AN NMF BASED MODEL LIBRARY FOR BUILDING THERMAL SIMULATION

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ABSTRACT

Object-oriented or modular simulation methods represent a concrete alternative to present monolithic building simulation technology. Modular methods have previously been used primarily for component based systems modeling, while envelope models have remained monolithic. In this paper, the advantages of the new technology are reviewed and an equation-based models library for systems as well as envelope modelling is introduced. The new library has been developed within IEA SHC Task 22 and is available as NMF source code. Airflow network models are combined with thermal. Model fidelity is generally higher than for present tools. When used in IDA, the library has been validated and shown to be sufficiently fast and robust for commercial application.

INTRODUCTION

Today most industrial decision-makers agree that the use and impact of building simulation is likely to grow. A primary driving mechanism in this process is the emerging generation of computer-aware engineers. Several workshops have been held to discuss the future directions of the field and the requirements that will have to be fulfilled by the tools of the future [Crawley 1997, Clarke 1985]. The conclusion of these discussions is clear: the present generation of building simulation software is unlikely to be able to meet the needs of the future.

Present tools are too rigid in their structure to accommodate the improvements and flexibility that will be called for. Each added feature to the existing tools requires a larger implementation effort than the previous one. Basic methodological improvements, such as a complete change in solution strategy, are close to impossible to carry out since most of the program structure is affected.

Several groups are working to find alternatives to the present approaches to building simulation. The resulting tools are sometimes called equation-based, object-oriented or modular simulation environments. We will not attempt to provide a thorough presentation of this body of work here. An overview of new building simulation technologies is given in [Gough 1999]. Here, we will focus on consequences of the equation-based technology for end-users and developers and to present the results of a recent application project that has been carried out within IEA SHC Task 22.

CONSEQUENCES OF THE NEW TECHNOLOGY

Two things are fundamentally new:

1. General-purpose solvers for differential-algebraic systems of equations are used.

2. Models are formally described using standardized modelling languages.

Simply speaking, a developer can write down the equations that govern the process to be simulated and automatically have them solved by the new tools.

To the developer, the main advantages with respect to present methods are the following:

- It is now possible to take full advantage of state-of-the-art methods, such as computer algebra, modern numerical solution techniques and parallel computing, without being an expert in these fields. The developer is allowed to concentrate on application specific issues.

- By working with a standardized modelling language, it is possible to efficiently archive, reuse and share models. The same models can be used in several simulation environments. This, in turn, makes it possible to systematically compare and evaluate alternative simulation environments.

End-user tools based on the new simulation approach may on the surface look very similar to present programs. However, the underlying advantages are as significant for the end-user as for the developer:

- The tool can easily be customized to suit a particular study. Experienced users know that most projects contain some twist that cannot be adequately modelled in any of the programs, that are practically available in the project. With an equation-based tool, the user can then access the development tools directly or, at a reasonable cost, have someone carry out the required change.

- The new equation-based tools are transparent; every variable, parameter and equation in the model is available for inspection. Every variable can be plotted.
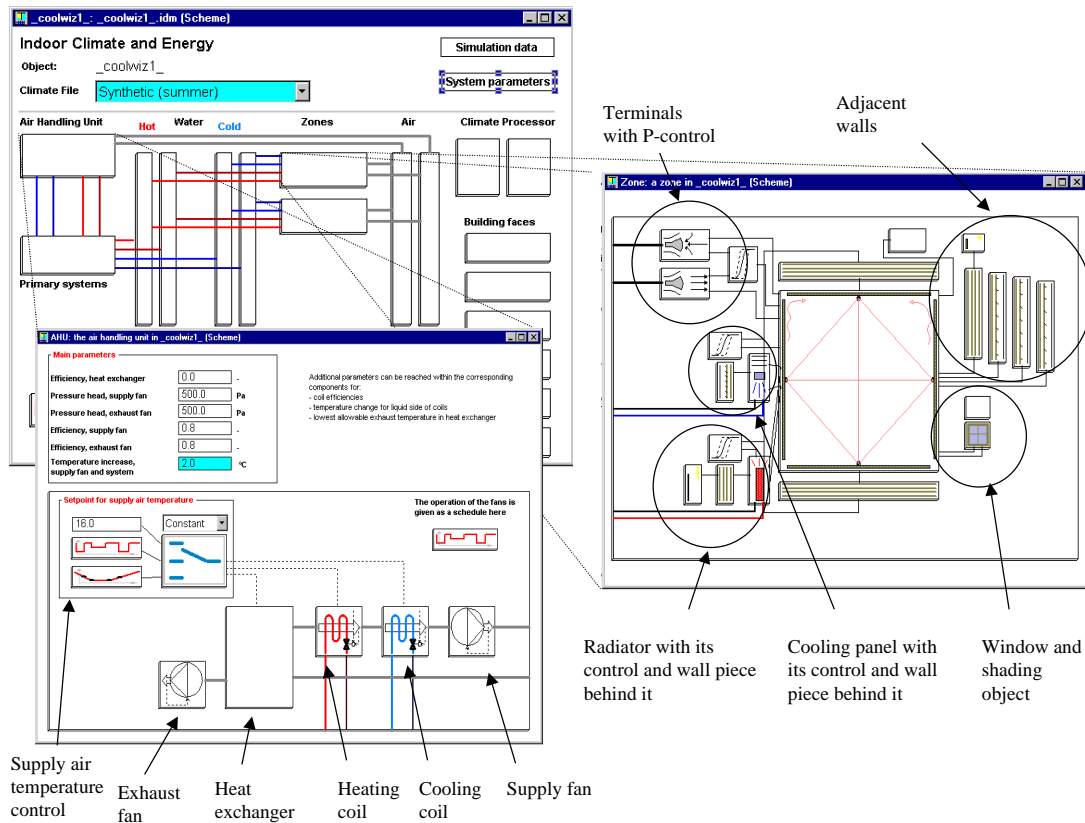
Figure 1. A system example from IDA Indoor Climate and Energy.

- The modelling language serves directly as model documentation. There is never any doubt as to what is being solved. It is the responsibility of the environment provider to correctly solve the given equations. It is the responsibility of the tool developer to justify the equations used.

Few will argue against the value of these advantages. However, many will raise doubts regarding the efficiency and robustness of the new methods. "Does it really work on my problems?" The answer to most of these questions is yes. Today the methods are sufficiently developed to be truly useful on a very large range of problems. As an example of this, the remainder of this paper is devoted to the presentation of a set of state-of-the-art building simulation models. The models form the basis for an end-user simulation tool, IDA Indoor Climate and Energy (ICE) that is presented in an accompanying software demonstration paper [Björsell et al. 1999.]

THE IEA TASK 22 MODELS LIBRARY

The objective of the library is to provide models for all relevant processes involved in a thermal building simulation. The library in its current form is sufficient for a very large range of studies. Nevertheless, the real value lies in the fact that it provides an infrastructure for third party development. The models are listed in Appendix 1. The full library source code and associated documentation can be downloaded from http://www.brisdata.se/nmf/simone.htm.

The Neutral Model Format

The library is written in the Neutral Model Format [Sahlin, Sowell 1989]. NMF is a program independent language for modelling of dynamical systems using differential-algebraic equations. NMF serves both as clear model documentation for human readers and as input for automatic translation into the format of several simulation environments. Translators have been developed for IDA[1], TRNSYS[2], HVACSIM+[3] and MS1[4]. Prototypes have been developed for SPARK[5] and ESACAP[6]. See also the NMF home page at http://www.brisdata.se/nmf.

SIMONE, **si**mulation **mo**del **ne**twork is a web-based network of NMF-model libraries and developers (http://www.brisdata.se/nmf/simone.htm).

A great deal of work has been done with traditional languages and it is crucial that well-known and validated subroutines can be reused. This is accomplished via external function calls in NMF. Calls to external routines can be made for initial parameter processing (e.g. view factors from geometry information) and/or in the equation section.

Detailed Zone Model

The key models of the library are the two zone models, detailed and simplified. The detailed zone model

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[1] http://www.brisdata.se/
[2] http://sel.me.wisc.edu/trnsys/
[3] http://www.eren.doe.gov/buildings/tools_directory/software/hvacsim.htm
[4] http://www.lorsim.be/
[5] http://www.eren.doe.gov/buildings/tools_directory/software/spark.htm
[6] http://www.it.dtu.dk/~el/ecs/esacap.htm

with full Stefan-Boltzman long-wave radiation is intended for indoor climate studies and design tasks. With the detailed zone model it is possible to study e.g. displacement ventilation, mean radiant and operative temperatures, comfort indices and daylight level. The simplified zone model has been made for multizone energy simulations.

Both models have balance equations for CO_2, humidity, air mass and energy. The moisture and heat loads from people are modeled with the equations from ISO 7730. Loads are a function of the activity and clothing levels, air moisture contents and so on.

The convective heat load from occupants is calculated with the equation [ISO 7730]

$$Q_{cv} = \frac{f_{cl}\, h_{cl}\, 1.8\, (T_{cl} - T_{air}) +}{1.8\, 0.014\, M\, (34 - T_{air})} \qquad (1)$$

The convective heat transfer coefficient, h_{cl}, between clothes and air is calculated with the equation [ISO 7730]

$$h_{cl} = \frac{2.38\,(t_{cl} - t_a)^{0.25} \quad for\ 2.38(t_{cl} - t_a)^{0.25} > 12.1\sqrt{v_{air}}}{12.1\sqrt{v_{air}} \qquad for\ 2.38(t_{cl} - t_a)^{0.25} < 12.1\sqrt{v_{air}}}$$

and the f_{cl} factor is calculated with the equation [ISO 7730]

$$f_{cl} = \frac{1.00 + 1.29\, I_{cl} \quad for\ I_{cl} < 0.078}{1.05 + 0.645\, I_{cl} \quad for\ I_{cl} > 0.078} \qquad (3)$$

The radiative heat load from the occupants is calculated with the equation [ISO 7730]

$$Q_{rad,occ} = 1.8\, 3.96\, 10^{-8}\, f_{cl}\,(T_{cl}^{\,4} - T_{mrt}^{\,4}) \qquad (4)$$

The moisture load from the occupants is calculated [ISO 7730]

$$HumOcc = \begin{array}{l} 1.8(3.05\,10^{-3}(5733 - 6.99(M\,58 - W) - P_{vap}) \\ + 0.42((M\,58 - W) - 58.15) + \\ 1.7\,10^{-5}\,M\,58(5867 - P_{vap}))/2501000 \end{array} \qquad (5)$$

VAV systems controlled by CO_2 level have become come quite popular in buildings with highly varying loads. The CO_2 balance is introduced into the zone models and the CO2 emission from occupants is modeled as a function of their activity level. The CO_2 load from the occupants is [IEA 1993]

$$X_{CO_2} = M / 3.6\, 1.8 \qquad (6)$$

The power of NMF is that no solution algorithm has to be described. The actual NMF code of the parts described above is shown at Appendix 2. From the code it is possible to find the equations described above in a similar format.

Designers are interested in temperatures and energy consumption, but also in how occupants experience the indoor environment. To answer this question, comfort indices are supplied.

To study the influence of the location of an occupant in the zone, the mean radiant temperature is calculated, weighted with the view factors from the location point to the zone surfaces. Thus, the comfort indices will differ between locations close to the windows or in the middle of the zone.

Comfort indicators supplied by the model are the standard PPD- and PMV-indices and mean radiant and operative temperature. Average air velocity is needed to calculate these indices and is currently given by the user as a parameter.

Some results that may be obtained are:

- air temperatures at different heights,
- mean radiant temperature as a function of location,
- operative temperature as a function of location,
- directed radiant temperature to study temperature asymmetry,
- PPD and PMV comfort indices,
- relative humidity,
- condensation warning,
- daylight calculation at the desk surface,
- CO_2 concentration.

Simplified Zone Model

The detailed zone model is designed for climate and design tasks and may be unnecessarily complex and time consuming for full year energy simulations. The simplified zone model is created to reduce the problem size for large multizone simulations.

In the simplified zone model, the internal constructions, which connect to similar zones or else can be assumed to lack net heat transfer, have been combined into one active heat capacity.

The envelope constructions are modelled as RC-networks, and optimization of their parameters is made within the frequency domain. The analytical responses of the RC-networks are known as functions of frequency, and the active heat capacities are calculated to give optimum response over a frequency interval. The optimization assumes that the oscillations are identical at both sides of the wall. The active heat capacity of the walls is optimized for 24 hours oscillation. [Akander 1995]

The long wave radiation between zone surfaces is modeled with a mean radiant temperature approach.

Other model features are the same as in the detailed zone model, thus e.g. the loads from occupants are modeled with the same level of detail.

Models Around the Zone

To complement the zone models, some further models are needed: radiators, cooling panels, leaks, terminals, controllers, etc. The whole set of models surrounding the zone is shown in Figure 1.

Radiators and cooling panels are connected to the zone with two TQ-links (temperature and heat flux). The first link deals with the front surface and the second one with the convection from the back side. A

third TQ-link connects the device to a separate wall segment behind the device.

Windows are connected to the zone with two links: a TQ-link, just as for any other surface, and an RRRWW-link. The latter link models direct and diffuse incoming radiation, radiation from the zone back to the ambient, and angles of incoming rays, to enable, not yet implemented, ray tracing calculation.

The terminals, leaks, and doorways are connected with bidirectional links, to be able to model airflows to and from the zone. Link variables are: pressure, dry air massflow, temperature, heat flux, absolute humidity, humidity flow, CO_2 concentration and CO_2 flow.

Airflows

One of the main features of the library is simultaneous solving of temperatures and airflows, which are highly dependent phenomena. Using this feature, the temperature and pressure dependent air flows in doorways and openable windows can be solved.

Flows of air mass, humidity, and CO_2 are calculated in the terminal and leak models. In the case of mechanical ventilation, the airflows in supply and exhaust terminals are determined by signals from controllers. If natural ventilation is used, the airflows are determined by the mass-pressure balance, taking into account pressure drops over leaks and terminal devices.

A Simulation Example

The system shown in Figure 1 is used as an example. The schema shown in the figure was generated from the standard user interface of the IDA ICE application. As an example, the P-controller of the radiator is replaced first by a PI-controller and then by a thermostat. The results are presented in Figure 2. The temperature variations observed are reasonable relative to the change.

In IDA ICE the actual replacement of the controller is done by typical Windows operations. This flexibility opens almost unlimited possibilities to test different variations, which more often than not are impossible in traditional environments.

Primary and Secondary System Models

The library has component models for primary as well as secondary systems. The standard set of models have a minimum number of supplied parameters, but are able to simulate limited and time dependent cooling and heating power.

The number of parameters has been kept low, in order to provide a full system simulation with minimum required effort. This means that no specific design information, only efficiencies, are given for heating and cooling coils, etc. If detailed sizing of these devices is desired, the ASHRAE Secondary Toolkit models could be used instead.
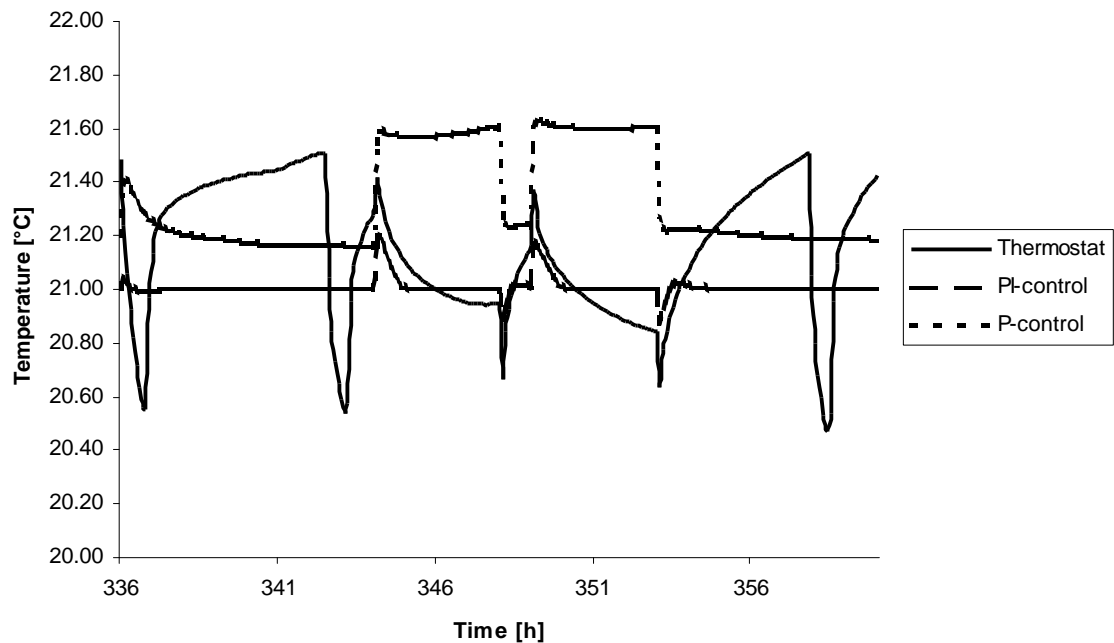
Figure 2. Temperatures with different controllers.

Secondary Systems Toolkit Models

For detailed secondary system simulations, the ASHRAE secondary toolkit models have been translated into NMF and made connectable to the other models of the IEA library. The ASHRAE toolkit is a collection of models used in well-known simulation tools, like DOE-2, TRNSYS, HVACSIM+. It allows a detailed simulation of secondary systems [ASHRAE 1993].

The toolkit models have been augmented with air pressure, which was not modelled in the original version. In this way, pressure drops over ventilation devices are introduced, and actual pressure is used to calculate moist air properties.

A complete set of psychrometric functions is included in the toolkit as Fortran routines. These routines have been made available in the IEA library by providing them with NMF wrappers. A complete set of analytical Jacobians, with NMF wrappers, has also been provided to improve simulation stability. The Secondary Toolkit library in NMF is also available from http://www.brisdata.se/nmf/simone.htm.

The secondary toolkit models are intended for design calculation of secondary systems. The standard secondary models of the application have built-in control; when they are replaced with toolkit models, sensors, controllers, and actuators will have to be added separately. To make this replacement smooth, some macros have been created.

The secondary toolkit contains only steady-state models, thus, for detailed control simulations, dynamic models would have to be created.

Usability

The IEA library has been developed in the IDA Simulation Environment and has been delivered to more than a hundred paying end-users as part of the specialized application IDA Indoor Climate and Energy (ICE). In this context, the robustness and general usability of the library has been verified. Testing in other possible environments has not yet been done. The library could be used within any modular simulation environments for which a translator exists.

It is difficult to assess execution times for these models, since no relevant points of comparison exist. In a previous project [Vuolle and Bring 1997] a direct comparison was made with a special purpose program. A penalty factor of two to four was then estimated for the general purpose implementation. The factor is likely to have decreased since then, based on improvements made.

Currently, a ten zone ICE model (containing some five thousand simultaneous equations) runs at approximately 20 s per 24 hour simulated period on a 300 MHz PC with a time resolution in the results of less than a minute. Projects are underway to improve this further on sequential hardware.

A parallel version of IDA Solver is also available. At the time of writing, no measurements have yet been done on full-scale problems.

Validation

During the implementation process normal verification has been done. The view factor calculation has been checked against known analytical solutions. The energy balance has been checked.

Extensive comparative studies have been done against the BRIS program [Brown 1990]. BRIS is a heat balance program for room climate studies; it was developed in Sweden in the early sixties. The program is based on detailed non-linear physical relations. BRIS has been validated against measurements in a number of studies. After several extensions, it is still widely used and well trusted by the Swedish building industry.

The central models have been validated against measurements in the scope of IEA Task 22. Preliminary validation results are published at this conference [Guyon, Moinard and Ramdani 1999]. The full validation report will be available from IEA.

The IEA tests were carried out in the spring of 1998 with a beta version of IDA ICE. Some problems with the library models were revealed and rectified in this process. Unfortunately, a severe impact of thermal bridges in the test cell was discovered. They were accounted for by some but not all participants. This creates some difficulty in correctly assessing the results. However, after correction of thermal bridges, IDA ICE performed very well in the test.

Availability

The current version of the library is available on http://www.brisdata.se/nmf/simone.htm together with documentation and some other NMF libraries.

The main part of the HTML web presentation of the library has been automatically created (See Appendix 1, for an example of this). A free converter (NMF2HTML) is available to help developers generate HTML documentation for NMF libraries and components.

CONCLUSIONS

NMF and IDA technology has been used to develop a comprehensive library for thermal building simulation. The library contains more detailed models than most comparable simulation tools.

-   The library has been validated in the framework of an international validation exercise.

-   The library has in conjunction with the IDA Simulation Environment been shown to hold commercial quality, both with respect to accuracy, robustness and attainable execution speed.

-   The library is publicly available.

These conclusions allow us to say the following about the state of object-oriented simulation methods in general:

- The technology is now sufficiently mature to be of excellent service to both developers and end-users.

- The major remaining obstacle is the low level of awareness and expertise among developers, funders and end-users.

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NOMENCLATURE

f_{cl}	ratio of man's surface area while clothed to man's surface area while nude, -
h_{cl}	convective heat transfer coefficient between air and clothes, W / m^2 K
HumOcc	humidity load from occupants, kg / s
M	metabolic rate, -
P_{vap}	partial water vapour pressure, Pa
Tair	air temperature, °C
T_{cl}	surface temperature of clothing, °C
T_{mrt}	mean radiant temperature, °C
v_{air}	relative air velocity (relative to human body), m/s
W	external work , W / m^2
X_{CO2}	CO_2 load from occupants, μg / s

ACKNOWLEDGEMENTS

APPENDIX 1. THE LIST OF MODELS.

A slightly modified version of the HTML table that is generated by the NMF2HTML utility.

GLOBAL DECLARATIONS:

Name:	Last modified:	
global.nmf	29 Mar 1999	

CONTINUOUS_MODELS:

Name:	Last modified:	Abstract:
Adder	29 Mar 1999	Adds n input signals. Sends sum to multiple output links.
AdWall	31 Mar 1999	ADiabatic WALL, represented by an RC-net w one capacity.
AirMerge	29 Mar 1999	n-way merge of air streams. Unidirectional flow. No pressure drop.
AirSplit	29 Mar 1999	n-way split of air stream. Unidirectional flow. No pressure drop.
CCSimCtr	31 Mar 1999	SIMplified air-to-liq Cooling Coil w liquid massflow ConTRol.
CeBeam	31 Mar 1999	Idealized supply terminal w damper and active cooling ceiling BEAM.
CeColPnl	7 Apr 1999	Water fed COoLing PaNeL or convector.
CeDetZon	7 Apr 1999	DETailed ZONe w T**4 lw radiation, view factors, displacement vent...
CeExhT	31 Mar 1999	Idealized EXHaust Terminal for VAV or natural ventilation.
CeFan	1 Apr 1999	FAN w On/Off control (low flow when off). Efficiency & temp rise given.
CeLeak	7 Apr 1999	Powerlaw LEAK. Bidirectional transport of energy, humidity, & mass fraction.
CeLVO	7 Apr 1999	Two-way flows thru a Large Vertical rectangular Opening at any height.
CeSimZon	31 Mar 1999	SIMplified ZONe, single mass for parts of envelope, MRT w area factors.
CeSupT	31 Mar 1999	Idealized SUPply Terminal for VAV or natural ventilation.
CeSurf	31 Mar 1999	Boundary object for envelope SURFace, not exposed to solar.
CeWatHet	7 Apr 1999	WATer fed HEaTer in front of room surface; radiator or convector.
CeWind	1 Apr 1999	WINDow, internal shading controlled by schedule or heat flux.
Comparator	31 Mar 1999	Comparator of two signals, with dead band.
dummy	31 Mar 1999	Place holder for new component.
Elrad	1 Apr 1999	ELectric RADiator in front of room surface.
EnvLeak	31 Mar 1999	The model EnvLeak is obsolete and should be replaced with CeLeak.
EnvLVO	31 Mar 1999	The model EnvLVO is obsolete and should be replaced with CeLVO.
EvHumCtr	31 Mar 1999	adiabatic EVaporative HUMidifier with On/Off ConTRol.
HCSimCtr	31 Mar 1999	SIMplified air-to-liq Heating Coil w liquid massflow ConTRol.
HXSimCtr	1 Apr 1999	SIMplified air-to-air latent Heat eXchanger with ConTRol.
MinMax	1 Apr 1999	Select MINimum or MAXimun of multiple input signals.
MixBxCtr	1 Apr 1999	Recirculating MIXing BoX w ConTRol.
Multiplier	1 Apr 1999	Multiply n_in input signals. Multiple output links. CONTINUOUS model.
PIContr	1 Apr 1999	PI-controller w multiple output signals.
PLinSegC	1 Apr 1999	P-controller w a number of LINear SEGments. CONTINUOUS model.
PMTContr	1 Apr 1999	Idealized CONTRoller for liquid w PMT links.
PSmooth	1 Apr 1999	SMOOTHed (no events) approximation to P-controller.
PSmooth2	1 Apr 1999	SMOOTHed (no events) version of P-controller. Variable setpoint.
RCWall	1 Apr 1999	WALL model based on RC network. Auto select 2 or 3 nodes.
SimBoil	1 Apr 1999	SIMplified BOILer and water pump w ideal control.
SimChil	1 Apr 1999	SIMplified CHILler and water pump w ideal control.
StatSens	1 Apr 1999	Multi-purpose STATic SENSor with UniAir links
StInjCtr	1 Apr 1999	Dry STeam INjection humidifier w On/Off ConTRol.
Switch	1 Apr 1999	Switch between n_in input signals. Muliple output links.
Thermost	1 Apr 1999	THERMOSTat w variable setpoint.
Timer	29 Mar 1999	A timer for testing purposes.
TqFace	1 Apr 1999	Wall surface exposed to solar radiation
WatMerge	1 Apr 1999	n-way MERGE of WATer streams w PMT links.
WatSplit	1 Apr 1999	n-way SPLIT of a WATer stream w PMT link.

ALGORITHMIC_MODELS:

Name:	Last modified:	Abstract:
Climate	1 Apr 1999	Process CLIMATE data from file; calc sun pos; send data to facade.
EMeter	1 Apr 1999	Calculate total power consumption and hourly energy cost
Face	1 Apr 1999	Process climate data for FACadE. Calc wind, film coeff & solar radiation.
MultA	1 Apr 1999	Multiply n_in input signals. Single output link. ALGORITHMIC model.
PLinSegm	1 Apr 1999	P-controller w a number of LINear SEGments. ALGORITHMIC model.
Schedule	1 Apr 1999	Fetch data from SCHEDULE. Handle leap yrs & DST. Generate events.
Shade	7 Apr 1999	Calc window SHADEing from external objects (fins and buildings).
SyntClim	1 Apr 1999	Generate SYNThetic data for input into CLIMate model.
WinShade	7 Apr 1999	This model is obsolete. Use Shade instead.

FUNCTIONS:

Name:	Last modified:
activcap	29 Mar 1999
adiawall	29 Mar 1999
CalcShad	29 Mar 1999
DEWPNT	7 Apr 1999
DEWPNTJ	7 Apr 1999
DRYBULB	7 Apr 1999
DRYBULBJ	7 Apr 1999
ENTHAL	7 Apr 1999
ENTHALJ	7 Apr 1999
ENTHSAT	7 Apr 1999
ENTHSATJ	7 Apr 1999
hcout	29 Mar 1999
hcrad	29 Mar 1999
HUMRAT	29 Mar 1999
HUMRATJ	29 Mar 1999
HUMTH	29 Mar 1999
HUMTHJ	29 Mar 1999
litefac	29 Mar 1999
lwfac	29 Mar 1999
lwfacrad	29 Mar 1999
Perez	29 Mar 1999
rcopt	29 Mar 1999
RELHUM	29 Mar 1999
RELHUMJ	29 Mar 1999
RHODRY	29 Mar 1999
RHODRYJ	29 Mar 1999
RHOMOIS	29 Mar 1999
RHOMOISJ	29 Mar 1999
SATPRES	7 Apr 1999
SATPRESJ	7 Apr 1999
SATTEMP	7 Apr 1999
SATTEMPJ	7 Apr 1999
sw_fac	29 Mar 1999
TAIRSAT	7 Apr 1999
TAIRSATJ	7 Apr 1999
U_film	29 Mar 1999
view_fac	29 Mar 1999
view_mrt	29 Mar 1999
WETBULB	7 Apr 1999
WETBULBJ	7 Apr 1999
XITERATE	29 Mar 1999

APPENDIX 2: NMF SAMPLE SHOWING CODE FOR PPD CALCULATION

EQUATIONS

```
/*********    PPD and PMV    **********/

/*!! Nomenclature according to SS 02 40 01 (ISO 7730) */
  FOR j=1, nOp
    TMrtOp[j]:= SUM i = 1, nSurf
                   fiMrt[i,j]*TSurf[i]
             END_SUM / SumFiMRT[j];
  END_FOR;


  FOR j = 1, nOp
    TOp[j] := 0.5 * (TAirOp[j] + TMrtOp[j]);
  END_FOR;


  PVap :=  (P+10**5) * XHum / (0.62198 + XHum);


  FOR i=1, nOp

    hCl[i] := IF ABS(TCl[i]-TAirOp[i]) < (12.1/2.38 * SQRT(AirVel[i]))**4
              THEN
                   12.1 * SQRT(AirVel[i])
              ELSE_IF ABS(TCl[i]-TAirOp[i]) < 0.001 THEN
                   2.38 * ABS(0.001)**0.25
              ELSE
                   2.38 * ABS(TCl[i]-TAirOp[i])**0.25
              END_IF;


    TCl[i] = IF LINEARIZE(1) THEN (35.7+TAir)/2
             ELSE_IF  schedOcc[i] > 0 THEN
               35.7 - 0.028 * (M[i]*58-W[i]) - 0.155*iCl[i]*
               ( 3.96E-8 * fCl[i] *
               ((TCl[i]-ABS_ZERO)**4 - (TMrtOp[i]-ABS_ZERO)**4) +
               fCl[i] * hCl[i] * (TCl[i]-TAirOp[i]) )
             ELSE
               (35.7+TAir)/2
             END_IF;


    PMV[i] := IF schedOcc[i] > 0 AND PVap > 0 THEN
              (0.303*EXP(-0.036*M[i]*58)+0.028) *
               ( ( M[i]*58-W[i]) -
               3.05E-3 * (5733 - 6.99*(M[i]*58-W[i]) - PVap ) -
               0.42 * ((M[i]*58-W[i]) - 58.15) -
               1.7E-5 * M[i] * 58 * (5867-PVap) -
               0.0014 * M[i] * (34-TAirOp[i]) -
               3.96E-8 * fCl[i] *
               ( (TCl[i]-ABS_ZERO)**4 - (TMrtOp[i]-ABS_ZERO)**4 ) -
               fCl[i] * hCl[i] * (TCl[i]-TAirOp[i]) )
              ELSE
               0
              END_IF;
```

```
    PPD[i]:=  IF schedOcc[i] > 0 THEN
              100 - 95*EXP(-(0.03353*PMV[i]**4+0.2719*PMV[i]**2))
            ELSE
              0
            END_IF;
  END_FOR;



/*  Convective heat from occupants */
  QCvOcc2Zone := SUM i = 1, nOp
                 IF schedOcc[i] > 0 THEN
                   schedOcc[i] * nOcc[i] * 1.8 *
                 ( fCl[i] * hCl[i] * (TCl[i] - TAirOp[i]) +
                   0.0014 * M[i] * (34 - TAirOp[i]) )
                 ELSE
                   0
                 END_IF
                 END_SUM;


/*  LW radiation from occupants */
  QLwOcc2Zone = SUM i = 1, nOp
                 IF schedOcc[i] > 0 THEN
                   schedOcc[i] * nOcc[i] * 1.8 *
                   (3.96E-8 * fCl[i] *
                   ((TCl[i]-ABS_ZERO)**4-(TMrtOp[i]-
                   ABS_ZERO)**4))
                 ELSE
                   0
                 END_IF
                 END_SUM;


/*  Vapour flow from occupants */

  VapFOcc2Zone := SUM i=1, nOp
                 IF schedOcc[i] > 0 THEN
                   schedOcc[i] * nOcc[i] * 1.8 *
                 ( 3.05E-3 *
                 ( 5733 - 6.99 *(M[i]*58 - W[i]) - PVap) +
                   0.42 * ((M[i]*58 - W[i]) - 58.15) +
                   1.7E-5 * M[i]*58 * (5867 - PVap) )
                 ELSE
                   0
                 END_IF
                 END_SUM / HF_VAP;
```