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SCIENCE DIRECT
Environmental Modelling & Software 21 (2006) 1598–1606
Environmental Modelling & Software
www.elsevier.com/locate/envsoft

Bond graph modeling of heat and humidity budgets of biosphere 2

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Received 3 May 2006; accepted 3 May 2006
Available online 19 June 2006

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.
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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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doi:10.1016/j.envsoft.2006.05.006

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.

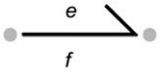

Fig. 2. Alternate graphical representation of a bond.

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