Thermal Modeling of Buildings

- This lecture deals with the model of a space heating system of a building by means of a passive solar system.
- The system is designed after a solar experimental building constructed in Tucson near the airport.
- The model is quite sophisticated. It models not only the physics of radiation through glassed windows, but also the weather patterns of Tucson.

Table of Contents

Passive Solar Space Heating I

Southside view with (dismantled) sunspace.

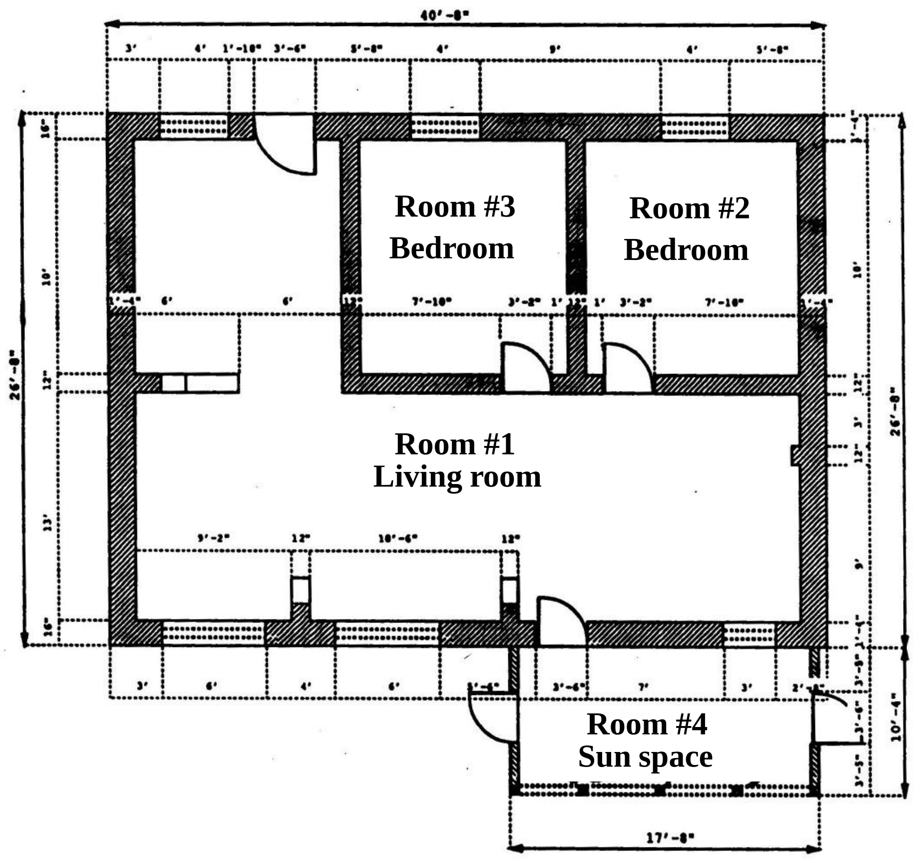
Northside view.

The house is constructed from Adobe brick. The photographs are rather recent. By the time they were taken, the house was no longer being used and had fallen a bit in disarray.

Passive Solar Space Heating II

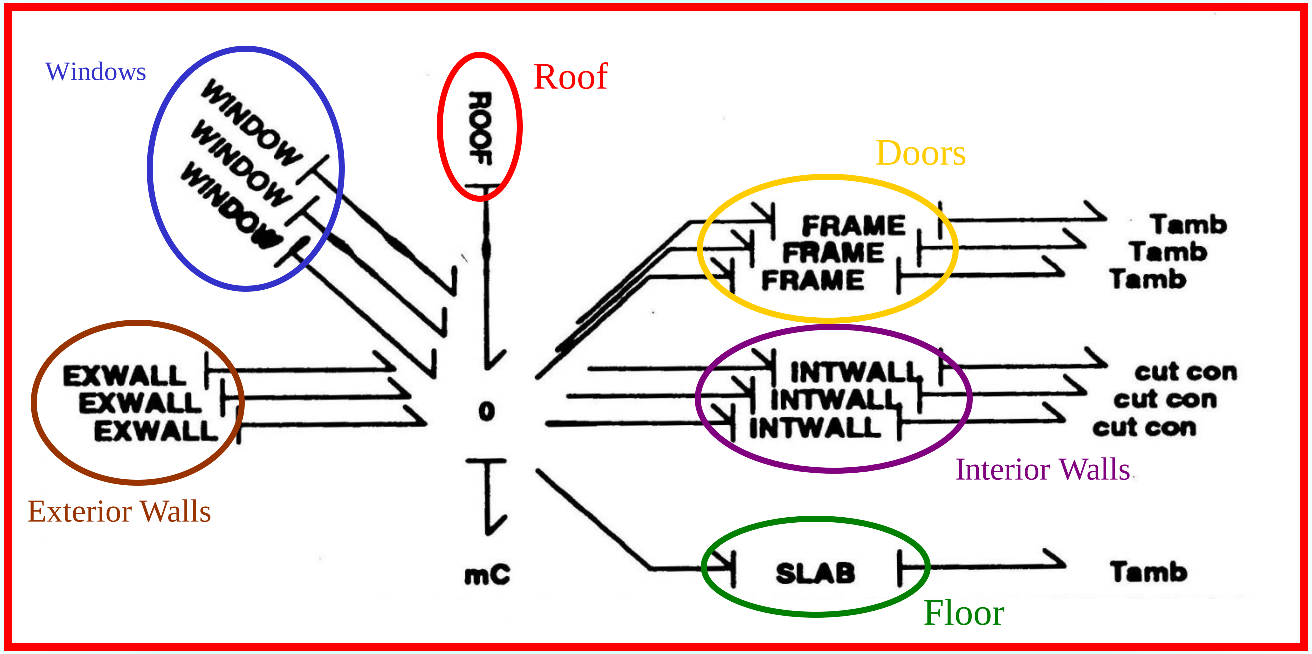
- The experimental solar building is shown here from three sides.
- Solar radiation through the walls, the windows, and the ceiling is to be modeled.
- Losses are also being modeled, including the losses through the slab.

Passive Solar Space Heating III



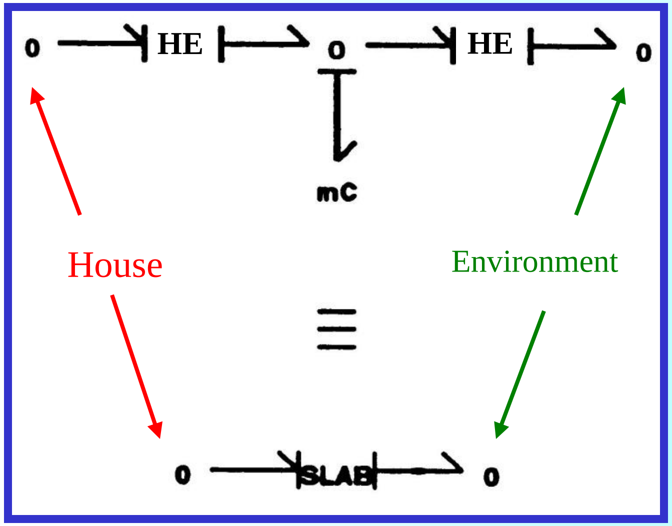
- The house has four rooms to be modeled: a living room, two bed rooms, and a sun space.
- It is assumed that the temperature within each room is constant, which makes it possible to model each room as a single 0-junction.
- … This is clearly an experimental house, as there is neither a bathroom nor a kitchen.

The Bond Graph of a Room



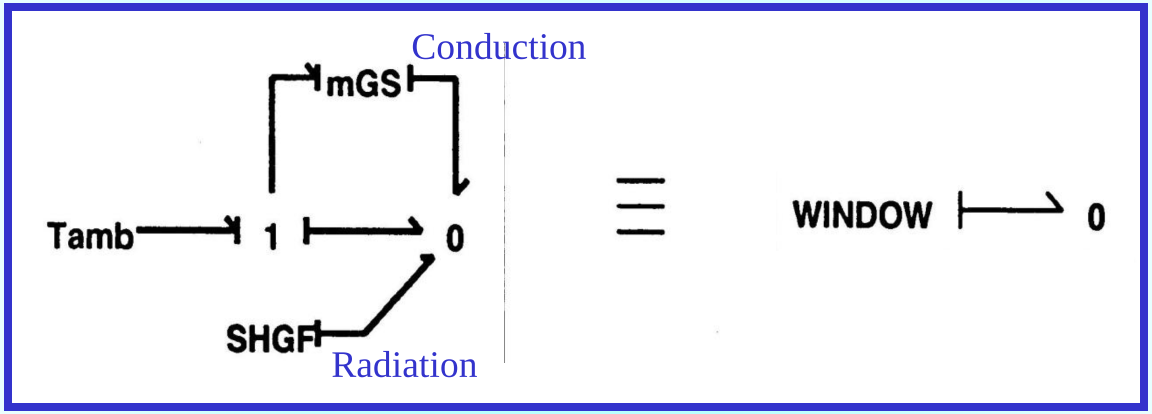
- Every room is modeled in approximately the same fashion. The model shows the heat capacity of the room as well as the interactions with the environment.

The Floor



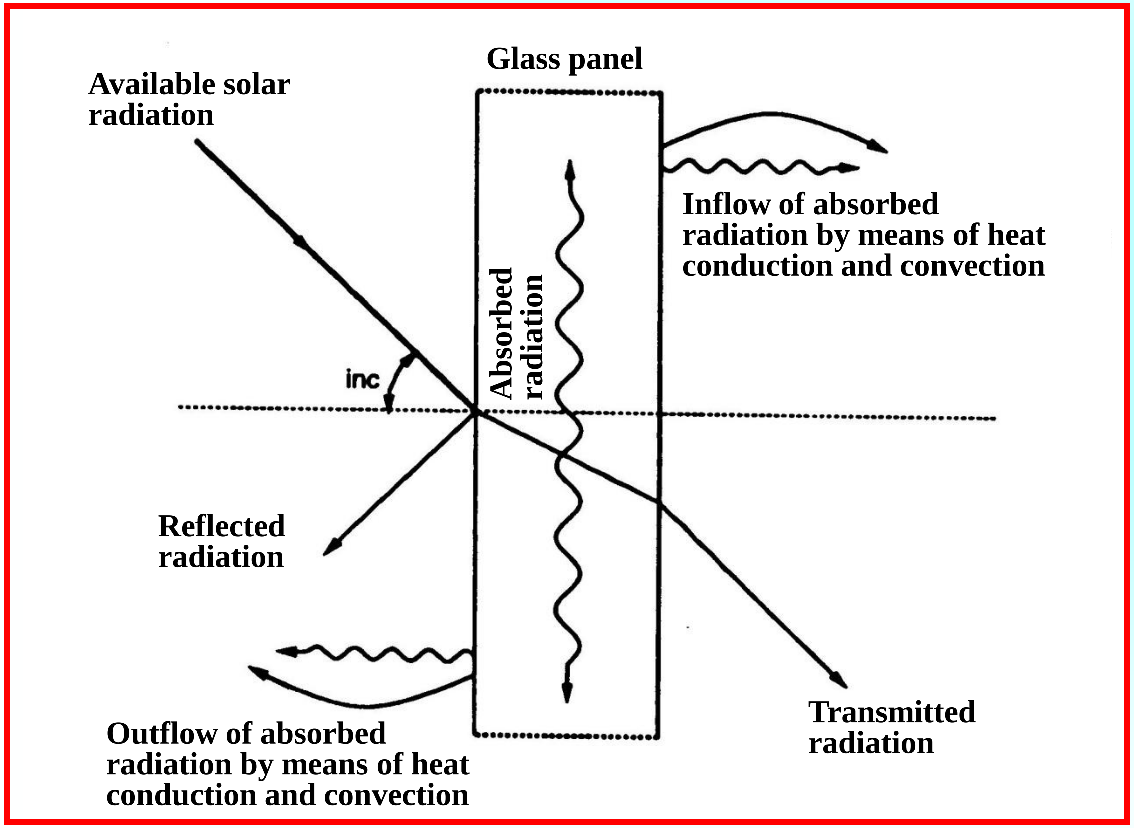
- The floor is modeled like a room.
- It has its own heat capacity (the slab under the house consists of gravel).
- It exchanges heat with the house.
- It also exchanges heat with the environment.
- It is important, not to represent the exchange with the environment as a loss, since during the summer, heat is also entering the building through the slab.

The Windows I



- Heat transport across the windows occurs partly by means of ***heat conduction***, and partly by means of ***radiation***.

The Windows II



- Modeling the radiation accurately is not easy, since several different phenomena must be considered, and since the radiation is furthermore a function of the day of the year and the time of the day.

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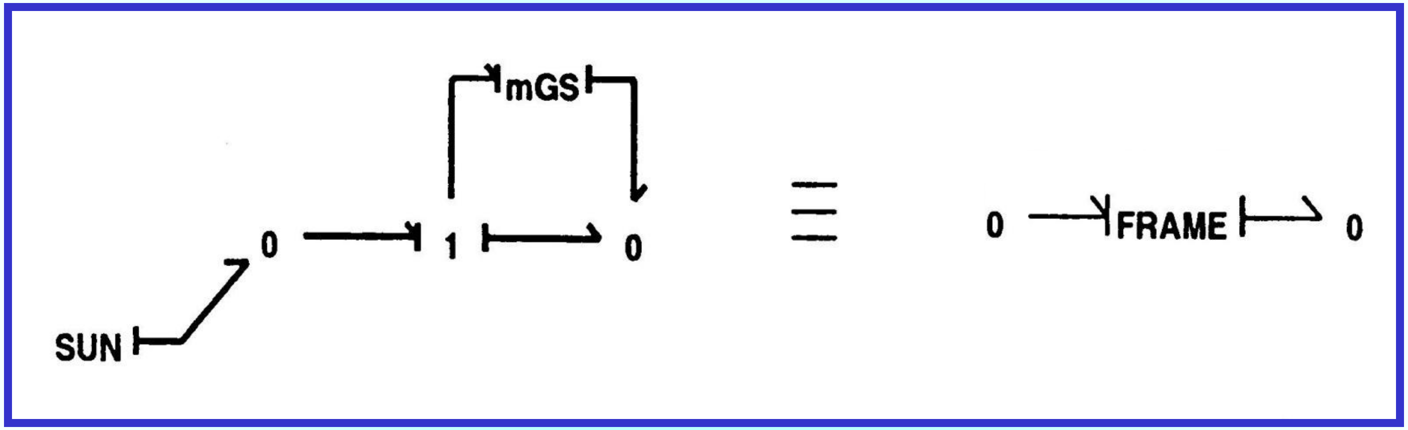
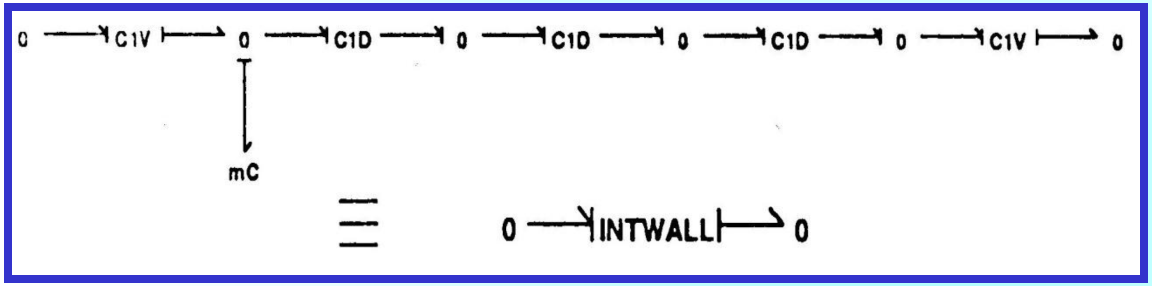
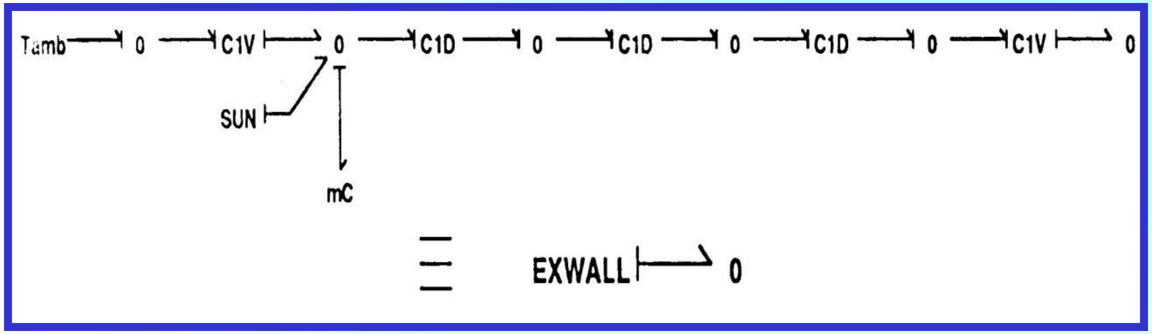
The Doors



- The doors are modeled similarly to the windows, yet there is no glass, and there exists an additional heat conduction through the wood of the door.

The Walls

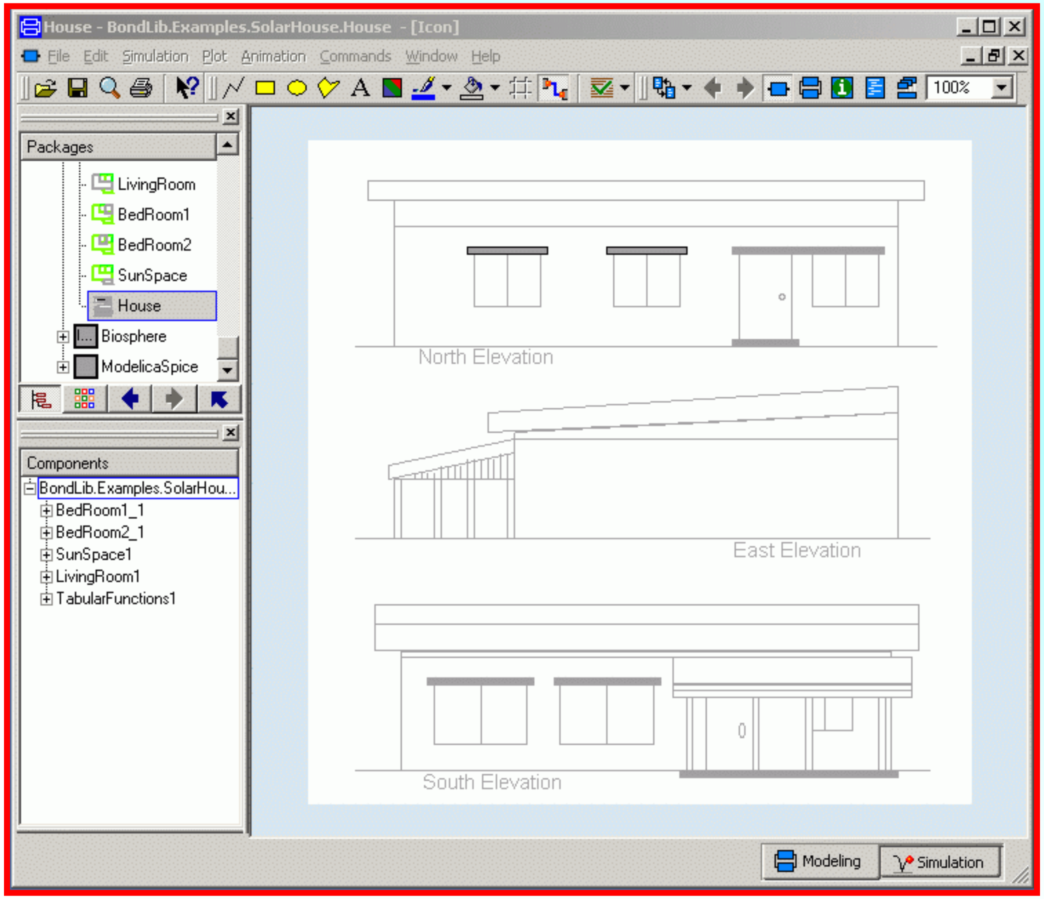




- Each wall is described by three heat conduction elements.
- At the two surfaces, there are additional convection elements modeling the transport of heat in the boundary layer.

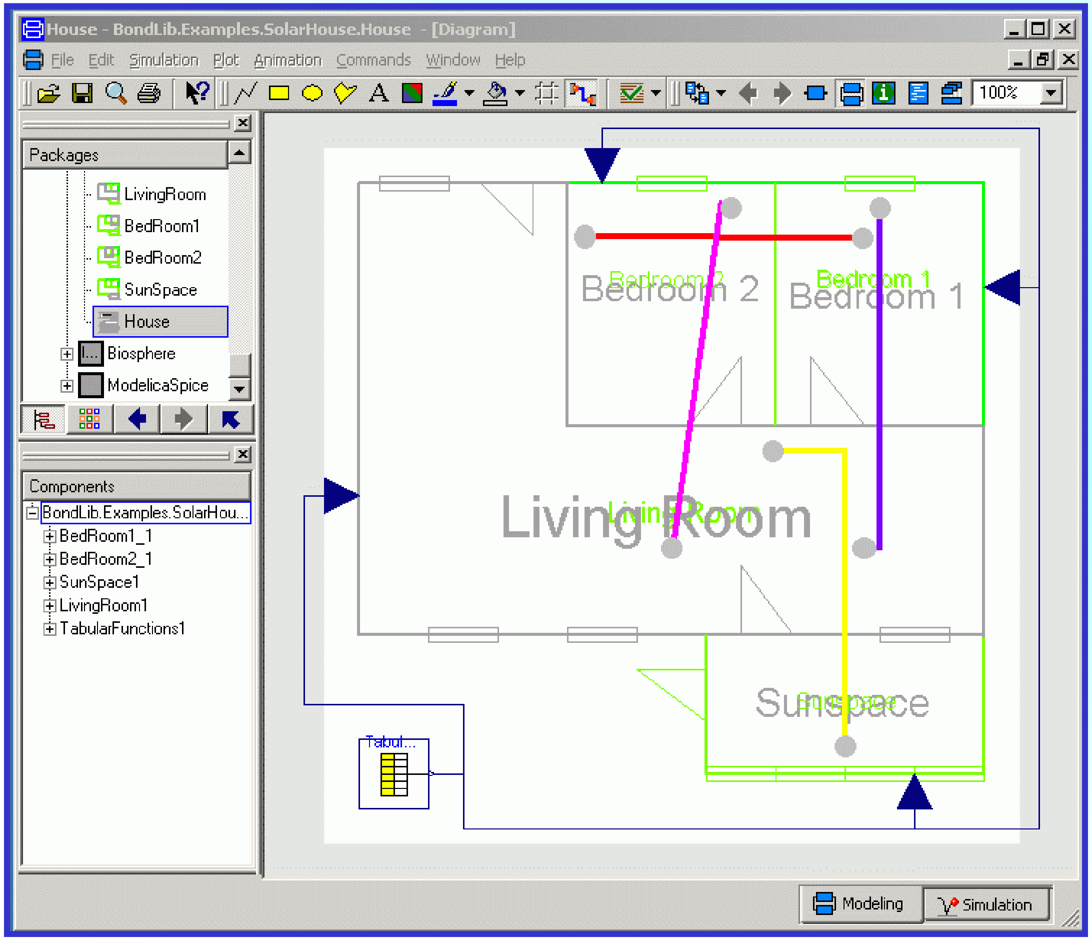
- The exterior walls consider in addition the influence of solar radiation.
- In this program, the heat conduction elements ***C1D*** contain on the right side a capacitor, whereas the convection elements ***C1V*** do not contain any capacity.

The *Dymola* Model I



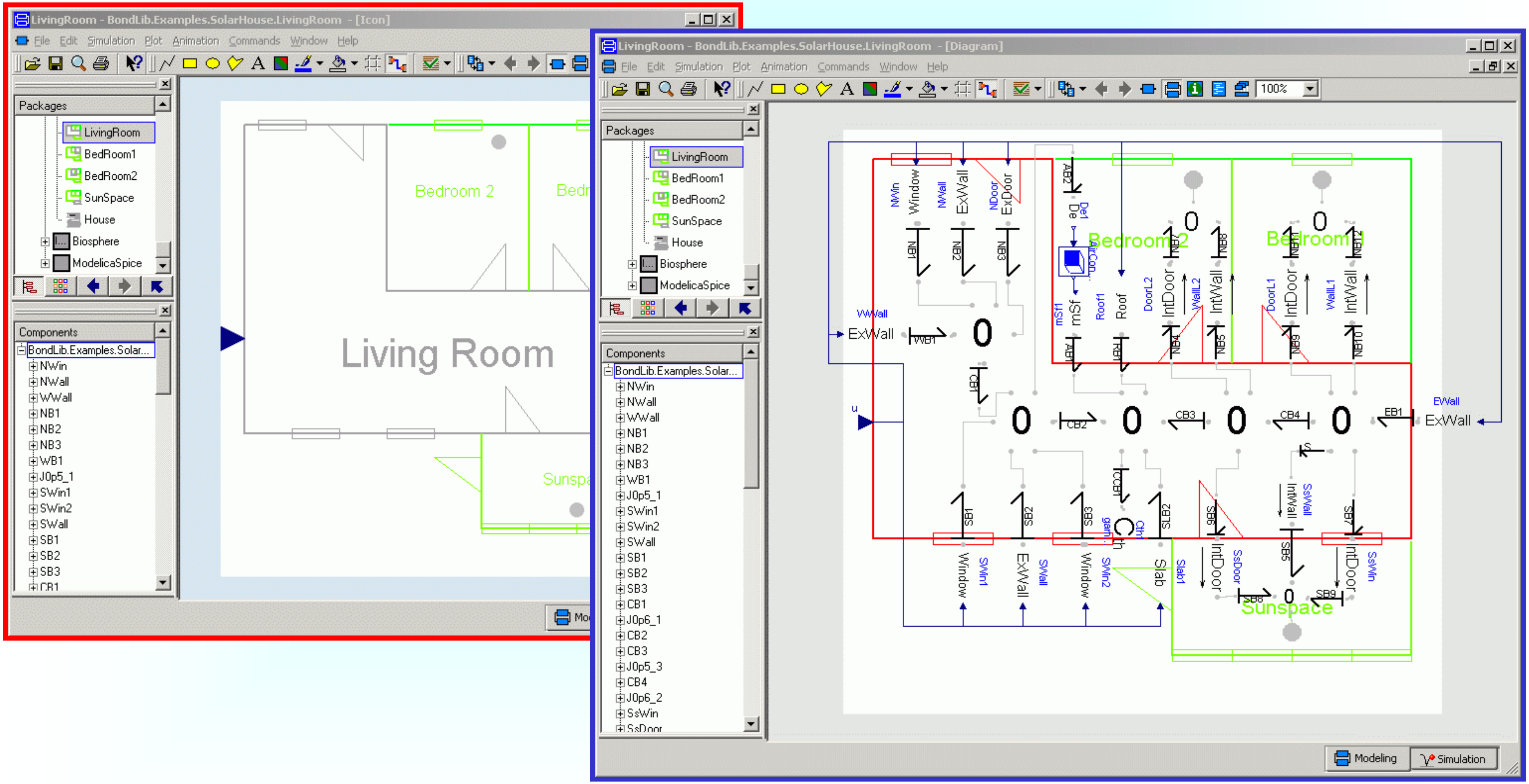
- The overall ***Dymola*** model is shown to the left.
- At least, the picture shown is the top-level icon window of the model.

The *Dymola* Model II

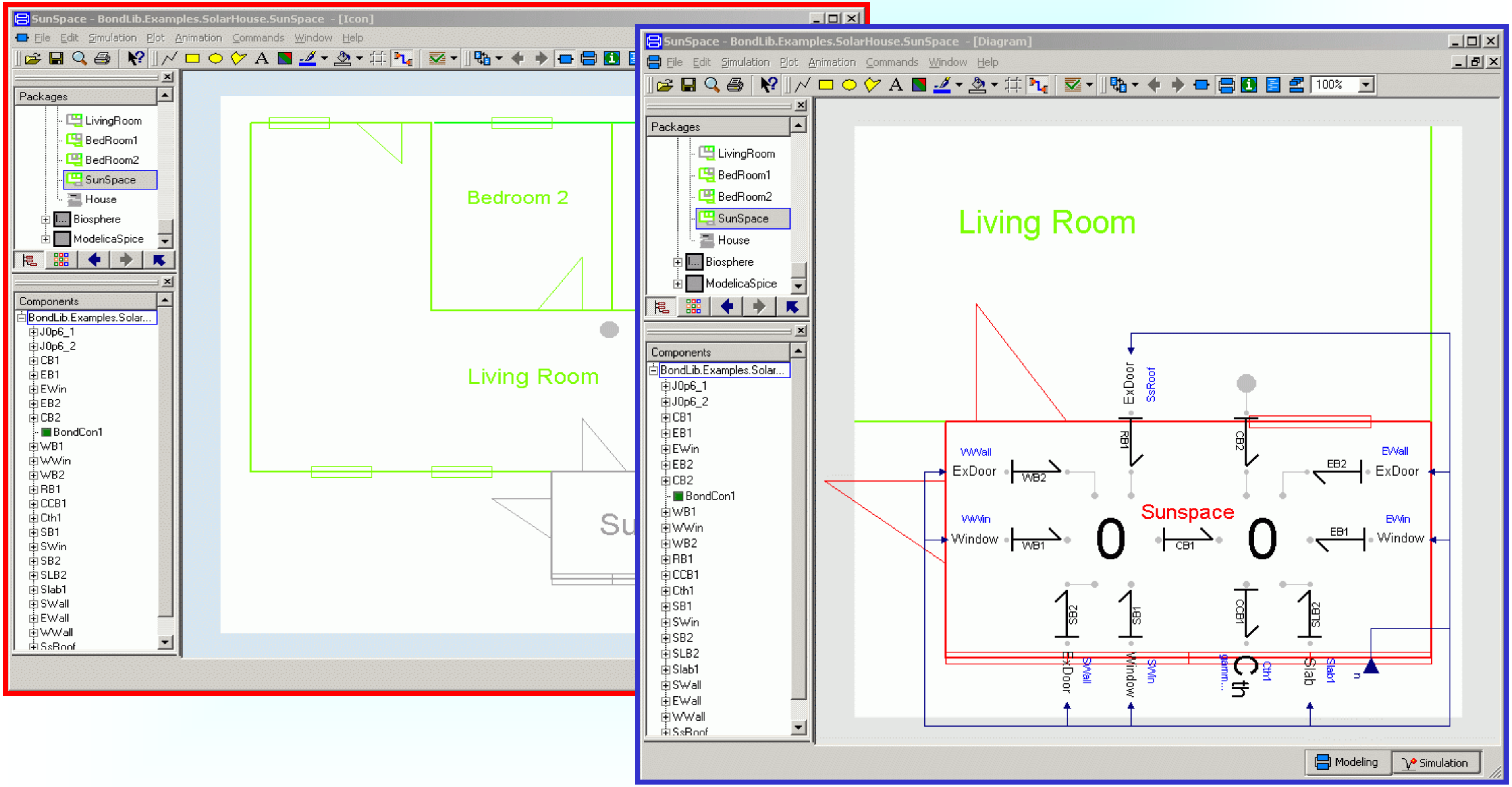


- Shown on the left side is the corresponding top-level diagram window.
- Each of the four rooms is a separate model.
- The four models are overlaid to each other.
- The bond graph connectors are graphically connected, connecting neighboring rooms to each other.

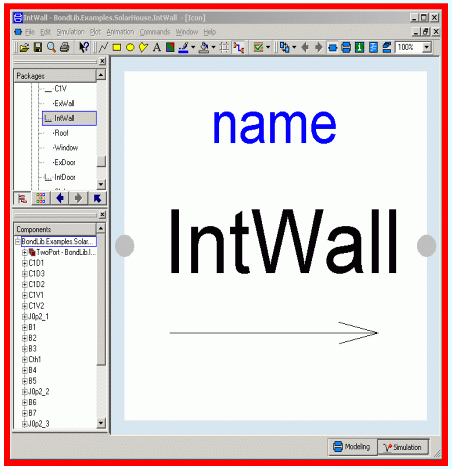
The Living Room

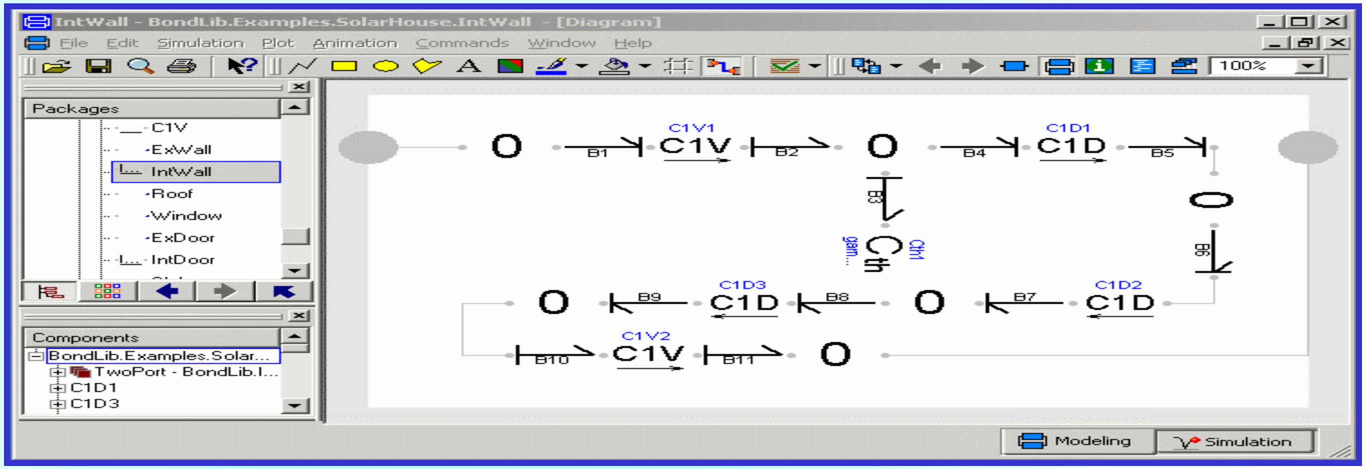


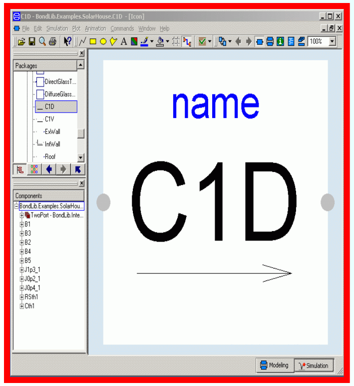
The Sunspace

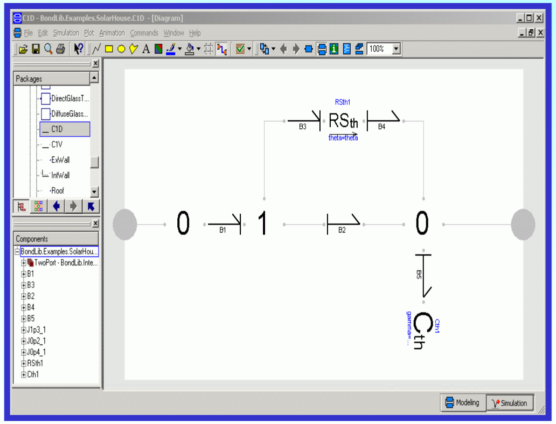


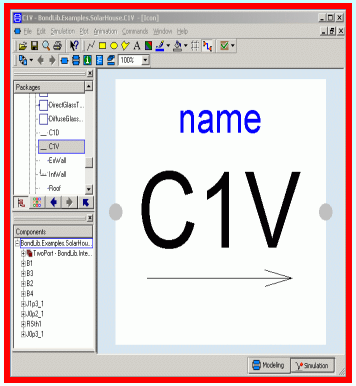
The Interior Wall

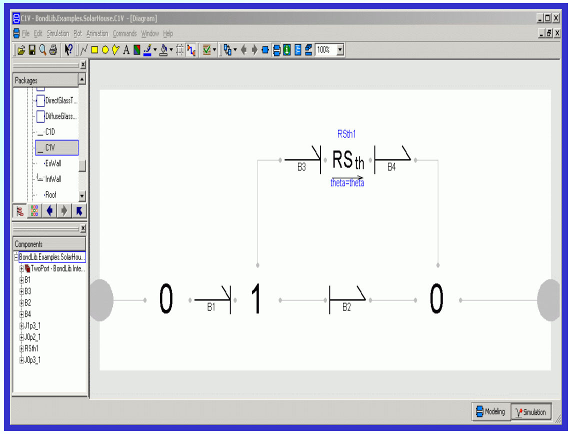




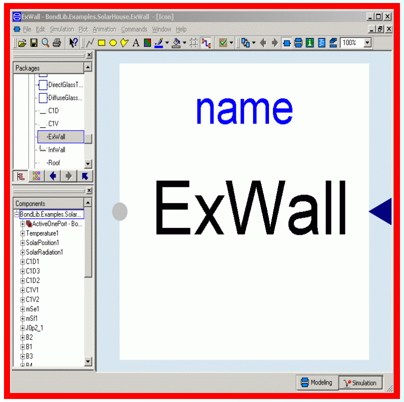


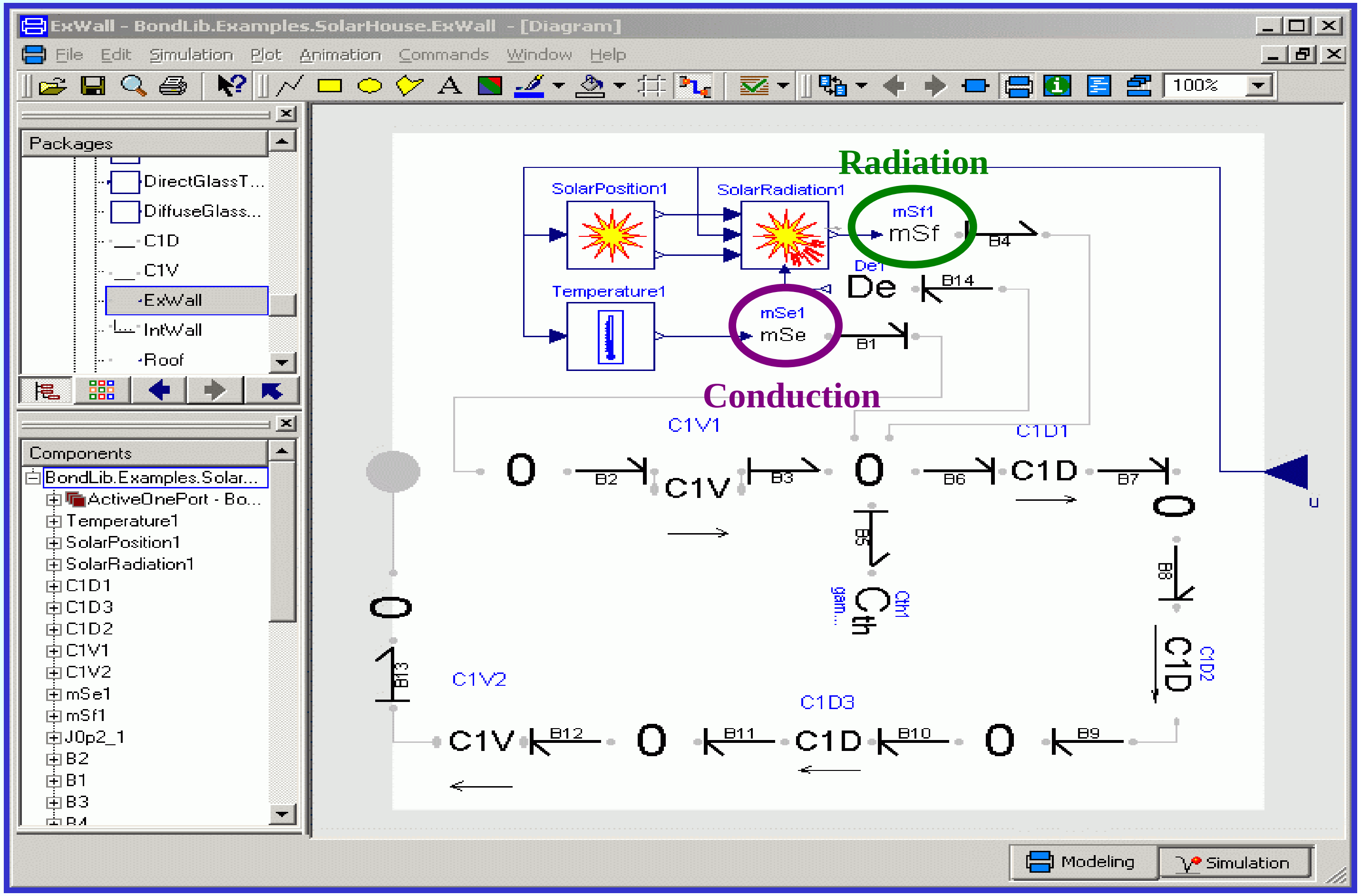




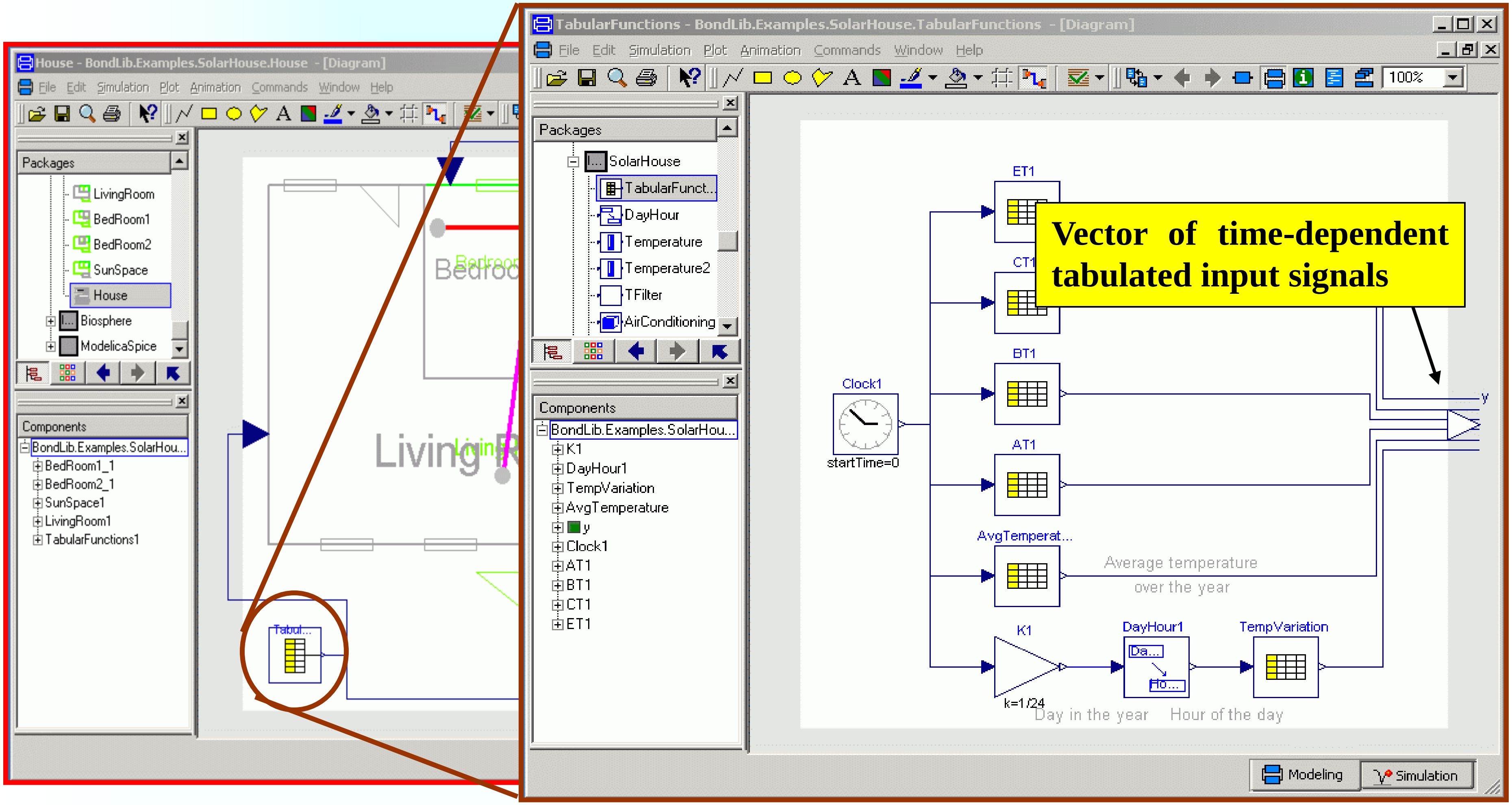


The Exterior Wall

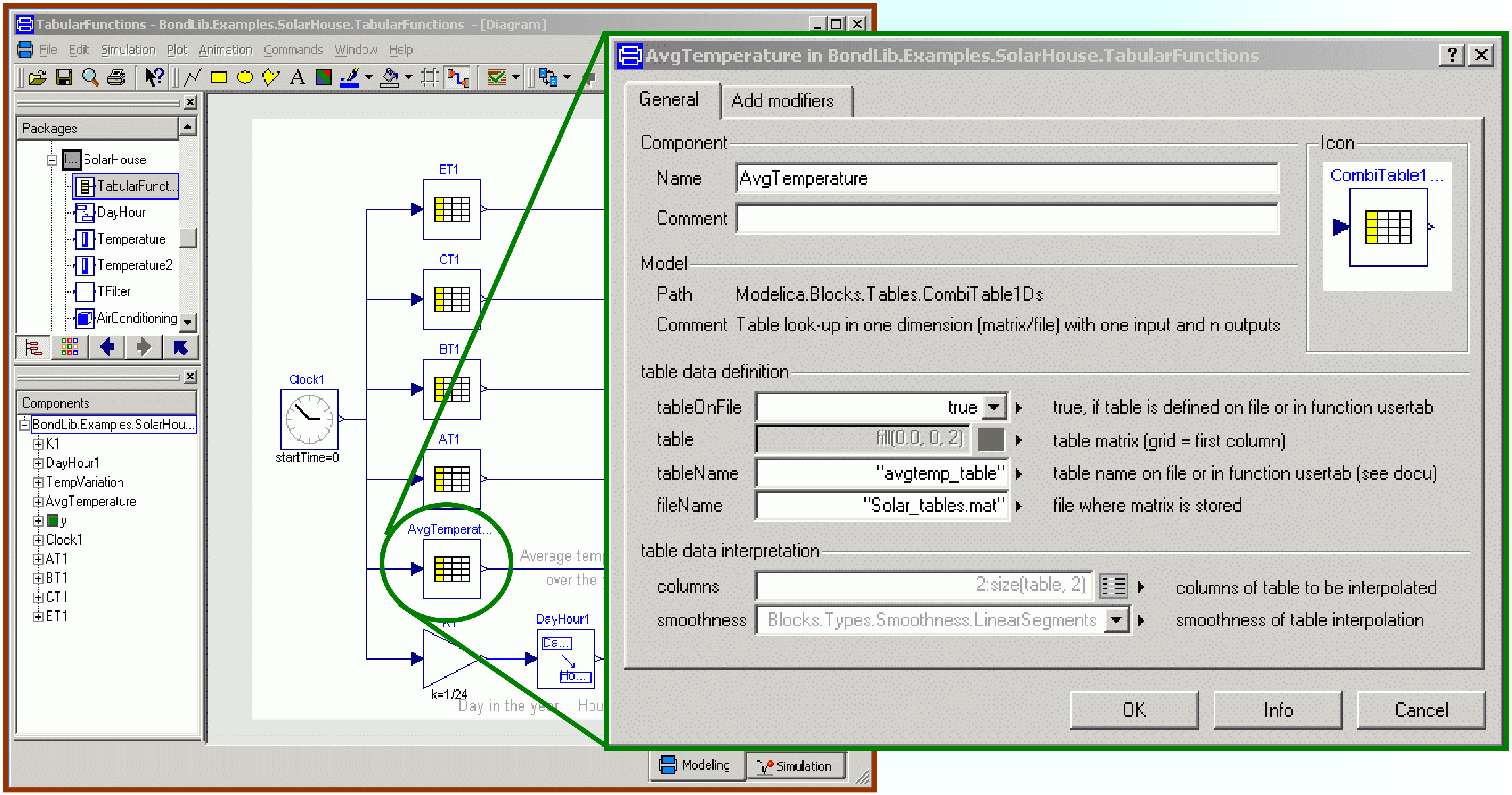




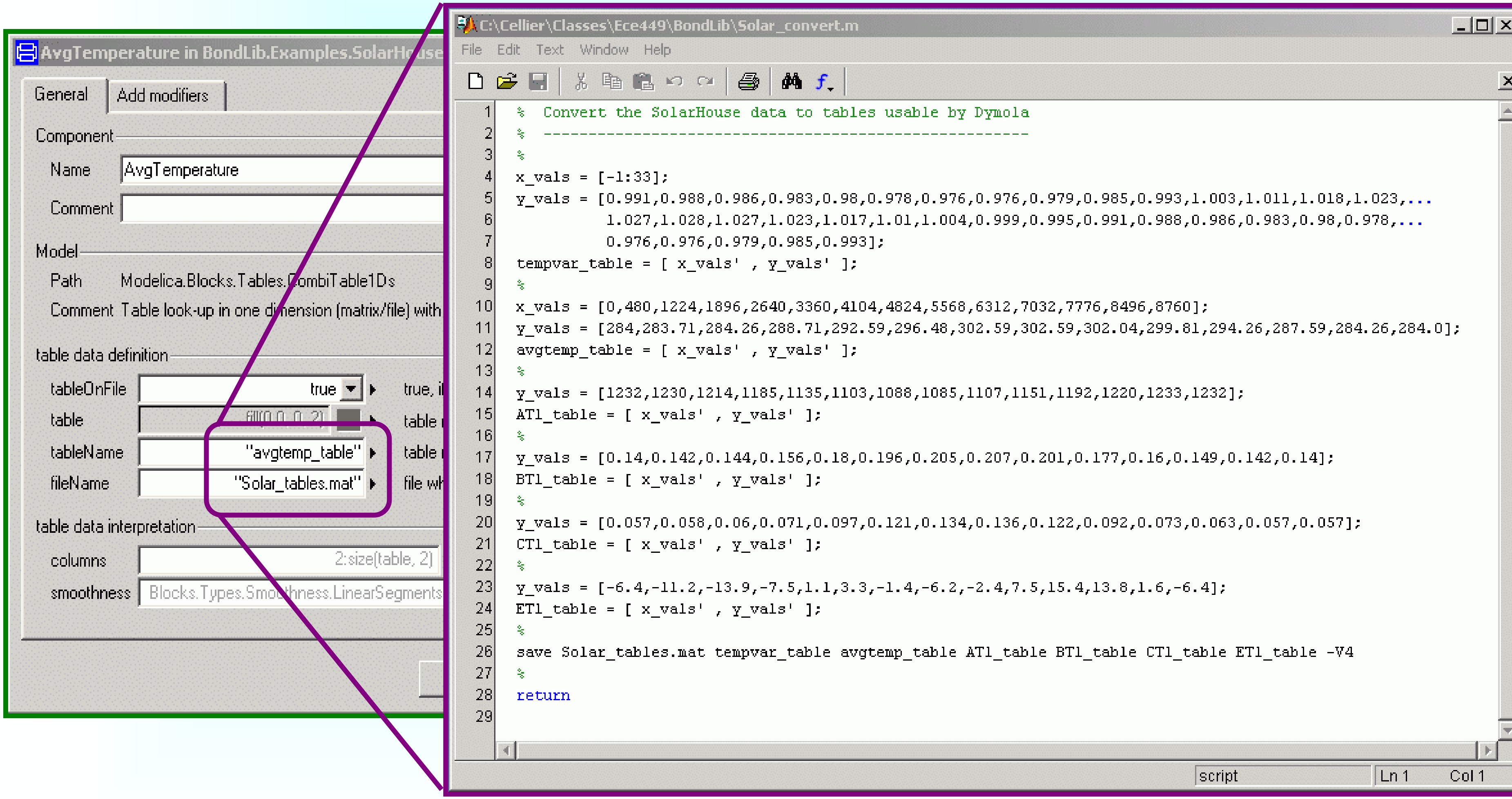
The Tabular Functions



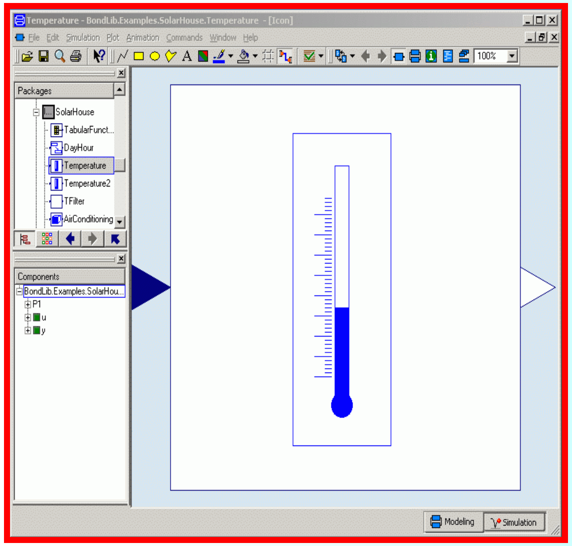
The Tabular Functions II

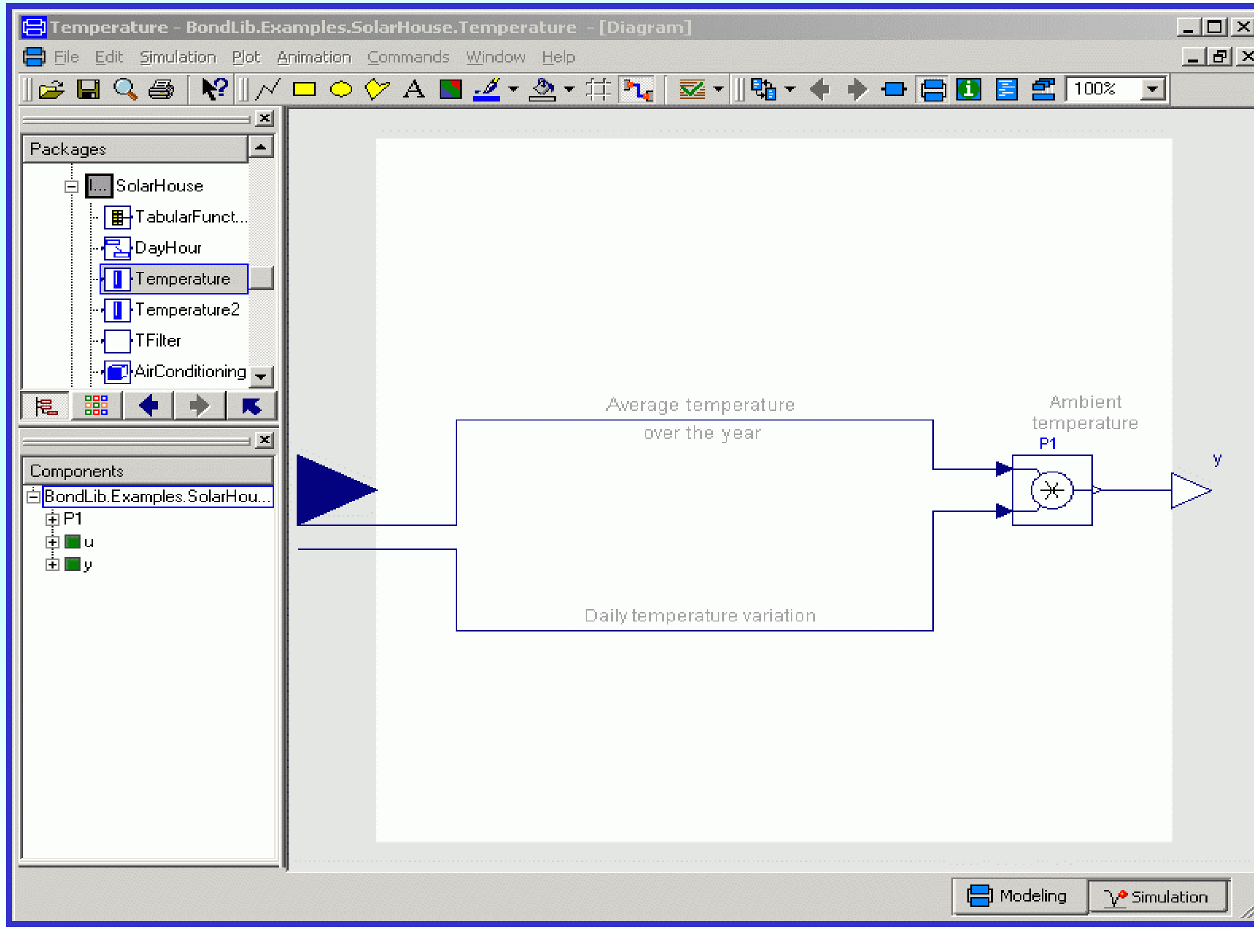


The Tabular Functions III

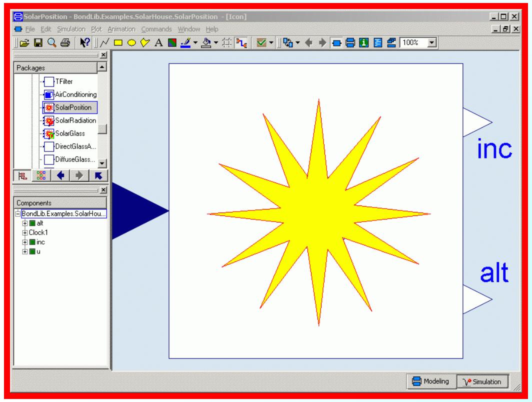


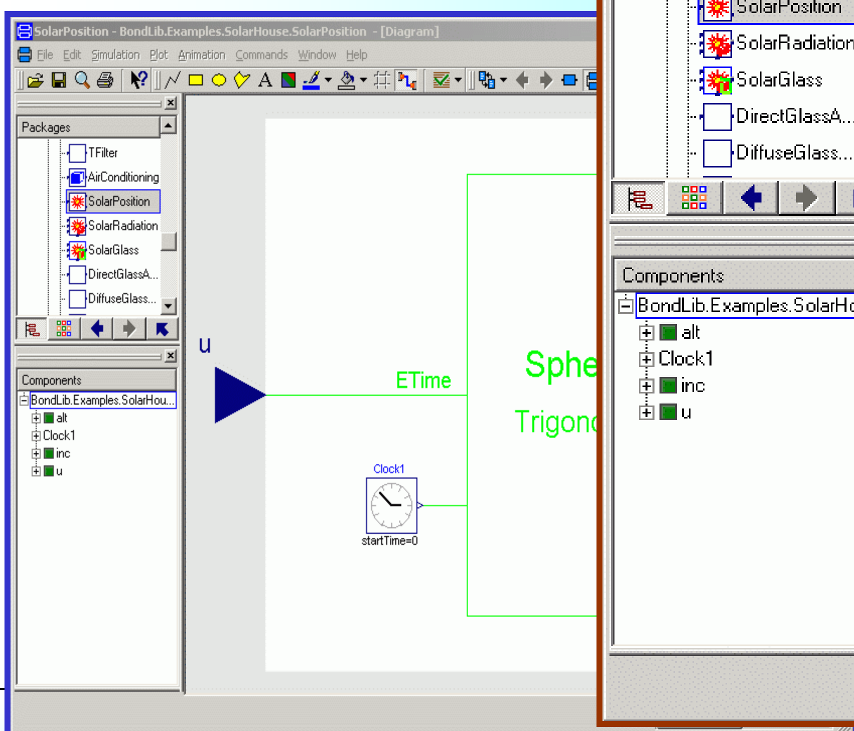
The Temperature

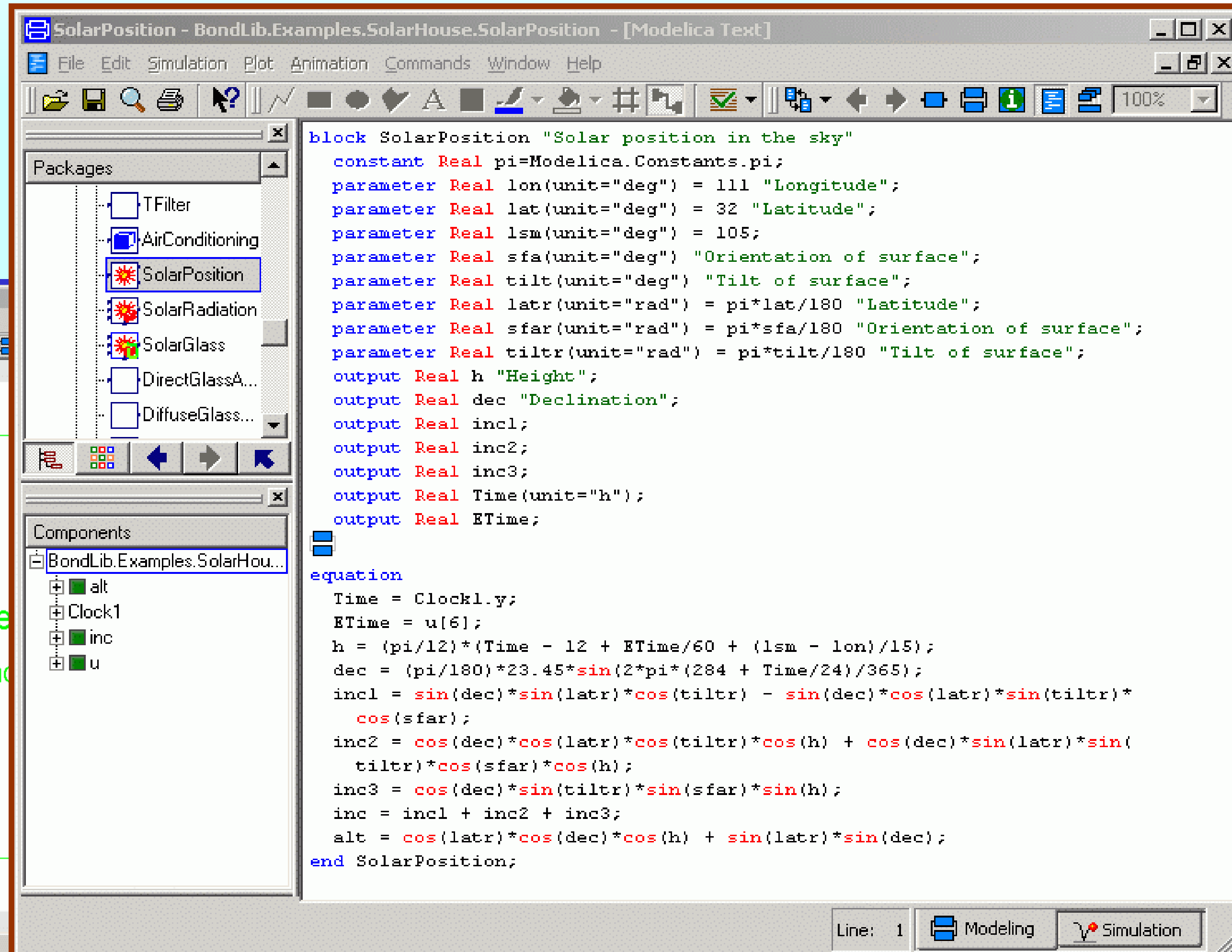




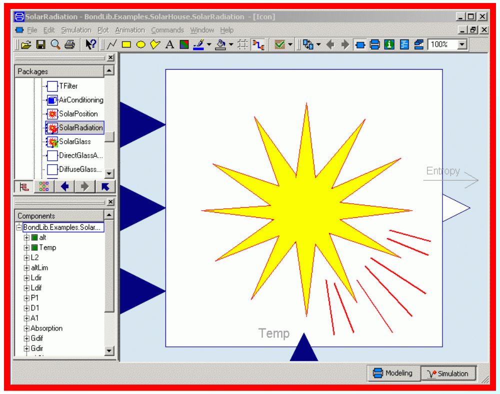
The Solar Position

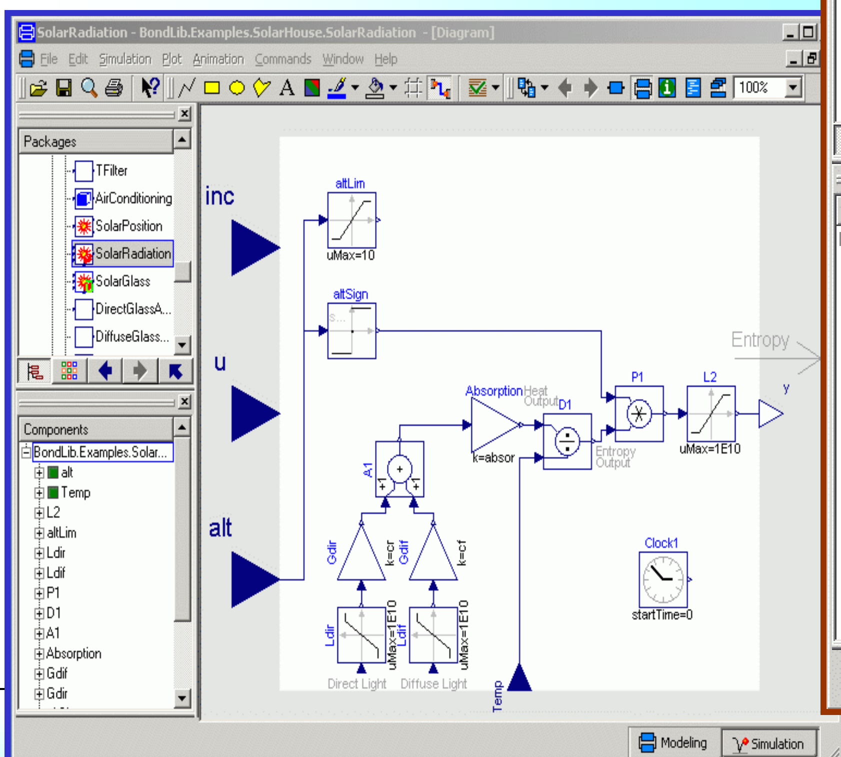


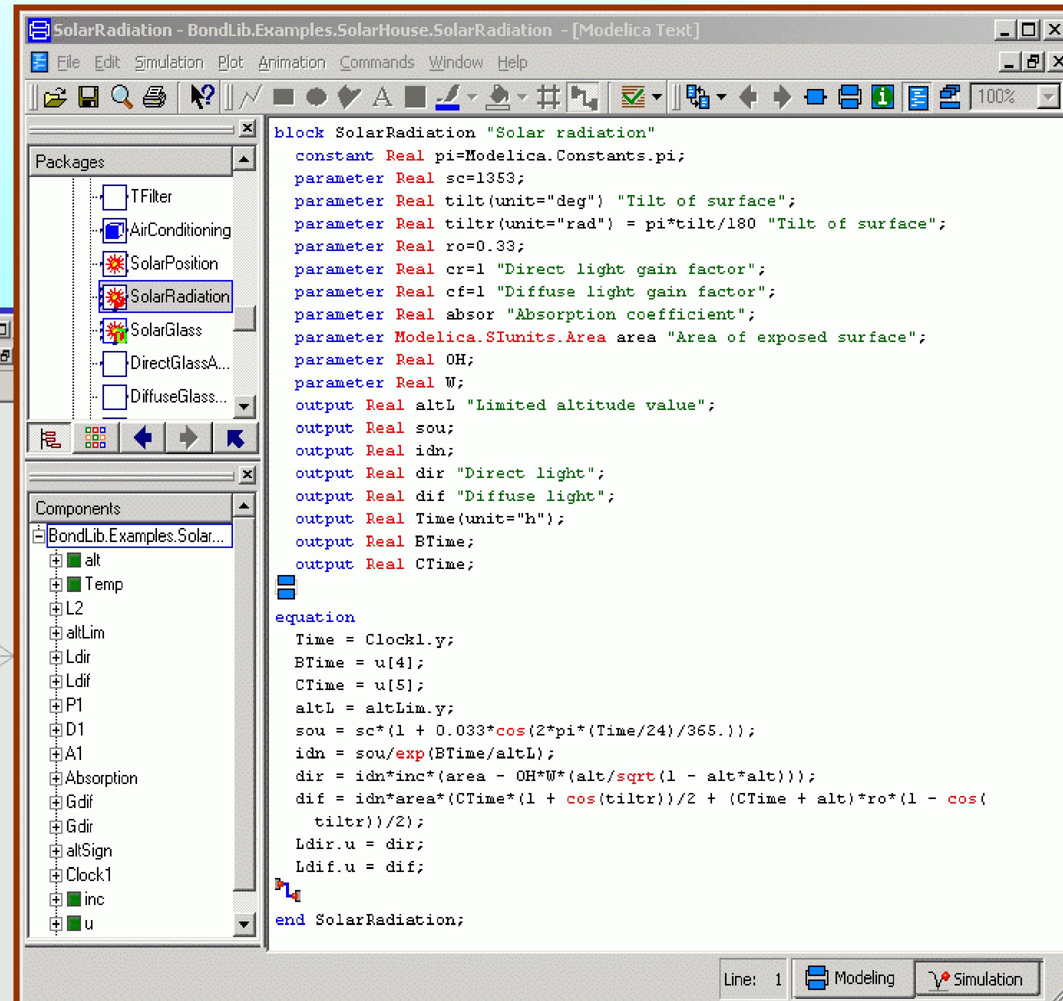




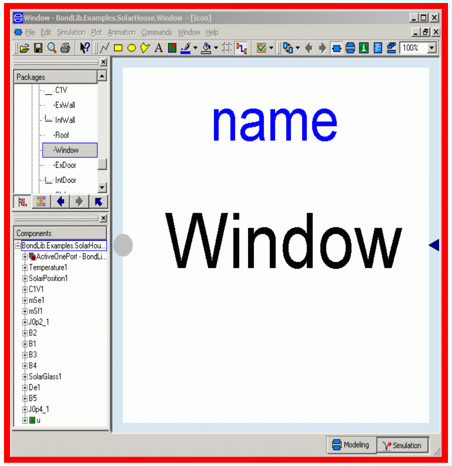
The Solar Radiation

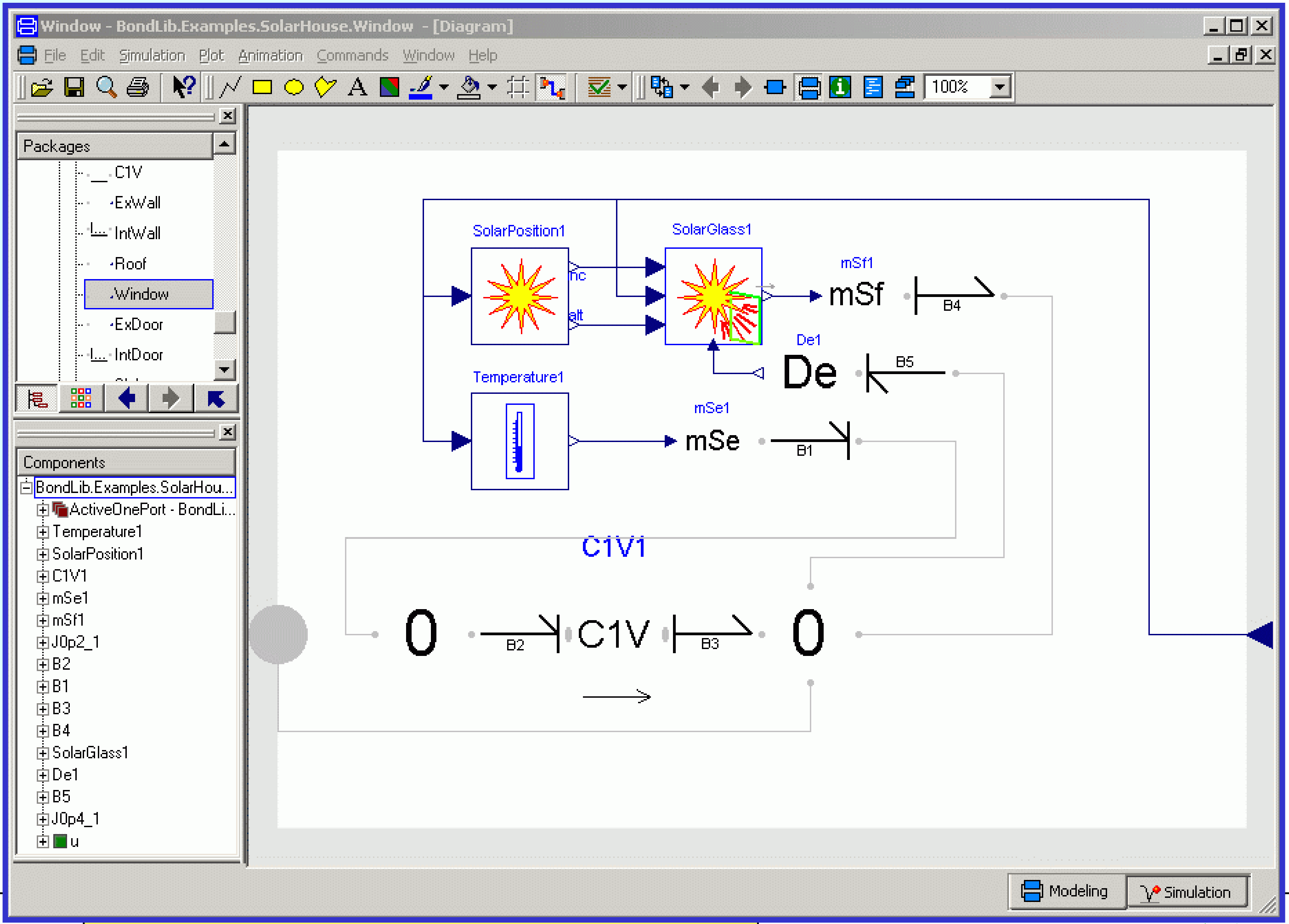






The Window


Window - BondLib.Examples.SolarHouse.Window - [Icon]
name
Window


Window - BondLib.Examples.SolarHouse.Window - [Diagram]
File Edit Simulation Plot Animation Commands Window Help
100%
Packages
C1V
ExWall
IntWall
Roof
Window
ExDoor
IntDoor
Components
BondLib.Examples.SolarHou...
ActiveOnePort - BondLi...
Temperature1
SolarPosition1
C1V1
mSe1
mSf1
J0p2_1
B2
B1
B3
B4
SolarGlass1
De1
B5
J0p4_1
u
SolarPosition1
SolarGlass1
hc
alt
mSf1
mSf
B4
De1
De
B5
Temperature1
mSe1
mSe
B1
C1V1
0
B2
C1V
B3
0
Modeling
Simulation

Translation and Simulation Logs

Messages - Dymola

Syntax Error | Translation | Dialog Error | Simulation

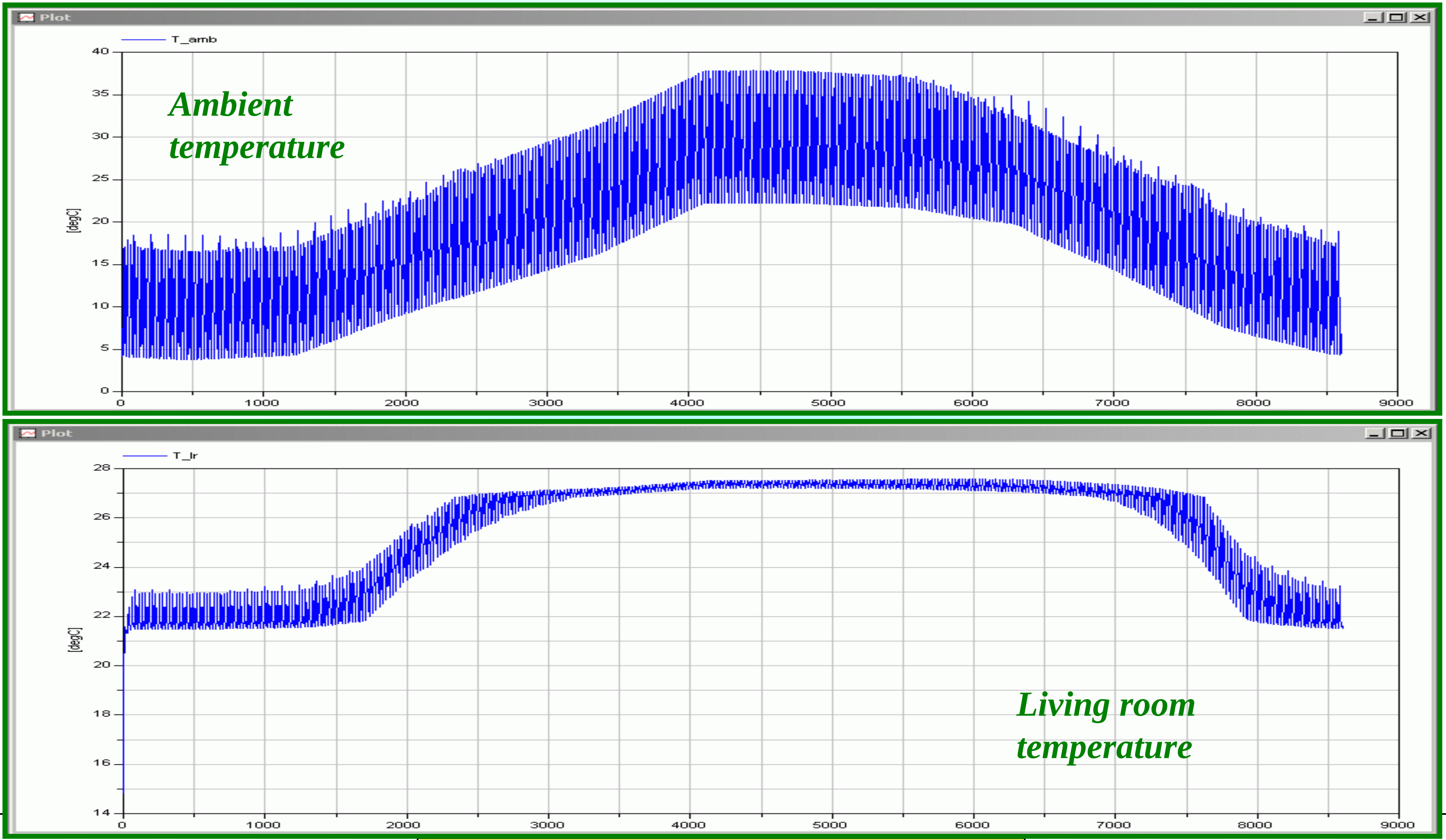
```
Translation of BondLib.Examples.SolarHouse.House:
DAE having 15853 scalar unknowns and 15853 scalar equations.

STATISTICS

Original Model
  Number of components: 2071
  Variables: 16042
    Constants: 51 (51 scalars)
    Parameters: 1793 (1787 scalars)
    Unknowns: 14198 (15859 scalars)
    Differentiated variables: 64 scalars
  Equations: 11574
    Nontrivial : 7026


Translated Model
  Constants: 3660 scalars
  Free parameters: 908 scalars
  Parameter depending: 761 scalars
  Inputs: 0
  Outputs: 16 scalars
  Continuous time states: 64 scalars
  Time-varying variables: 1329 scalars
  Alias variables: 11039 scalars
  Assumed default initial conditions: 64
   LogDefaultInitialConditions=true; gives more information
  Number of mixed real/discrete systems of equations: 0
  Sizes of linear systems of equations: { }
  Sizes after manipulation of the linear systems: { }
  Sizes of nonlinear systems of equations: { }
  Sizes after manipulation of the nonlinear systems: { }
  Number of numerical Jacobians: 0

Finished
// experiment StopTime=8600
Finished
```

Messages - Dymola

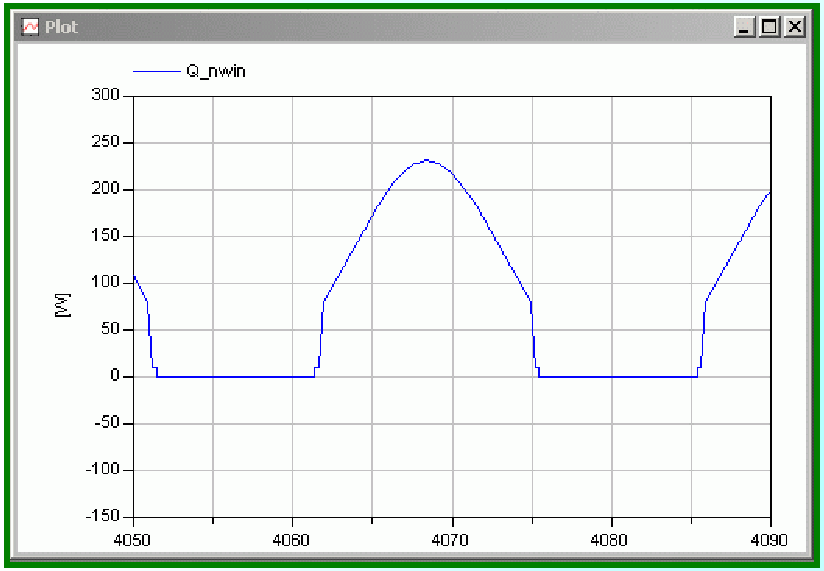
Syntax Error | Translation | Dialog Error | Simulation

```
Log-file of program ./dymosim
(generated: Thu Oct 25 14:52:37 2007)

dymosim started
... "dsin.txt" loading (dymosim input file)
... "Solar_tables.mat" loading (tables for interpolation)
... "House.mat" creating (simulation result file)

Integration started at T = 0 using integration method DASSL
(DAE multi-step solver (dassl/dasslrt of Petzold modified by Dynasim))
The following error was detected at time: 401.6598918572815
Error: Singular inconsistent scalar system for LivingRoom1.SWin1.C1V1.RSth1.f1
Solver will attempt to handle this problem.

The following error was detected at time: 833.8987732753258
Error: Singular inconsistent scalar system for SunSpace1.EWin.C1V1.RSth1.f1 = (
Solver will attempt to handle this problem.

The following error was detected at time: 1002.000381787843
  ⋮
Solver will attempt to handle this problem.

The following error was detected at time: 7529.398573012541
Error: Singular inconsistent scalar system for LivingRoom1.SWin1.C1V1.RSth1.f1
Solver will attempt to handle this problem.

Integration terminated successfully at T = 8600
  WARNING: You have many state events. It might be due to chattering.
  Enable logging of event in Simulation/Setup/Debug/Events during simulation
   CPU-time for integration      : 332 seconds
   CPU-time for one GRID interval: 665 milli-seconds
   Number of result points       : [illegible]
   Number of GRID   points       : 501
   Number of (successful) steps  : 60734
   Number of F-evaluations       : 2409197
   Number of H-evaluations       : 114000
   Number of Jacobian-evaluations: 35910
   Number of (model) time events : 0
   Number of (U) time events     : 0
   Number of state    events     : 6527
   Number of step     events     : 0
   Minimum integration stepsize  : 1.03e-006
   Maximum integration stepsize  : 1.51
   Maximum integration order     : 4
Calling terminal section
... "dsfinal.txt" creating (final states)
```

Simulation Results I

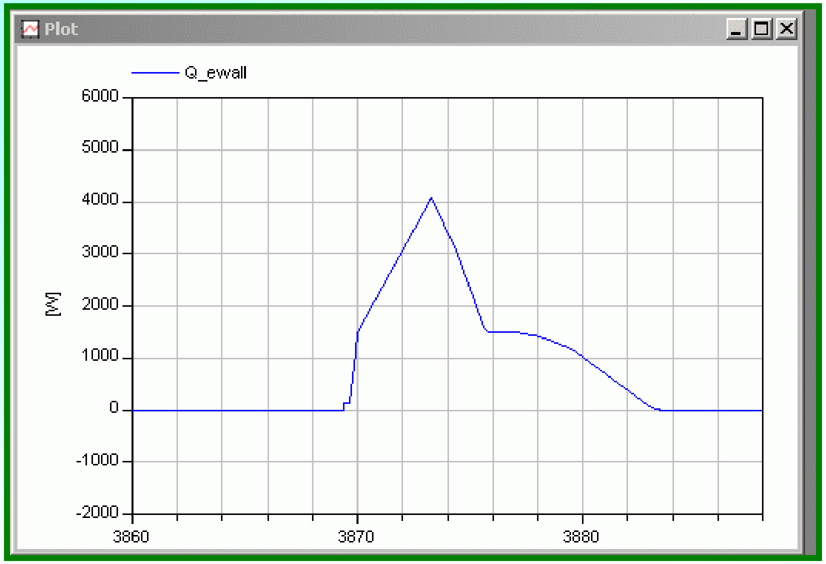


Simulation Results II

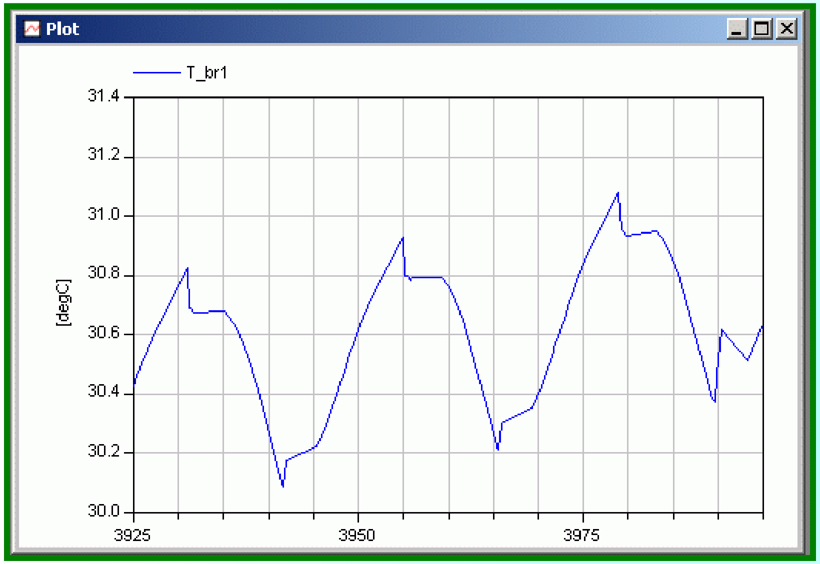


Radiation through North-exposed window

Radiation through East-exposed wall

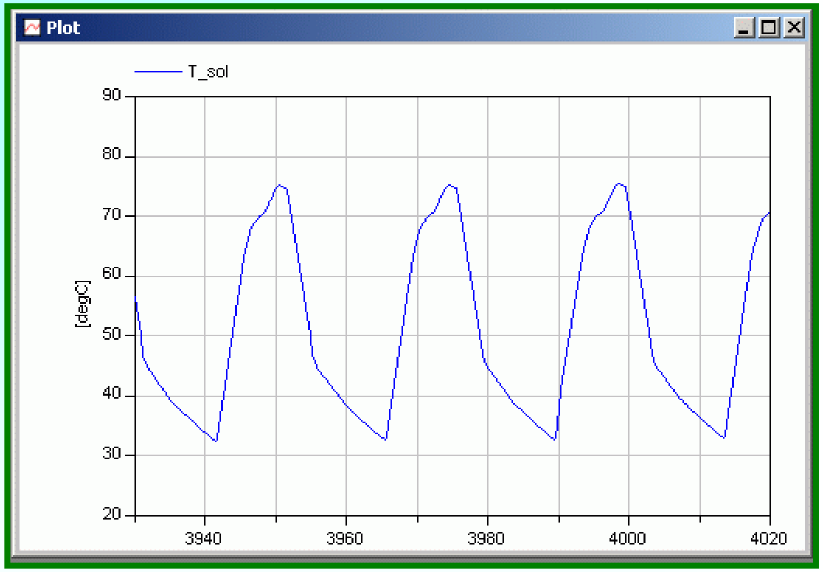


Simulation Results III



Temperature in bedroom #1

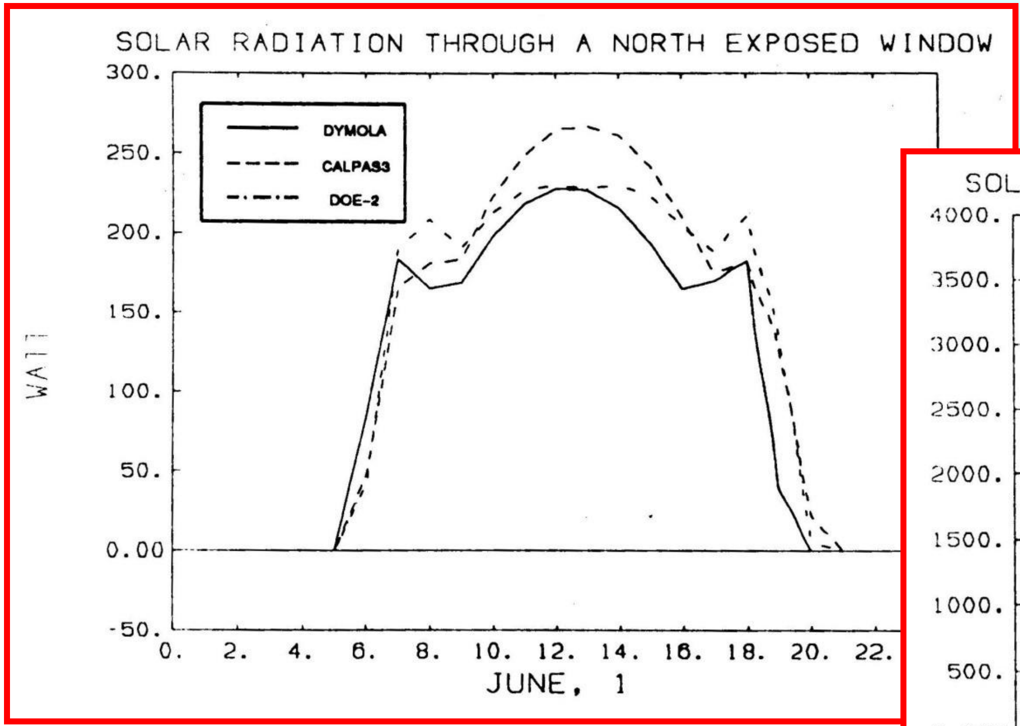
Temperature in sunspace

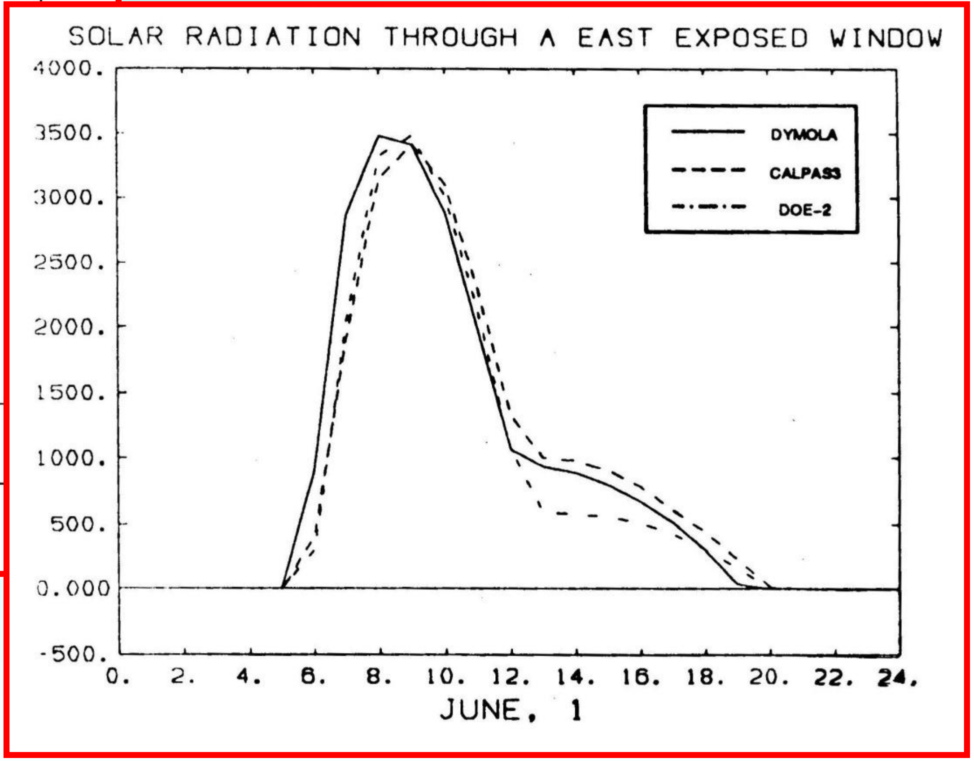


Passive Solar Space Heating III

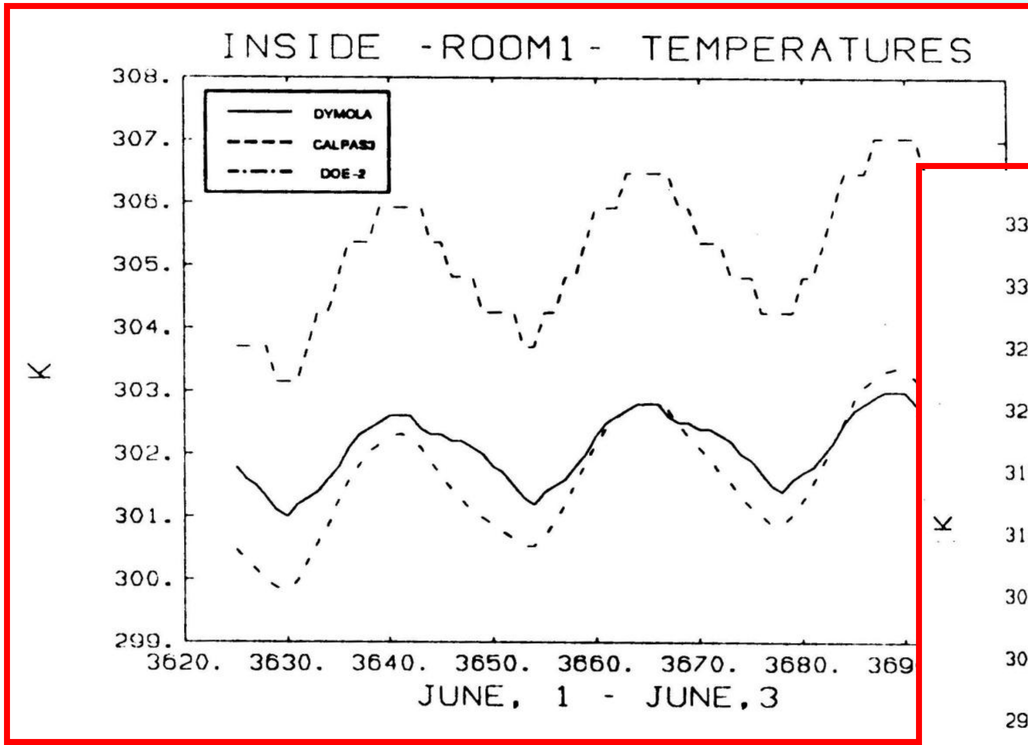
- The simulation results of three different programs were compared. These programs had been coded in ***Dymola***, ***Calpas 3***, and ***DOE 2***.
- ***Calpas 3*** and ***DOE 2*** are commercial simulation programs specialized for space heating.
- ***Calpas 3*** is a fairly simple Program. It computes rapidly and is easy to use, as it offers only few parameters. However, the results aren't very precise.
- ***DOE 2*** is a much more accurate and rather expensive program. It computes slowly and is not easy to use, as it offers many parameters, for which the user must supply values.

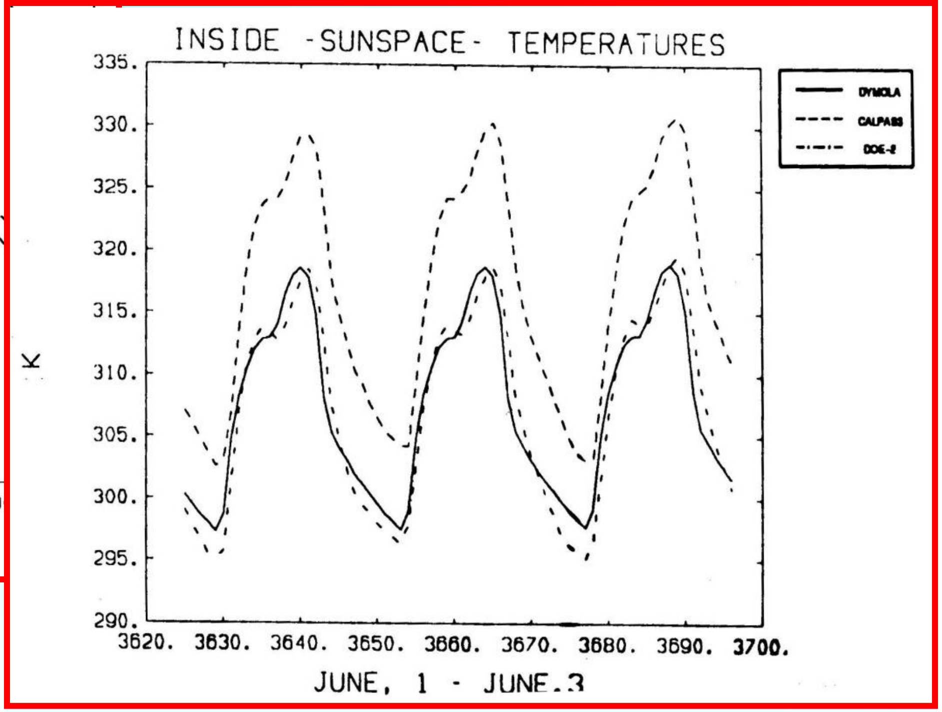
Simulation Results IV





Simulation Results V





Passive Solar Space Heating IV

- ***Dymola*** computes about as accurately as ***DOE 2***. However, the time needed to complete a simulation run is shorter by about a factor of 50 in comparison with ***DOE 2***.
- ***Dymola*** is much more flexible, as the program is not specialized for space heating simulations.
- The model assumptions, on which the simulation results are based, are clearly visible in the case of ***Dymola***. This is not the case for either of the other two programs.

References

- Weiner, M. (1992), *Bond Graph Model of a Passive Solar Heating System*, MS Thesis, Dept. of Electr. & Comp. Engr., University of Arizona, Tucson, AZ.
- Weiner, M., and F.E. Cellier (1993), "Modeling and Simulation of a Solar Energy System by Use of Bond Graphs," *Proc. SCS Intl. Conf. on Bond Graph Modeling*, San Diego, CA, pp.301-306.
- Cellier, F.E. (2007), *The Dymola Bond-Graph Library*, Version 2.3.