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Bond graph modeling of heat and humidity budgets of biosphere 2

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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.

Keywords: Biosphere; Bond graph modeling; Thermodynamics

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 that needed to be cultivated as well. The plants required water and nutrients that 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 on planet Earth to this date, involving 1800 sensors of different kinds, measuring the state of Biosphere 2 at 15 min 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 sunshine 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 et al., 1999). Due to the use of bond graphs, the model was no longer monolithic,

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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 and 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. This conversion made it possible to correct a number of additional errors that had slipped through the earlier conversion.

The paper presented here starts out in Section 2 with a short introduction into bond graphs and power flows. It continues in Section 3 with an elaboration of the relevance of bond graphs in the context of modeling thermodynamic systems. Section 4 introduces Biosphere 2. Sections 5–7 deal briefly with some of the basic physical mechanisms of thermodynamic modeling: heat storage, conduction, and radiation. In Section 8, the paper elaborates on models of evaporation and condensation, explaining, how bond graphs were used in modeling the transitions from sensible to latent heat, and vice versa. It then elaborates on the shortcomings of this approach to modeling the phenomena of evaporation and condensation in the context of the Biosphere 2 model, and proposes an improved model based on thermo-bond graphs (Cellier and Greifeneder, 2003). Section 9 summarizes some simulation results obtained with the model. In Section 10, shortcomings of the current model are explained, especially as they concern the simulation of convective flows. Finally, Section 11 offers a short outlook on other related activities and future research.

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:

$$P = ef \tag{1}$$

A bond represents the flow of power from one location to another. Its iconic representation is shown in Fig. 1. 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. A bond, in Dymola, is realized as a graphical object. A name is associated with each object. The name, here B1, is depicted below the bond.

In the bond graph literature, the two adjugate variables, e and f, are often depicted next to the bond in place of the object name. In that case, the effort, e, is presented on the side of the harpoon, whereas the flow, f, is shown on the opposite side. This alternate graphical representation of a bond is shown in Fig. 2.

In order to simulate a bond graph, it is necessary to determine equations for the two adjugate variables. In all physical systems, it so happens that each of the two connectors generates one of the two equations capturing the behavior of the two adjugate variables. The side, where the flow variable is being computed, can be graphically marked by a so-called causality stroke. The so enhanced bond is shown in Fig. 3. In the given example, the flow variable is computed at the emanating node, whereas the effort variable is computed at the receiving node of the bond. In the bond graph literature, bonds with a causality stroke are called causal bonds, whereas bonds without such a stroke are called a causal bonds.

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).

Fig. 4 shows the natural effort and flow variables of the most common physical domains. Also shown are two additional variables that play a central role in the bond graph methodology: the generalized momentum, p, and the generalized position, q, whereby p is the integral of e over time and q denotes the integral of f over time. The names of these two variables were borrowed from the mechanical domain, and these two variables are indeed the same p and q variables that are commonly used in the modeling of mechanical systems by means of a Hamiltonian.

The three central modeling elements of the bond graph methodology are two energy storage elements: the capacitance, C, and the inductance, I, as well as one dissipative element: the resistance, R. Here, the names are borrowed from the electrical domain. Fig. 5 shows the three basic modeling elements in relation with the four fundamental variables of the

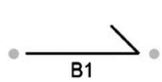

Fig. 1. Graphical representation of a bond.

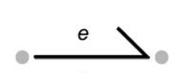

Fig. 2. Alternate graphical representation of a bond.

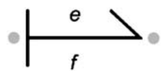

Fig. 3. Graphical representation of a causal bond.

bond graph methodology. A dissipative phenomenon can always be written in the form of a (possibly non-linear) algebraic relationship between an effort, e, and a flow, f. A capacitive storage is a (possibly also non-linear) algebraic relationship between e and q. Finally, an inductive storage is a (possibly non-linear) algebraic relationship between f and p. All of these functional relationships must exist strictly in the first and third quadrant of the plane spanned by the two variables in question.

It is beyond the scope of this paper to explain in detail, how bond graphs are being constructed in general (Cellier, 1991), and how they are being implemented in Dymola with Modelica. We refer to (Cellier and 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 and 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,

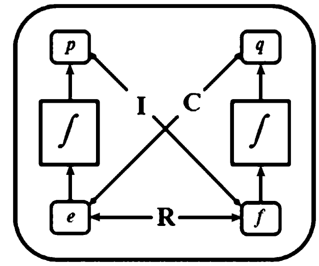

Fig. 5. Basic modeling elements of the bond graph methodology.

which may cause difficulties, when thermodynamic models are coupled to other models (Thoma and 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 nonlinear 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 and Cellier, 2001a,b,c).

The reader may further observe that there is no entry in Fig. 4 for thermodynamic systems in the column of the generalized momentum, p. Thermodynamic and chemical systems

	Effort	**Flow**	**Generalized Momentum**	**Generalized Position**
	e	***f***	***p***	***q***
Electrical Circuits	Voltage u (V)	Current i (A)	Magnetic Flux Φ(V·sec)	Charge q (A·sec)
Translational Systems	Force F (N)	Velocity v (m / sec)	Momentum M (N·sec)	Position x (m)
Rotational Systems	Torque T (N·m)	Angular Velocity ω (rad / sec)	Torsion T (N·m·sec)	Angle φ (rad)
Hydraulic Systems	Pressure p (N /m2)	Volume Flow q (m3 / sec)	Pressure Momentum Γ (N·sec /m2)	Volume V (m3)
Chemical Systems	Chem. Potential μ (J /mol)	Molar Flow ν (mol/sec)	-	Number of Moles n (mol)
Thermodynamic Systems	Temperature T (K)	Entropy Flow S' (W / K)	-	Entropy S (J / K)

Fig. 4. Fundamental variables of the bond graph methodology.

have the peculiar property that they do not seem to possess inductive storage elements.

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.

Fig. 6 shows a view of Biosphere 2 from the outside. 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 Sonora desert biome. The agricultural biome cannot be seen on this picture, as it is behind the building.

Fig. 7 shows an inside view of Biosphere 2. Depicted are the salt-water 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 5 m deep, and houses a variety of salt-water fish and even a corral reef. Artificial tides were introduced to keep the mangroves healthy.

Fig. 8 shows a part of the air-conditioning system installed in the basement of Biosphere 2. The engineering system of Biosphere 2 is highly impressive. Huge 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, before it is blown back into the vegetation area of Biosphere 2. The extracted water is collected in channels, through which it flows down-hill into one of the two lungs, the lowest point of the Biosphere 2 system, where it forms a small sweet-water lake. From there, the water is recycled by pumps to generate rain over the tropical rain forest, located at the highest point of the Biosphere 2 structure.

Fig. 6. Glass-panel frame construction of Biosphere 2.

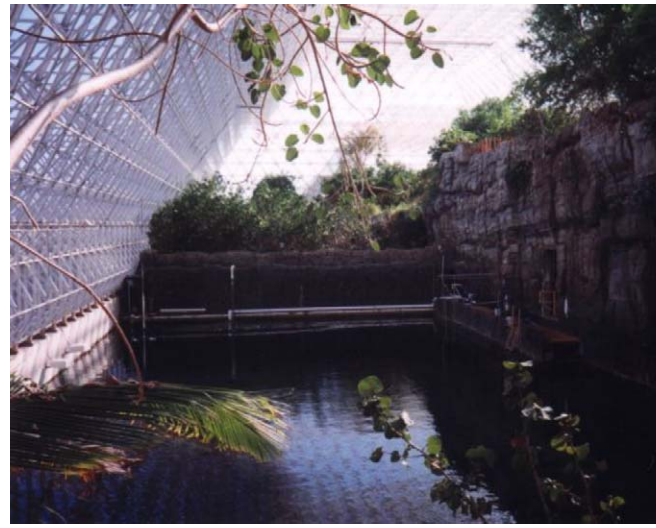

Fig. 7. Inside view of Biosphere 2.

Fig. 9 depicts one of the two lungs. 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 means of 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. The engineering concept used in the construction of the lungs is shown in Fig. 10.

In the model presented in this paper, 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. Fig. 11 shows the bond graph of the entire Biosphere 2 structure.

In order to understand this model, it is necessary to dig more deeply into bond graph modelling.

5. Heat storage

We need to discuss how power is being transported through a bond graph. The bond graph methodology offers two junctions that enable the user to model the splitting or merging of power flows: the 0-junction and the 1-junction. These two modeling elements are shown in Fig. 12. The effort variables around a 0-junction assume the same value, whereas the flow variables add up to zero. In a 1-junction, the opposite assumption is being made.

Consequently, each thermodynamic body that is characterized by homogeneous temperature, i.e., a distinct effort value, can be modeled as a 0-junction. The temperature of that body is computed by the heat capacitance associated with that 0-junction, i.e., one of the models attached to each of the 0-junctions is a capacitor. Yet, the capacitance values of a true thermodynamic bond graph are not constant. They are divided by the temperature (Cellier, 1991). Hence, we use

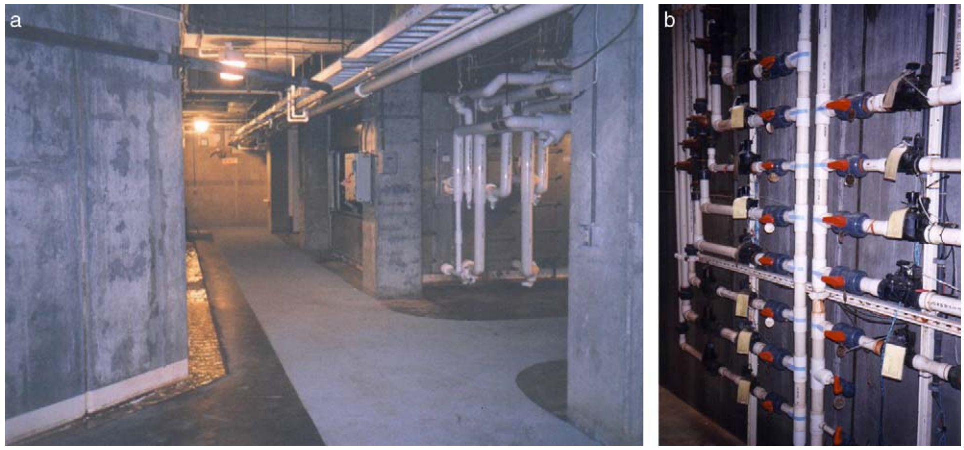

Fig. 8. Air-conditioning system of Biosphere 2.

a special thermal capacitance model, the C_{th} element, to represent heat storage.

Distinct heat storages are used in the Biosphere 2 model to represent the soil, the vegetation, the salt-water pond, the dome, and the inside atmosphere.

6. Heat conduction

Heat flows from a hotter to a cooler body by means of heat conduction, i.e., potential equilibration. The heat conduction is proportional to the difference between the temperatures of the two bodies. Fig. 13 illustrates this concept.

The two 0-junctions to the left and to the right represent the two bodies that are at temperatures T_1 and T_2, respectively. The 1-junction in between them computes the temperature difference, ΔT. A heat flow, $\dot{S}$, is generated that is proportional to the temperature difference, ΔT. Consequently, we need a resistance, R. Yet, since we compute a flow rather than an effort, it may be more natural to model this phenomenon as a conductance, G. For symmetry reasons, the conductance is split into two separate conductance elements of equal size, each generating a flow of $\dot{S}/2$. Since thermal resistances are multiplied by the temperature T, the thermal conductance is divided by T, and we therefore use special non-linear thermal conductance elements, G_{th}. Yet, the heat dissipated in these conductance elements cannot disappear. It has to come out from the other end. Therefore, the conductance elements act, on their secondary sides, as entropy flow sources. We thus use GS_{th} elements. The additional entropy flows generated in this fashion are routed right back to the neighboring 0-junctions.

The heat conductance model is represented at the next hierarchical level as a CV element. Many of these CV elements are shown in Fig. 11, representing heat flow from one body to another by means of conduction.

7. Heat radiation

Another mechanism for exchanging heat between bodies is by means of heat radiation. A body radiates heat proportional to the fourth power of the temperature. Hence this is another resistive phenomenon. A bond graph representation of two bodies radiating against each other is shown in Fig. 14.

As radiation heat flow is a function of the temperature of the radiating body itself, rather than a function of a temperature difference, the bond leading to the corresponding GS element emanates now directly at the 0-junction representing the radiating body. A different type of GS element, GS_{rad}, is used here, since the radiation conductance needs to be multiplied by the square of the temperature, rather than being divided by it (Cellier, 1991). The bond graph of Fig. 14 is represented at the next higher hierarchical level as an RA element. Several of these RA elements are shown in the bond graph of Fig. 11 that represents the entire Biosphere 2 structure.

Fig. 9. South lung of Biosphere 2.

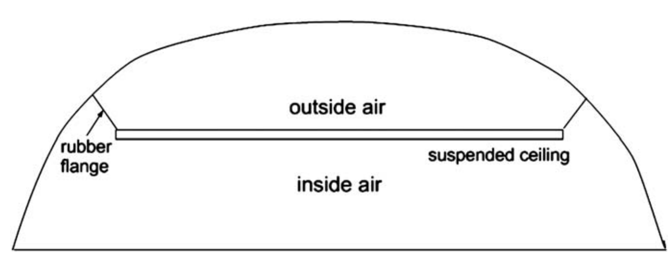

Fig. 10. Operational principle of the lungs at Biosphere 2.

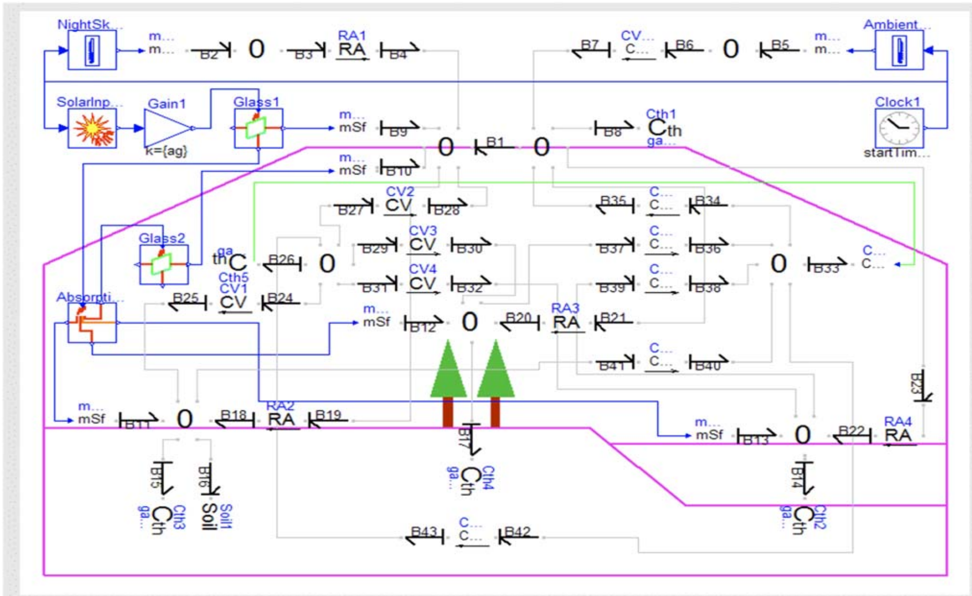

Fig. 11. Bond graph representing Biosphere 2.

8. Evaporation and condensation

The atmosphere is represented as two separate storages in the bond graph of Fig. 11, 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.

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).

A conceptual bond graph model of the process of evaporation is shown in Fig. 15. 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 humidity as the effort variable. Thus, the effort is now measured in kg water/kg air. Since power was expressed in the Biosphere 2 model in

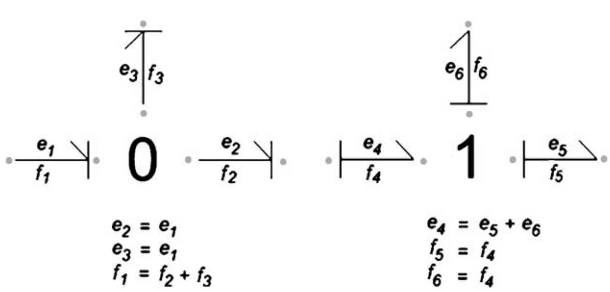

Fig. 12. The two junction types of the bond graph methodology.

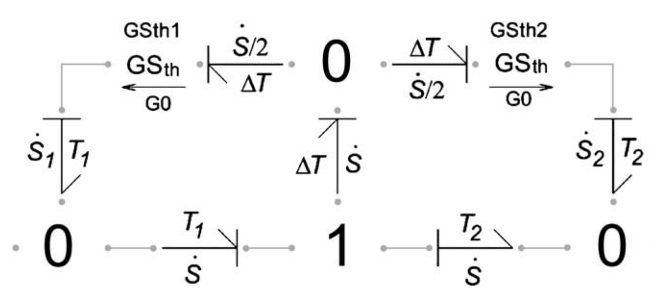

Fig. 13. Bond graph heat conductance model.

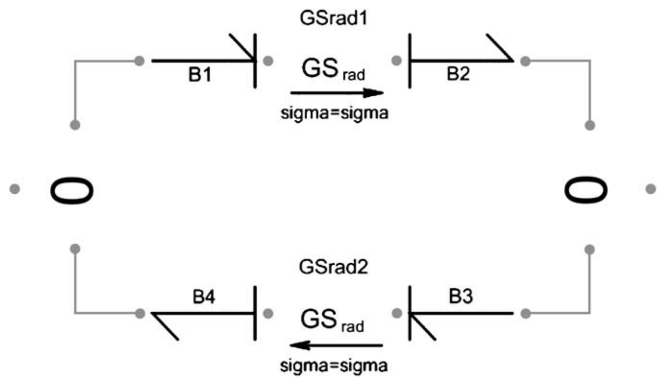

Fig. 14. Bond graph heat radiation model.

kJ/h, the units of flow had to be kJ kg air/(h kg water). There is no choice in that matter any longer, since the product of effort and flow must be power.

Since linear resistance is defined by the equation:

$$e = Rf \tag{2}$$

we know that linear 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 resistors of the humidity domain are non-linear. They need to be multiplied with the effort variable, just as in the case of the thermal domain (Cellier, 1991).

Since the linear capacitance is defined by the equation:

$$f = C\,\mathrm{der}(e) \tag{3}$$

where der( ) is the derivative operator, linear capacitance would have to be expressed in the units kJ kg air^2/kg water^2. However, the capacitance of the humidity domain will be also non-linear. It must equal the linear capacitance divided by the effort variable, 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 the variables used for modeling latent heat are not 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.

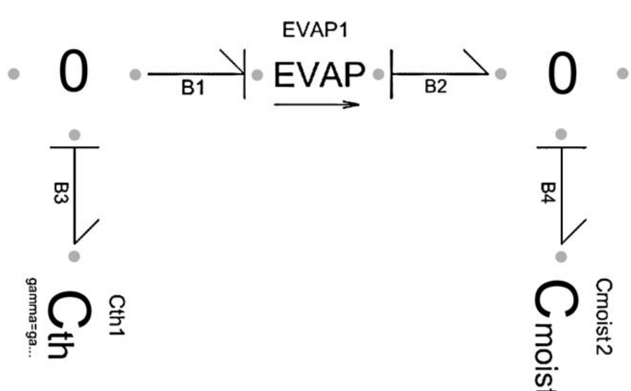

Fig. 15. Conceptual bond graph model of evaporation.

9. Simulation results

The bond graph model of Fig. 11 was simulated in Dymola (Brück et al., 2002; Elmqvist, 1978) across 8600 hours of simulated time, representing a full year, using its graphical bond graph library (Cellier and McBride, 2003; Cellier and Nebot, 2005). The simulation took only a few seconds to complete.

Fig. 16 shows the temperature of the air inside Biosphere 2 as a function of time. Since no air-conditioning was taken into account, the structure heats up tremendously during the summer. The average temperature difference between day and night is roughly 10 °C.

Fig. 17 shows the relative humidity as a function of time plotted over a three-day period. Water evaporates constantly from the salt-water pond and the vegetation into the air. There is no mechanism in place to ever get rid of that humidity again. Hence the structure is almost always at 100% relative humidity. Condensation will just be enough to drive the water out that the atmosphere cannot hold. In the evening, as it gets cooler, more condensation takes place, as the dew point drops down. Yet, the relative humidity still remains at 100%. Only in the morning, when the air heats up and the dew point rises again, the relative humidity will fall below 100% for a short while, until renewed evaporation saturates the air once more.

In the real Biosphere 2 system, air-conditioning controls not only the temperature, but also the humidity levels. This is why the air is cooled down not only to the desired temperature, but below that value, so that enough of the humidity condensates out. The air is then re-heated to its desired temperature value. The tropical rain forest reaches 100% relative humidity during evening hours, i.e., when the atmosphere

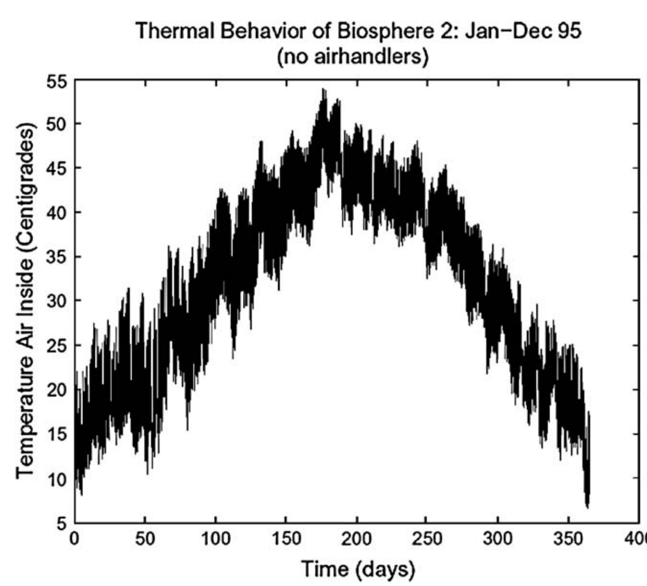

Fig. 16. Air temperature inside Biosphere 2 as a function of time.

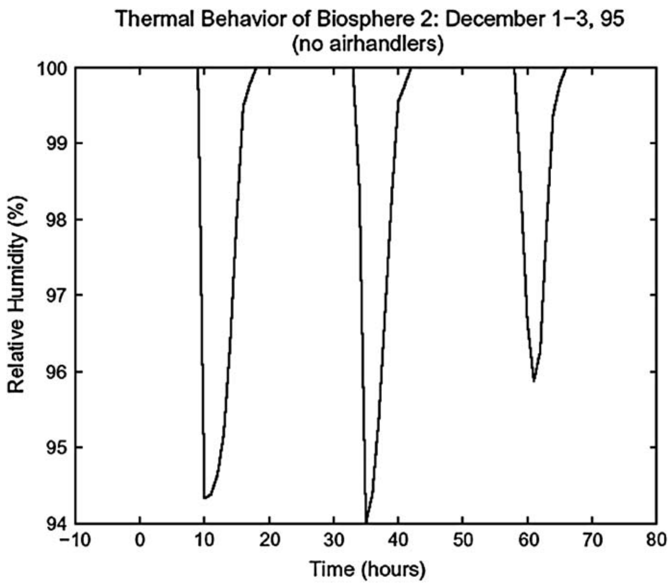

Fig. 17. Relative humidity inside Biosphere 2 as a function of time.

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.

10. Shortcomings of the model

Leaving out the air-conditioning system was by no means a small omission, as air-conditioning invariably means moving air around. Until now, we did not concern ourselves with moving masses, and this simplified the modelling task tremendously. It is possible to consider (and model) heat flow without accompanying mass flow, but it is not possible to model mass flow without accompanying heat flow, as the moving masses always carry their heat along.

If we wish to consider moving masses, we must recognize that *mass* is always associated with *volume* and *heat* (or entropy). Each of the three state variables is associated with a corresponding potential variable. In the case of entropy flow, that potential variable is temperature, T. In the case of volumetric flow, the associated potential variable is the pressure, p. Finally in the case of mass flow, the corresponding potential variable is the free Gibbs potential, g. The product of the potential variable with the derivative of the corresponding state always has the dimension of power.

In order to facilitate the thermodynamic modelling of convective flows, Greifeneder introduced a new thermo-bond graph library (Cellier and Greifeneder, 2003; Greifeneder and Cellier, 2001a,b,c; Greifeneder, 2001). Thermo-bonds represent the three parallel flows of entropy, volume, and mass.

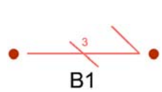

Fig. 18. Iconic representation of a thermo-bond.

The iconic representation of the thermo-bond is depicted in Fig. 18.

Each thermo-bond carries six variables: a thermal strand, consisting of the adjugate variables temperature, T, (as effort) and entropy flow, $\dot{S}$, (as flow); a volume strand, consisting of the adjugate variables pressure, p, (as effort) and volumetric flow, $\dot{V}$, (as flow); and a mass strand, consisting of the adjugate variables free Gibbs potential, g, (as effort) and mass flow, $\dot{M}$, (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:

$$\dot{U} = T\dot{S} - p\dot{V} + g\dot{M} \tag{4}$$

as shown in (Cellier, 1991).

The evaporation bond graph turns into the thermo-bond graph of Fig. 19. Each 0-junction here represents a body with its own temperature, pressure, and Gibbs potential. Attached to each 0-junction is a capacitive field, CF that models the physical properties of the associated body. In particular, the capacitive field computes the values of the three potential variables associated with the body. The model of Fig. 19 shows a capacitive field for the water, and another one for water vapor.

Transport of mass, volume, and/or entropy from one 0-junction to another is always a resistive phenomenon. It is described by a resistive field, RF. Transport occurs on its own as long as there are potential differences between neighboring bodies. Heat exchange is only one such equilibration mechanism. Others include the pressure/volume exchange, as well as evaporation and condensation. Transport can also be forced, as in the case of the air-conditioning system.

The new approach allows us to replace the strictly empirical model of Teten by a more physically based model. The so modified evaporation model is still fairly complex though, as the associated resistive (or conductive) fields are highly nonlinear. They are usually modeled using steam tables.

Also, the so enhanced model allows us to finally track the water through the system. The original model did not tell us, how much water was left in the salt-water and sweet-water ponds or stored in the plants at any point in time. The new model does proper book-keeping of all of the elements in

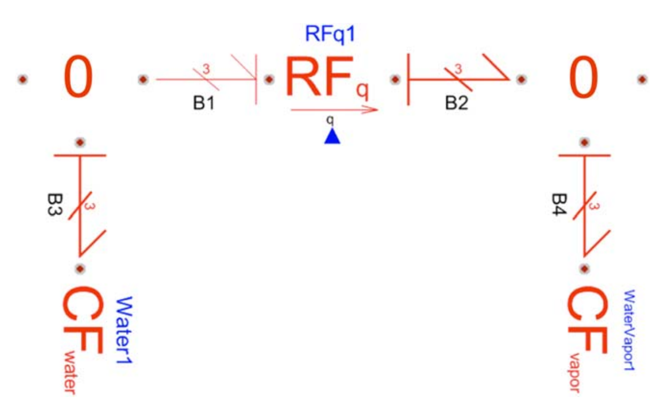

Fig. 19. Thermo-bond graph of evaporation.

the model. It tells us, how much water is where, and it also allows us to compute the height of the suspended ceilings in the two lungs at any point in time.

The enhanced model is considerably more complex than the original model. Yet, the added complexity remains mostly hidden inside the descriptions of the various types of capacitive and resistive fields. The topology of the overall bond graph does not change.

11. Outlook

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 bond graph description 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 bond graph methodology. 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 does not track any material flows through the model, which will ultimately be needed if these models are to attain significance.

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