Modeling and Simulation of a Solar Energy System by Use of Bond Graphs

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Abstract

This paper describes a new approach to determine the thermodynamic behavior of a building structure. The bond graph technique is used to model the physical laws of heat transfer between the basic components of a house regarding conduction, convection, and radiation. The modeling language Dymola is used to provide a convenient platform for creating hierarchical and modular component descriptions in readable code. This new approach is compared with two state-of-the-art building analysis programs, CALPAS 3 and DOE-2. For comparison, the thermal performance of an experimental house has been evaluated by all three programs. The results for temperature profiles and heat flow rates have been found to be very similar. Dymola proved to be an excellent modeling tool, very suitable for modeling systems with modular components.

1 Introduction

Modeling and simulation as analysis tools for designing buildings prior to their construction have become indispensable in finding the right performance data and providing essential information to the engineer or architect [7]. Point of interest is the thermal performance of the building. Temperatures are obtained in order to determine the living conditions inside the house, and load rates are of interest in order to devise the heating and cooling systems. Many parameters must be evaluated to optimize the general design. This can only be done if the used program provides flexible system description and variable outputs.

Flexibility in system description and accuracy in results are strongly related to the chosen modeling methodology. CALPAS 3 [3] as well as DOE-2 [4] are special-purpose ***procedural*** languages. They are fairly easy to use as long as the application fits precisely within the realm of what these programs were designed for. It is almost impossible to use these programs for anything else. Simulation results are obtained from hour-by-hour thermal network simulation, generally following the methods suggested by ASHRAE [6]. The new approach uses bond graphs to describe the physics of heat transfer. The bond graph models are then encoded in Dymola [1, 2]. Dymola is an ***object-oriented*** modeling language. The overall system is modeled by invoking models of subsystems. Thus, models of complex systems are assembled from models of simpler systems in a hierarchical fashion.

2 The Modeling Tool

Dymola (DYnamic MOdeling LAnguage), a software designed by H. Elmquist in his PhD. Dissertation [2], serves as a front end to several simulation languages. In this application, it acts as an advanced macro handler (preprocessor) for the simulation language ACSL (Advanced Continuous Simulation Language) [5]. Dymola is an object-oriented modeling language, very suitable for bond graph applications. Some of its advantages are the convenience to define ***submodels*** with well-structured interfaces (***cuts*** and ***paths***) that can easily be invoked and linked by use of the ***connect*** statement.

The major strength of Dymola is its capability to handle hierarchically structured models such as bond graph models. The cut concept of Dymola allows to declare across and through variables to the cut. Dymola provides nodes that are equivalent to 0-junctions in bond graph terminology. This means that elements attached to a 0–junction in the bond graph can be connected to a node in Dymola. There is no Dymola equivalent to a 1–junction. However, since in bond graph models, the junction–types always toggle between 0– and 1–junctions, a model type ***bond*** can be provided that simply interchanges flow and effort variables. If such a ***bond*** object is placed between all adjacent junction pairs, both 0– and 1–junctions can be described by Dymola nodes.

```
- bond graph bond "
model type bond
  cut A (x / y), B (y / -x)
  main cut C [A B]
  main path P <A - B>
end
```

3 The Model Description

The main model *HOUSE* invokes a variety of smaller models that are related to the constructive elements of the house. Consequently, model types need to be provided that describe external walls, internal walls, roofs, windows, and the slab. All these models invoke yet smaller submodels that describe the physics of heat transfer considering ***conduction***, ***convection***, and ***radiation***.

3.1 Conduction

The thermal process of conduction is also called heat transfer by diffusion. This phenomenon can be expressed in the so–called ***heat diffusion equation***, which, in the case of one–dimensional heat transfer, takes the form:

$$\frac{\partial T}{\partial t} = \sigma \frac{\partial^2 T}{\partial x^2} \tag{1}$$

Partial differential equations (PDEs) can be simulated by using the method–of–lines approach, i.e., by discretizing the space axes, while keeping the time axis continuous. Thereby, the former PDE is mapped into a set of ordinary differential equations (ODEs) that can be simulated using standard simulation technology. In this application, a centered difference formula was used to discretize the x–axis into n intervals.

$$\frac{dT_k(t)}{dt} = \frac{\sigma}{\Delta x^2}[T_{k+1}(t) - 2T_k(t) + T_{k-1}(t)] \tag{2}$$

By applying the electrical analogon shown on Fig. 1, the bond graph for one segment of the diffusion chain can be found as given in Fig. 2. The Dymola code for this bond graph model is presented in Fig. 3.

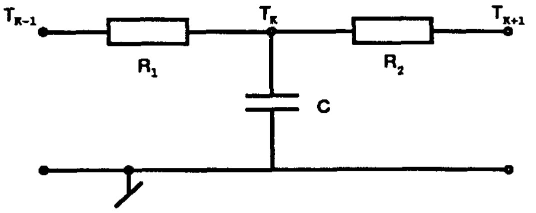


Figure 1: Electrical analogy of diffusion cell

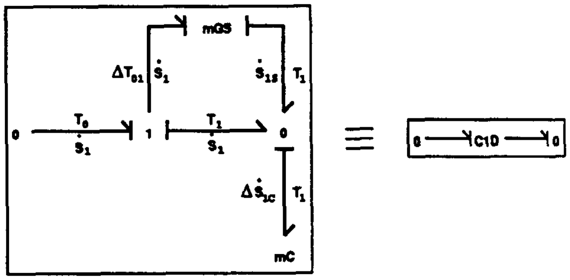
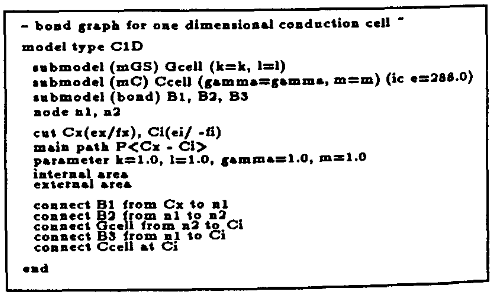


Figure 2: Bond graph of a one-dimensional conductive cell



```
- bond graph for one dimensional conduction cell "
model type C1D
  submodel (mGS) Gcell (k=k, l=l)
  submodel (mC) Ccell (gamma=gamma, m=m) (ic e=288.0)
  submodel (bond) B1, B2, B3
  node n1, n2
  cut Cx(ex/fx), Ci(ei/ -fi)
  main path P<Cx - Ci>
  parameter k=1.0, l=1.0, gamma=1.0, m=1.0
  internal area
  external area
  connect B1 from Cx to n1
  connect B2 from n1 to n2
  connect Gcell from n2 to Ci
  connect B3 from n1 to Ci
  connect Ccell at Ci
end
```

Figure 3: Dymola code of the *C1D* model

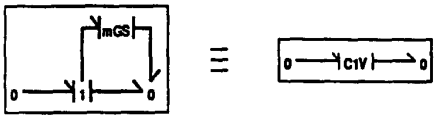


Figure 4: Bond graph of a one-dimensional convective cell

```
- bond graph for one dimensional convection cell "
model type C1V
  submodel (mGS) Gcell (k=h, l=1.0)
  submodel (bond) B1, B2, B3
  node n1, n2
  cut Cx(ex/fx), Ci(ei/ -fi)
  main path P<Cx - Ci>
  parameter h=1.0
  internal area
  external area
  connect B1 from Cx to n1
  connect B2 from n1 to n2
  connect Gcell from n2 to Ci
  connect B3 from n1 to Ci
end
```

Figure 5: Dymola code of the *C1V* model

3.2 Convection

Convective heat transfer is determined by two mechanisms: the energy transfer due to random molecular motion (diffusion), and bulk motion of fluid. In the case of convective heat transfer occurring between a fluid/gas and a bounding surface, *Newton's law of cooling* can be applied.

$$\dot{Q} = Ah\Delta T \qquad (3)$$

The *film coefficient h* encompasses all parameters that influence convective heat transfer along the surface. The bond graph for a one–dimensional convective cell is shown in Fig. 4, and the corresponding Dymola code is given in Fig. 5.

3.3 Radiation

Thermal radiation is energy emitted by matter at a finite temperature. Because the surface temperatures inside the house are quite low, radiation exchange between surfaces was omitted. The solar power applied by irradiation was implemented as a flow source. Two phenomena were modeled. The absorbed energy of all exposed surfaces, *model SUN*, and the transmitted energy though a glazing, *model SHGF*. The irradiation on an exposed surface is determined overall by the extraterrestrial radiation, the Earth atmosphere, and the effects of orienting a receiving surface. These calculations were obtained following the methods proposed by ASHRAE [6].

The radiation transmitted through a glazing is calculated by using Solar heat gain factors (SHGF) and a shading coefficient (SC) as suggested by ASHRAE.

Figure 6: Bond graph of the *SUN* model

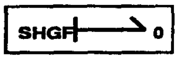


Figure 7: Bond graph of the *SHGF* model

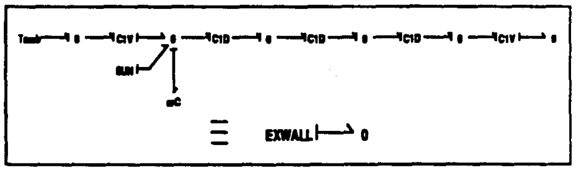


Figure 8: Bond graph of the *EXWALL* model

3.4 External and Internal Walls

The external wall is exposed to solar radiation and outside temperature. The *model type EXWALL* invokes submodels providing the solar radiation (*SUN*), the outside temperature (*Tamb*), conduction (*C1D*), and inside/outside convective heat transfer (*C1V*), as shown on Fig. 8. The outside temperature (*Tamb*) is modeled as an effort source. In order to avoid an algebraic loop, a capacity was added to the conduction chain. The bond graph model for an internal wall provides the connection between two adjacent rooms, as seen in Fig. 9. These bond graph models can be easily encoded in Dymola by envoking the needed submodels and supplying appropriate data. As an example, the Dymola code of the *EXWALL* model is given in Fig. 10.

3.5 Window

Heat flow through fenestration areas is affected by solar irradiation and transmittance as well as by outdoor/indoor temperature difference. The bond graph describing these phenomena is shown in Fig. 11.

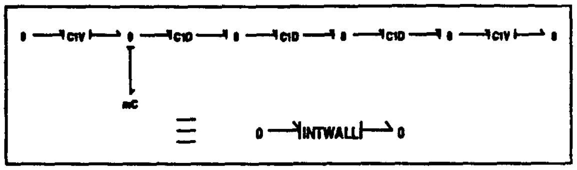
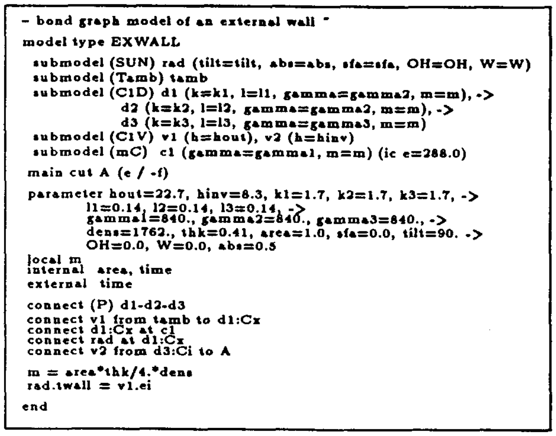


Figure 9: Bond graph of the *INTWALL* model



```
- bond graph model of an external wall "
model type EXWALL
  submodel (SUN) rad (tilt=tilt, abs=abs, sfa=sfa, OH=OH, W=W)
  submodel (Tamb) tamb
  submodel (C1D) d1 (k=k1, l=l1, gamma=gamma2, m=m), ->
                 d2 (k=k2, l=l2, gamma=gamma2, m=m), ->
                 d3 (k=k3, l=l3, gamma=gamma3, m=m)
  submodel (C1V) v1 (h=hout), v2 (h=hinv)
  submodel (mC)  c1 (gamma=gamma1, m=m) (ic e=288.0)
 main cut A (e / -f)
 parameter hout=22.7, hinv=8.3, k1=1.7, k2=1.7, k3=1.7, ->
          l1=0.14, l2=0.14, l3=0.14, ->
          gamma1=840., gamma2=840., gamma3=840., ->
          dens=1762., thk=0.41, area=1.0, sfa=0.0, tilt=90. ->
          OH=0.0, W=0.0, abs=0.5
 local m
 internal  area, time
 external  time
 connect (P) d1-d2-d3
 connect v1 from tamb to d1:Cx
 connect d1:Cx at c1
 connect rad at d1:Cx
 connect v2 from d3:Ci to A
 m = area*thk/4.*dens
 rad.twall = v1.ei
end
```

Figure 10: Dymola code of the *EXWALL* model

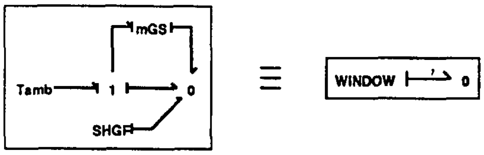


Figure 11: Bond graph of a sunlit glazing surface

3.6 Slab

The slab affects the building because of its large mass and heat capacity as well as heat loss. The bond graph model therefore consists of a convection, a capacity, and a loss submodel as shown in Fig. 12.

3.7 The House

The previously derived models for the construction elements were used to express the rooms/spaces of the building. Each space is modeled with a capacity (*mC*) representing the air mass inside the space. All elements at the boundaries of each space are connected to that capacity. In this way, all required submodels are referenced and assigned with the adequate properties.

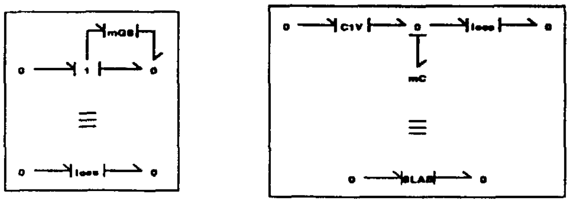


Figure 12: Bond graph of a slab

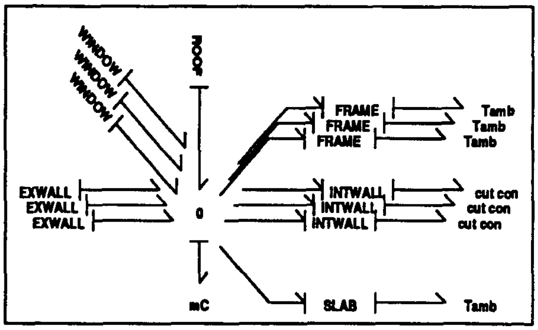


Figure 13: Bond graph of a space

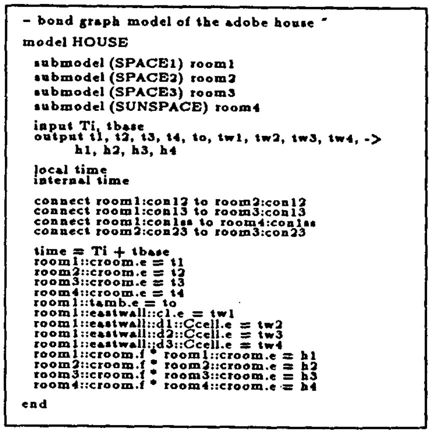
Cuts, called *cut con*$_{ij}$, are provided that correspond to the adjacent spaces. The bond graph of any given space can be seen in Fig. 13.

The last step of assembling the overall building connects the spaces together and results in the model *HOUSE*, the Dymola code of which is shown in Fig. 14. The connection cuts of the spaces are used to put the whole structure together, and the desired input and output variables are assigned. For the time–varying equations in some of the submodels, the simulation time *Ti* needs to be accessed. In order to be able to start the simulation at any time of the year, a starting point *tbase* is added, which can be modified between simulation runs. Values of the output variables can be collected with each simulation run. It has been found meaningful to collect the four room temperatures *t1* – *t4*, the outside temperature *to*, the temperatures following the distribution along an external wall *tw1* – *tw4*, and the heat flow rates into and out of each space.

4 Results

The performance of the new approach was studied by means of an experimental building. This house is an adobe structure that comprises three rooms and an attached sunspace. The building was modeled, and results were obtained using all three programs. Points of consideration were the capability of each of the programs to model the experimental building, the accuracy of the results, and the computation time.

In the analysis of the results, three perspectives were emphasized, namely radiation heat transfer through glazing, temperature profiles, and load analysis. It was found that, although the three programs approach the radiation calculations and heat transfer phenomena differently, the obtained results were quite similar.



```
- bond graph model of the adobe house "
model HOUSE
  submodel (SPACE1) room1
  submodel (SPACE2) room2
  submodel (SPACE3) room3
  submodel (SUNSPACE) room4
  input Ti, tbase
  output t1, t2, t3, t4, to, tw1, tw2, tw3, tw4, ->
        h1, h2, h3, h4
  local time
  internal time
  connect room1:con12 to room2:con12
  connect room1:con13 to room3:con13
  connect room1:con1ss to room4:con1ss
  connect room2:con23 to room3:con23
  time = Ti + tbase
  room1::croom.e = t1
  room2::croom.e = t2
  room3::croom.e = t3
  room4::croom.e = t4
  room1::tamb.e = to
  room1::eastwall::c1.e = tw1
  room1::eastwall::d1::Ccell.e = tw2
  room1::eastwall::d2::Ccell.e = tw3
  room1::eastwall::d3::Ccell.e = tw4
  room1::croom.f * room1::croom.e = h1
  room2::croom.f * room2::croom.e = h2
  room3::croom.f * room3::croom.e = h3
  room4::croom.f * room4::croom.e = h4
end
```

Figure 14: Dymola code of the *HOUSE* model

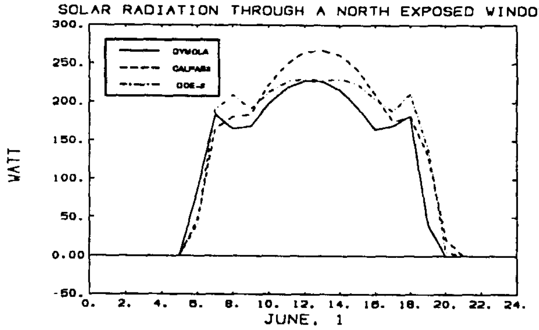


Figure 15: Solar radiation through a window exposed to the north

Fig. 15, Fig. 16, and Fig. 17 show examples of compared results.

5 Conclusions

A building analysis program was developed using bond graphs to describe the thermal behavior of the building. The bond graphs were encoded in Dymola, and the model was assembled in a hierarchical fashion using modular components. Bond graphs were found to be very well suited to model heat transfer phenomena, especially heat conduction. They are adequate to express the heat diffusion equation, preserving the topological structure of the physical system as well as giving access to the computational structure. In this way, bond graphs can be used to model thermal systems accurately and in a flexible manner. Dymola is a powerful tool for the modeling of modular and hierarchical systems. The cut concept and other features support the encoding of bond graphs, while the code preserves readability. The obtained results show that the new approach is capable of supporting building analysis. The difference in performance is a result of the different approaches taken by the three programs.

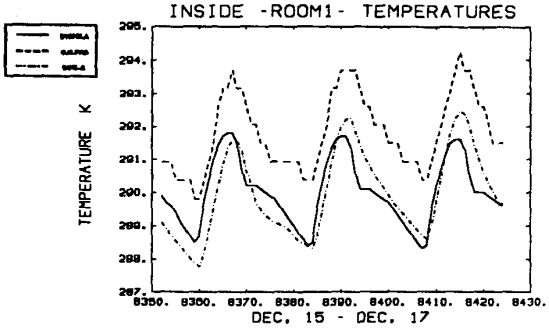


Figure 16: Inside temperatures for Dec. 15 – 17

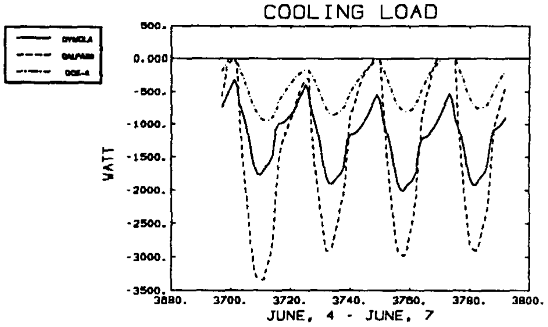


Figure 17: Cooling load in June

6 Acknowledgments

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