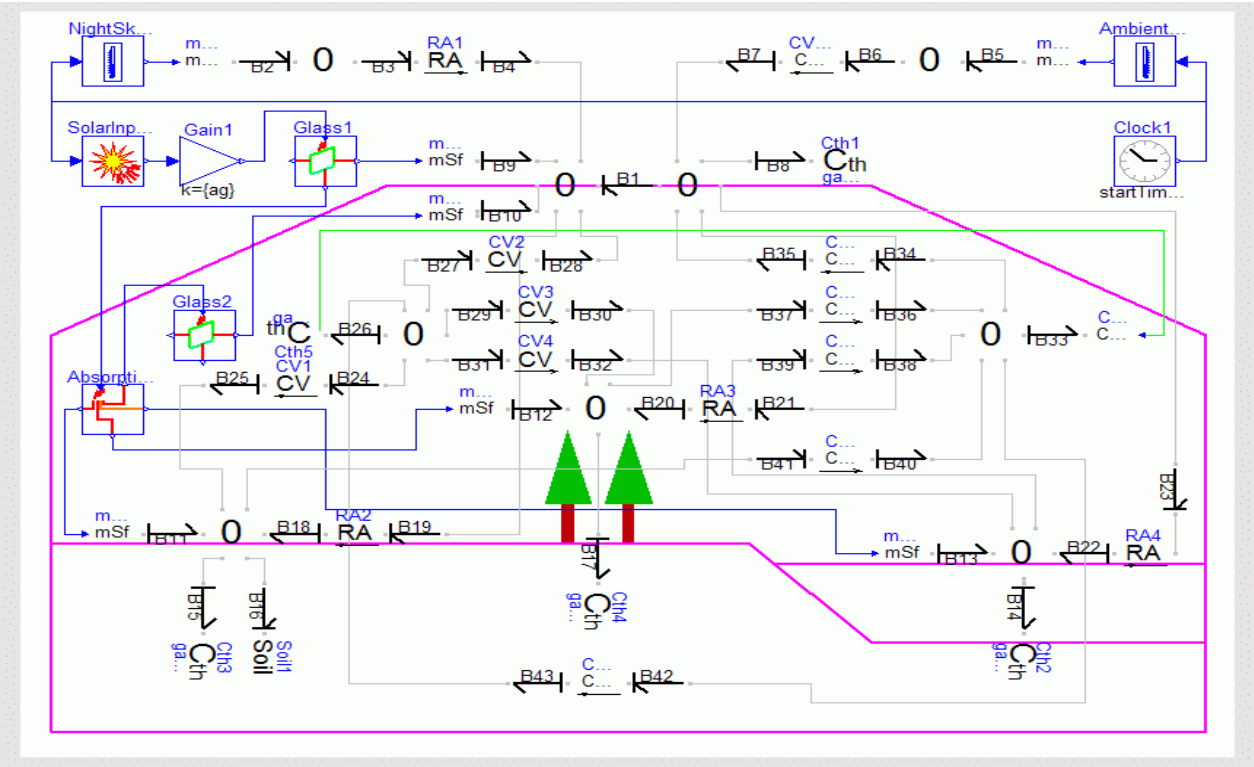


The engineering system in the basement is highly impressive. Air handlers suck in the humid air from the atmosphere of Biosphere 2, cool it down by means of heat exchangers to about 10°C to condensate the humidity out, then reheat the dried air to about 20°C using a second set of heat exchangers. The extracted water flows down-hill into one of the two lungs, the lowest point of the Biosphere 2 system, where it forms a small lake. From there, the water is recycled by pumps to generate rain over the tropical rain forest.

The two lungs are responsible for keeping the air pressure in the Biosphere 2 system constant. Heavy concrete ceilings are suspended from the dome of the lungs, sealing the inside atmosphere by flexible rubber flanges. When the temperature within Biosphere 2 increases, the pressure increases as well, pushing the ceilings up, until the pressure is again equalized by increasing the volume of Biosphere 2.

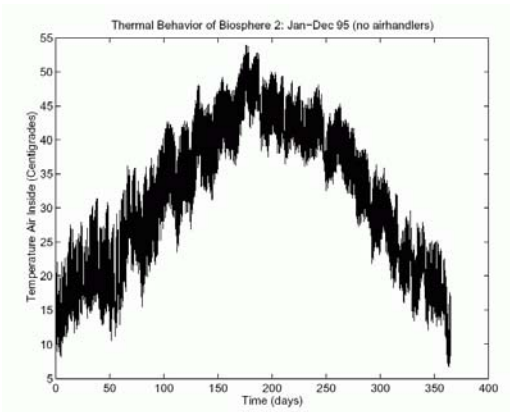


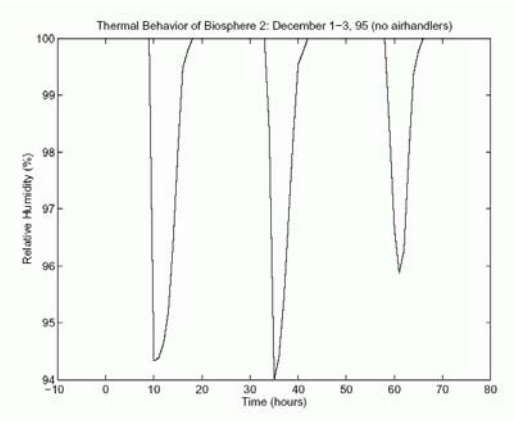
In the model, the Biosphere 2 system is simplified to a single biome, exhibiting the same temperature and humidity throughout the atmosphere, and all material flows (air flow and water flow) were omitted, in order to be able to describe the system by regular bond graphs:



Each 0-junction together with its associated capacitance represents a thermal storage and one temperature value. Different storages represent the soil, the vegetation, the pond, the dome, and the inside atmosphere. Conduction and radiation are modeled in the usual fashion (Cellier 1991), representing the thermal interactions between these thermal storages.

The atmosphere is represented as two separate storages, one modeling the sensible heat and the other modeling the latent heat, i.e., the humidity. Evaporation is considered from the pond, the vegetation, and the soil to the atmosphere, whereas condensation is considered on the glass panels and in the bulk.



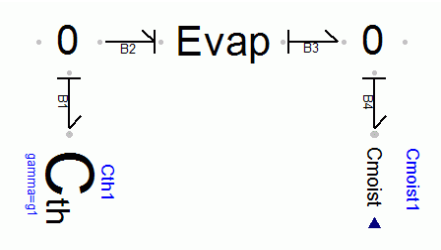


As no air conditioning was taken into account, the temperature rises in the summer to about 50°C, and the relative humidity is almost always at 100%. Only during the morning hours, i.e., when the sun heats up the atmosphere, the relative humidity reduces temporarily to somewhere around 94%. In the real system, temperature and humidity are regulated to suitable values for the individual biomes. The tropical rain forest reaches 100% relative humidity during evening hours, i.e., when the atmosphere cools down, leading temporarily to a thick London fog, though the structure is not big enough to produce real rain fall. Also above the high Savannah, clouds form during evening hours.

5. Evaporation and Condensation

When water evaporates, it becomes more highly energized. It receives the additional energy needed from the thermal domain by extracting heat. The extracted heat is no longer sensible; but as this heat can be regained in the process of condensation, it is called latent heat.

Different empirical models were postulated that describe the process of evaporation and the inverse process of condensation, among others the formula proposed by Magnus Teten (Murray 1967), which was the formula adopted in (Luttmann 1990).



The evaporation model is a non-linear thermal resistor, or rather a non-linear thermal conductor, draining sensible heat from the 0-junction to the left, representing the thermal domain, while augmenting the latent heat, represented by the 0-junction to the right, representing the humidity. As 0-junctions must have exactly one causality stroke, that of the associated capacitance, the causality strokes of the connecting bonds must both reside at the evaporation model, i.e., the evaporation model computes the entropy flow out of the thermal domain, and the mass flow into the humidity domain.

Which pair of adjugate variables should be used to describe the humidity? From today's knowledge, it might make sense to define the mass flow (water flow) into the air as the flow variable. The variable representing the effort would then have to be the specific enthalpy, *h*, of the water. The capacitance of moisture would then serve as the storage of water mass. It would furthermore compute the specific enthalpy of the water as a function of the current state. The evaporation model on the other hand would compute the mass flow of evaporation, and from the mass flow and the meanwhile available enthalpy, it could then compute the entropy flow needed, such that power in equals power out at the evaporation model.

Yet, this is not what Teten proposed. In order to be able to use Teten's law more directly, we defined the relative humidity as the effort variable. Thus, the effort is now measured in kg_water/kg_air. From this choice, everything else follows. Since power was expressed in the Biosphere 2 model in kJ/h, the units of flow had to be kJ·kg_air/(h·kg_water).

Since the bondgraphic linear resistance is defined by the equation:

$$e = R \cdot f$$

we know that the bondgraphic resistance must be measured in units of effort divided by units of flow, i.e., h·kg_water^2/(kJ·kg_air^2). Comparing this result with the units that Teten used for his resistances, we see that they are off by a factor of kg_water/kg_air. Thus, the bondgraphic resistors of the humidity domain need to be multiplied with the effort, just as in the case of the thermal domain (Cellier 1991).

Since the bondgraphic linear capacitance is defined by the equation:

$$f = C \cdot \mathrm{der}(e)$$

the bondgraphic capacitance must be expressed in the units kJ·kg_air^2/kg_water^2. However, the bondgraphic capacitance must equal the physical capacitance divided by the effort, such that the product of resistance and capacitance remains a time constant. Thus, the physical capacitance must be measured in kJ·kg_air/kg_water, which corresponds with Teten's law.

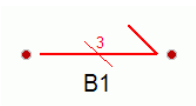
The model functions well, although the measurement units of some of the variables are anything but natural from a physical perspective. Bond graph modeling helps ensure that the power continuity equations are never violated, and also, helps us come up with consistent units for the different physical phenomena.

6. Shortcomings of Teten's Model

Unfortunately, Teten's model doesn't track the water through the system. It is incapable of telling us, how much water is depleted out of the salt water pond, and how much water gets stored down in the sweet water lake in the South lung. If we wish to track material flows, the situation becomes much more complicated, because moving mass carries both volume and entropy with it.

In the case of the Biosphere 2 model, this was not problematic, as it is impossible for the pond to ever get emptied out. The air volume of the Biosphere 2 dome can never store all of the available water in the form of water vapour. Thus, there is always water available to evaporate.

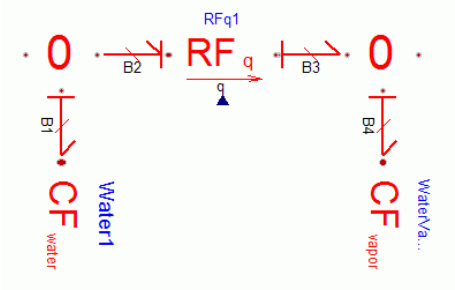
However, it we wish to model convective flows correctly, i.e., track masses through the model, each bond needs to be replaced by a triple bond, one carrying entropy, the second carrying volume, and the third carrying mass. These new bonds are called thermo-bonds. They are iconically represented as:



Each thermo-bond carries six variables: a thermal strand, consisting of the adjugate variables temperature, *T*, (as effort) and entropy flow, *Sdot*, (as flow); a volume strand, consisting of the adjugate variables pressure, *p*, (as effort) and volumetric flow, *Vdot*, (as flow); and a mass strand, consisting of the adjugate variables Gibbs potential, *g*, (as effort) and mass flow, *Mdot*, (as flow). The three parallel strands reflect the fact that, when a subset of mass is removed from a mass storage, the internal energy, *U*, changes by:

$$Udot = T \cdot Sdot - p \cdot Vdot + g \cdot Mdot$$

as shown in (Cellier 1991). The evaporation bond graph turns into:



There are two capacitive fields, CF, that store the state variables of the water and of the water vapor, respectively, i.e., entropy, volume, and mass. They compute the three potential variables (efforts): temperature, pressure, and Gibbs potential. The evaporation process, on the other hand, is described by a resistive field, RF, that computes the flows in and out of the two storages, such that the total power into the resistive field equals the total power out of the resistive field.

This approach to modeling condensation and evaporation was used by Greifeneder in a model of a pressure cooker, where it can very well happen that no liquid water remains at all in the pot Greifeneder 2001, Greifeneder/Cellier 2001c, Cellier/Greifeneder 2003).

This last bond graph shows the object-oriented nature of bond graph modeling. Whereas the bond graph elements of the regular bond graph library are fairly simple models, some of the elements of the thermo-bond graph library are quite elaborate. Yet, the overall model topology remained the same. The model complexity remains hidden inside the thermo-bond graph element models.

7. Summary

The paper describes a graphical approach to modeling aspects of ecological systems using bond graphs. Although the paper only dealt with questions of temperature and humidity, another student, Julia Miersch, worked on a bondgraphic model of plant growth inside Biosphere 2 (Miersch 1996). Her model was still fairly simple, identifying the major resistances and capacitances needed to describe plant growth using a bond graph. Whereas her model takes into account complex processes, such as photosynthesis and the opening and closing of pores in the context of evaporation, also her model doesn't track any material flows through the model, which will ultimately be needed if these models are to attain significance.

Although the Biosphere 2 project has meanwhile come to an end, it would still be interesting to translate the entire model to a thermo-bond graph, adding a model for the air handlers, such that both air and water can be tracked through the model. In this way, it would be possible to know, how much water is in the salt water pond at any point in time, how much water is down in the sweet water lake, at what level is the ceiling in the two lungs, etc.

8. Acknowledgments

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