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A MATLAB-BASED SIMULATION TOOL FOR BUILDING THERMAL PERFORMANCE ANALYSIS

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ABSTRACT

This paper presents the development of a simulation tool based on the Matlab computational environment for building temperature performance analysis with automatic control. The simulation tool contains mathematical models for buildings, HVAC (Heating, Ventilation and Air Conditioning) systems, sensors, weather data and control algorithms. The building mathematical model is described in terms of state-space variables, with a lumped approach for the room air governing equations – energy and mass balances. In this context, the simulation tool structure and components are explained. Five control strategies applied to HVAC systems, integrated to building zones, are discussed as well. A simulation example illustrates the use of the software presented.

INTRODUCTION

The mathematical description of thermal behavior of building systems is complex since it involves the modeling of several interconnect subsystems, each one containing long-time constants, non-linearities and uncertainties such as convection coefficients, material properties etc. Moreover, external unpredicted perturbations, i.e., external weather (temperature, humidity), soil temperature, radiation effects and other sources of energy, such as people, illuminations and equipments, should also be taken into account.

Some points related with building modeling include the analysis of thermal comfort and energy consumption. Several software environments for building simulation are available all over the world, for instance, DOE-2, BLAST, EnergyPlus, Genopt, SPARK, Energy-10. However, computer processing power has been considerably improved in the last decade so that the use of mathematical packages such as Matlab/Simulink can be considered also as a good option for performing simulation-based building thermal analysis. In addition, the use of Simulink features has provided a user-friendly environment for fast configuration of inputs and outputs of the different subsystems included in the building and equipments, such as HVAC (Heating, Ventilation and Air Conditioning).

In this way, a mathematical model for building simulation by using Matlab/Simulink environment is presented in Hudson and Underwood (1999). In this approach, the building is represented by an RC electric circuit and the model is considered adequate for high mass buildings since they are predominantly capacitive. In Mendes et. al. (2001), a lumped approach is used to model the room air temperature and a multi-layer model for the building envelope. The building model allows studying the transient analysis of room air temperature when it is submitted to sinusoidal variation of external air temperature. In Mendes et al. (2002), the model is extended in order to incorporate hygrothermal dynamics of the building and external humidity data. Both works use Matlab/Simulink environment. Another quite interesting example of Matlab/Simulink used in thermal system modeling is the SIMBAD Building and HVAC Toolbox (Riederer et al., 2001). This toolbox provides a large number of ready-to-use HVAC models and related utilities to perform dynamic simulation of HVAC plants. For simulation involving control, this toolbox must be connected to other existing toolboxes.

Another important aspect is the analysis of thermal comfort and energy consumption and its relation with HVAC system control. By using an adequate mathematical model of the building, it is possible to use techniques of automatic control in the regulation of thermal zone temperature and humidity. Some examples of this approach are Dion et al. (1991), Huang and Lam (1997), Ghoumari et. al. (2001), Oliveira et. al. (2003).

The present work describes the development of a toolbox based on the Matlab/Simulink software for hygrothermal building simulation and performance analysis of HVAC automatic control systems. The proposed software version is modularity written, allowing easy expansion and interchangeability of building, HVAC and control systems. The simulation tool contains models for buildings, HVAC systems, sensors and controllers, and actual or typical weather data. Therefore, analysis of energy consumption/demand and thermal comfort can be made and it is possible to compare different automatic control strategies applied to different building configurations. In the next sections, these main subsystems are described. The mathematical model for a thermal zone, for a HVAC system and a survey of related control techniques applications are also presented. To conclude, some simulation results are presented to illustrate the proposed software environment.

BLOCK-ORIENTED STRUCTURE

The approach of object-oriented software engineering provides a flexible and useful environment for design, development, and modification of classes and their relations in software development.

Each element of thermal system will be a separate module and can be represented by blocks constructed in Simulink. This approach based on blocks makes easier the composition of a complex thermal system. The different blocks of thermal systems for software engineering design based on object-oriented methodology are: building, controller, HVAC system, weather, sensor, and perturbation.

Description of the blocks

The block "Building" provides information about building geometry, material properties and mathematical modeling for predicting thermal loads. Some inputs of this block are the weather data file, ground temperature and perturbations. The outputs are the building zone temperature and humidity.

The block "HVAC system" is also described in the space state form and contains all information related to the available HVAC devices. For heaters, this block presents as inputs the control signal and building temperature and as output the heater temperature.

The block "Sensor" describes the measurement characteristics. The block "Controller" accepts as input the reference temperature or relative humidity (desired room air temperature and relative humidity) and as output the control signal.

The block "Weather" contains data files of several cities.

The block "Perturbation" is composed of perturbations (people, equipment etc.) on internal temperature based on general schedule data.

Building

The first step is the definition of the building geometry and thermophysical properties of all elements. In our first release only a Cartesian geometry can be entered. The mathematical model described below is based on the energy and mass conservation equations for a control volume of a thermally uniform zone.

Thus, for a room enclosed by *m* surfaces conditioned by an electric heater, we find,

$$\rho_A c_A V_A \frac{dT_A(t)}{dt} = \sum_{i=1}^{m} h_{\text{int}} A_i \left[T_{n,i}(t) - T_A(t)\right] + h_c A_c \left[T_c(t) - T_A(t)\right] + D(t), \quad (1)$$

where ρ_A, c_A, V_A, $T_{n,i}(t)$, $h_{int,}$ and A_i are respectively the air density, specific heat, room volume, the *n*-th layer temperature of wall *i*, the convection heat transfer coefficient and the *i* surface area. $T_A(t)$ the room air temperature and $T_c(t)$ the heater temperature (see HVAC systems section).

The perturbation $D(t)$ includes the heat exchanged with the external air through low mass surfaces of the building envelope such as doors and windows and internal gains of energy due to equipment, lights and people. This term can be written as:

$$\mathrm{D(t)} = \sum_{\mathrm{j=1}}^{\mathrm{m}} \frac{\mathrm{T_{eq}}(t) - T_A(t)}{R_j} + q_p + q_e + q_I \quad (2)$$

where q_p, q_e and q_I are the internal gains under the presence of people, equipment and lighting system. T_{eq} represents the equivalent temperature (Air-Sun). The thermal resistance R of *j*-th surface is calculated as a direct sum of external and internal film resistances and the global conduction resistance.

For each layer k within the wall i, we can obtain the following energy balance equation:

$$\rho_{k,i} c_{k,i} V_{k,i} \frac{dT_{k,i}(t)}{dt} = K_{k+1,i} A_i \left[T_{k+1,i}(t) - T_{k,i}(t)\right] - K_{k,i} A_i \left[T_{k,i}(t) - T_{k-1,i}(t)\right], \quad (3)$$

where the thermal conductance K, can be estimated by a harmonic mean as

$$K_{k,i} = \frac{1}{(L_{k-1,i}/2)/\lambda_{k-1,i} + (L_{k,i}/2)/\lambda_{k,i}},$$

where $L_{k,i}$ denotes the thickness of layer k and $\lambda_{k,i}$, its thermal conductivity. The boundary condition for the external layer can be written as,

$$K_{1,i}\left(T_{2,i} - T_{1,i}\right) = h_{ext}\left(T_{1,i} - T_{eq}\right),$$

For the internal layer ($k=n$) of the i-th wall, we can write the following boundary condition equation:

$$K_{n,i}A_i\left(T_{n-1,i}-T_{n,i}\right)=h_{\text{int}}A_i\left(T_{n,i}(t)-T_A(t)\right)+$$
$$\sigma\varepsilon_c A_c F_{s,c-i}\left[T_{n,i}^4(t)-T_c^4(t)\right]+$$
$$\sigma\varepsilon_i A_i\sum_{j=1}^{m}F_{s,j-i}\left[T_{n,i}^4(t)-T_{n,j}^4(t)\right],$$

where σ, ε and F_s are Stefan-Boltzmann constant, emissivity and shape factor.

However, for the floor, we consider for $k=1$, a constant soil temperature at a depth of 5m and we apply the boundary condition of imposed temperature.

In terms of water-vapor balance, it was considered ventilation, infiltration and internal generation from equipment and people breath so that the lumped formulation can be written as:

$$\rho_A V_A\frac{dw_A}{dt}=\left(\dot{m}_{\text{inf}}+\dot{m}_{vent}\right)\left(w_{ext}-w_A\right)+ \dot{m}_b+\dot{m}_{ger} \tag{4}$$

The water-vapor mass flow from people breath is calculated as described in ASHRAE (1997), which takes into account the room air temperature, humidity ratio and physical activity as well.

HVAC Systems

Heating, Ventilation and Air Conditioning (HVAC) systems are responsible for a considerable amount of energy consumption, especially in office buildings. Therefore, in order to provide some information for simulating thermally conditioned buildings, we present, in a first approach, the mathematical formulation for an electric heater, which can be modeled as:

$$\rho_c c_c V_c\frac{dT_c(t)}{dt}=Q(t)-h_c A_c\left[T_c(t)-T_A(t)\right] -\sigma\varepsilon A_c\sum_{i=1}^{m}F_{s,c-i}\left[T_c^4(t)-T_{n,i}^4(t)\right] \tag{5}$$

where $Q(t)$ is the energy rate generated within the heater by Joule effect, ρ_c, the oil density, c_c, the specific heat, V_c, the oil volume within the heater, h_c, heat transfer convection coefficient between room air and heater and A_c the heat exchange area.

For the air conditioning system, we have two approaches. The first one is based on a steady-state empirical correlation obtained from experimental data for predicting the total cooling capacity (TC), the sensible cooling capacity (SC) and the E.E.R. – Energy Efficiency Ratio. Pereira and Mendes (2003) describe the mathematical correlations for two different 10000-Btu/h room air conditioners; one with reciprocating compressor and the other one with rotating compressor. Those direct Expansion (DX) air conditioners use HCFC-22 as the refrigerant fluid. Their empirical correlations can be written in terms of partial thermal loads or in terms of internal wet bulb temperature and external dry bulb temperature as described by Cherem-Pereira and Mendes (2003).

This steady-state modeling is also used by the building Simulation Program DOE-2.0 and recommended by ASHRAE (1997).

The applicability and functionality of this kind of modeling is also investigated by integrating to the building simulation program DOMUS (Mendes et al., 2003) as this sort of room air conditioners are largely used in Brazil.

The second approach for modeling air conditioning systems is based on their transitory operation, which is much more time consuming and requires many input data that normally are not easy at all to be gathered. However, the dynamic response of HVAC components have a direct impact on the energy consumption/demand and thermal comfort evaluation so that a higher accuracy might be needed in some cases, specially when different control strategies are considered.

Control Approaches for Thermal Problems

The thermal comfort concept depends on some variables such as air temperature, radiant temperature, relative humidity, air velocity, metabolism rate, clothing thermal resistance. Due to such a wider concept, it is not trivial to handle all these features in only one control law. However, sometimes, it is possible to consider explicitly a subset of these factors in a control law. In the following, some control techniques for thermal comfort problems are reviewed, highlighting some favorable characteristics in the context.

Robust Control

In the methods of Classical Control, the knowledge of the system model to be controlled is estimated to be enough accurate, that is, the model uncertainties or the unexpected disturbances are not taken into account when modeling the system.

The uncertainty that affects the system model can have different origins: errors of modeling, parametric variations, parameter uncertainties due to precision, simplifications from linearization and the disregard of high frequency dynamics. Thus, it becomes necessary to adequately represent uncertainties, according to their origin in order to obtain a control law that take it into account.

In this software development, there is the possibility to carry out the control of indoor temperatures, considering, in the controller design stage, the parameter uncertainties of the model, for example, the uncertainties on the convection coefficients. Uncertain parameters may be fixed within pre-defined boundaries or may vary if such variation is slow compared to the system dynamics. The aim of a such new controller is controlling the room air temperature variations minimizing the influences of external temperature, when the room model is subjected to parameter uncertainties. Thus, the control guarantees the system robustness according to parameter uncertainties and/or variations, reducing the effect of external disturbances, by using H_2 (Araujo et al., 2001) or H_∞ (Colaneri et al., 1997) criteria.

Intelligent Control

Intelligent control has been developed for challenging problems that cannot be solved by conventional approaches. In intelligent methods, the representation and manipulation of knowledge are the key issues to be used as an attempt to minimize complexities and eliminate heuristic procedures in process control area providing good transitory and steady-state responses for different operation points of processes.

Intelligent control uses a diverse collection of tools, including expert systems, pattern recognition, and soft computing or computational intelligence (neural networks, fuzzy systems, evolutionary algorithms) methodologies. In general, the tools used for intelligent control depend upon the application.

Fuzzy systems have the advantage of working well with both structured and unstructured data (symbols and numbers input and output). The fuzzy logic controllers can be useful for obtaining thermal comfort. Thermal-comfort-influencing variables are classified in two categories: (i) personal-dependent variables such as activity and thermal resistance of clothing; and (ii) environment-dependent variables such air temperature, mean radiant temperature, relative air speed and air humidity. The fuzzy logic controllers can be employed for inside building air temperature and energy consumption control when the building is subjected to undesired effects of external ventilation, external temperature and humidity (Dounis et al., 1995; Kolokotsa et al., 2001).

The unsatisfactory performance of HVAC control systems is frequently due to the inability of conventional controllers to deal with non-linearities and to adapt to long-term change sin behavior of building thermal systems. Neural networks have been increasingly applied to the control of non-linear systems and are actually finding application in HVAC systems (Curtiss et al., 1994; Fargus and Chapman, 1998).

The evolutionary algorithms — genetic algorithm, evolution strategies, evolutionary programming, and genetic programming — are lines of investigation in simulated evolution, but they are broadly similar: each one maintains a population of trial solutions, imposes random changes to each solution, applies a selection criterion to assess the adequacy of proposed solutions, and determines which to retain for further exploration. The evolutionary algorithms are useful for controllers optimization and tuning procedures of HVAC systems (Huang and Lam, 1997).

A Modified Fuzzy Control for Thermal Comfort

Usually, in the thermal comfort field, there is no need to keep the indoor temperature (and/or relative humidity) in a rigid fixed value; a range of temperatures (and/or humidity) is sufficient to create a comfortable situation. From an economic point of view, there is a need to search for a good trade-off between thermal comfort and energy costs. So, from this point of view, the control schemes that can deal explicitly with these factors are desirable for obtain comfort in a given thermal zone. Thus, the aim is to reduce energy demand and energy costs by keeping some thermal comfort indices within an admissible band and one way to achieve this aim is by setting an appropriate control algorithm.

Fuzzy logic controllers have been used successfully in many applications related with thermal systems, as described in the previous section. However, the fuzzy control scheme proposed in Oliveira et al. (2003) is characterized by consider a band of admissible values for temperature instead of a fixed value. In this work, this is done by following a methodology for the controller membership function adjustment. The analysis is performed on a lumped approach based non-linear model for room air temperature and humidity. The heat transfer calculation is made considering multi-layer envelope for discretization of energy equation (Fourier's law), internal radiation effects and air infiltration. The focus is on the room air temperature control problem by using heating systems. Future works will also include humidity control and the results will be compared with the performance of classic strategies and simulations results show the effectiveness of the proposed strategy.

Adaptive Controllers

Adaptive control techniques include automated identification and control design. From an industrial perspective, adaptation can be considered as a set of methodologies that can significantly improve the performance of a process by providing controllers with automatic tuning, automatic generation of gain scheduling and continuous adaptation. Adaptive controllers are designed to accommodate variations of the behavior of controlled processes. Such controllers can modify their own control strategies to adapt to the new process behavior.

Over the last thirty years, many theoretical developments have been made on adaptive control methodologies but little has been transferred into HVAC systems practice. HVAC systems contain many time-varying and nonlinear processes. Adaptive control techniques are attractive in HVAC applications because process features change widely due to variations in weather and building occupancy (Nesler, 1986). Several adaptive control methods have been proposed in literature for control system of HVAC systems (Georgescu et al., 1994; Wang et al., 1999).

Predictive Control

Another approach that seams to be very appropriated to be used in this scenario is the predictive control scheme, which has already been mentioned in the thermal system control context, as in Ghoumari et al. (2001), Souza et al. (1997) and Dion et al. (1991). Model Based Predictive Controllers (MBPC) are, by definition, based on predicting the behavior of the process to be controlled. The principle of MBPC consists in calculating the control input by the minimization of a cost function over a future time horizon under certain process constraints (Clarke, 1994), and the closed loop performance depends on the choice of an appropriate model for prediction and of several tuning parameters. Predictive controllers can be implemented as adaptive or robust methodologies. So that, model uncertainties can be taken into account.

SIMULATION EXAMPLES

In this section, the building simulation environment is illustrated by two temperature control cases.

Simulation environment:

A workspace for simulation should be generated by connecting the system main blocks (i.e., subsystems) representing building, HVAC, controller, sensor and external weather data. This is based on the Simulink philosophy, where each subsystem is selected in its own library, as shown in Figures 1 and 2. An example of a complete system configuration, ready to perform a hygrothermal building system simulation and analysis, is given by Figure 5. In this environment, the selected building is modeled following the description given in the previous section. The selected HVAC system is a heater and the controller follows the on-off scheme. The libraries are open for further implementations, so more features can be added in the future.

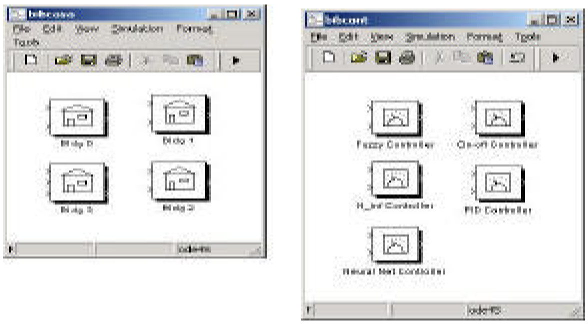

Figure 1: Building and controller library example.

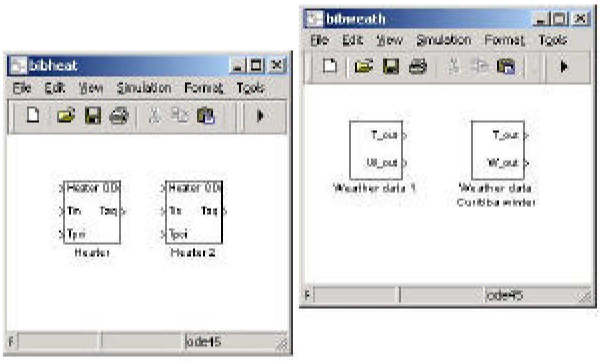

Figure 2: Heater and weather library example.

Simulation Results:

In the following, the closed-loop control performance of two control strategies are compared, the on-off and fuzzy logic based ones. The simulation environment is given by Figure 5 and the changes between the two cases are made just by picking the selected controller in the library. The next step is to set the subsystems parameters.

The building and heater system have the parameters given by tables 1 and 2. The simulations are computed during 48 hours and the unit of all mentioned temperatures is Celsius. The nominal temperature setpoint is 22°C. The internal, external and walls initial temperatures are 11°C and the profile of external temperature is a sinusoidal wave during the whole day.

Figures 3 and 4 present the indoor temperature profile for each controller. Figure 3 illustrates the performance of the on-off controller with a dead-zone defined by $\pm 2^{o}$ around the nominal set-point value. As it is expected, the temperature profile is very oscillatory around the set-point value (22°). The control system takes around 0.46 hours to take the room temperature from the initial state into the admissible temperature band. During the simulation, the registered total energy consumption is 269.7 KWh and the system stays 37.5% of the total time using more than 70% of the available power, that is, 15 KW.

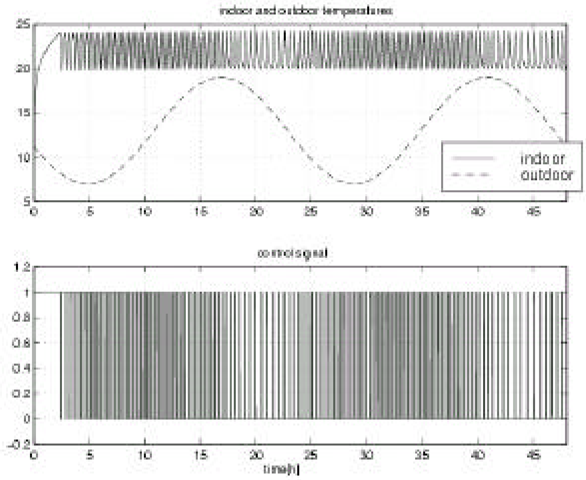

Figure 3: Temperature control using the on-off strategy.

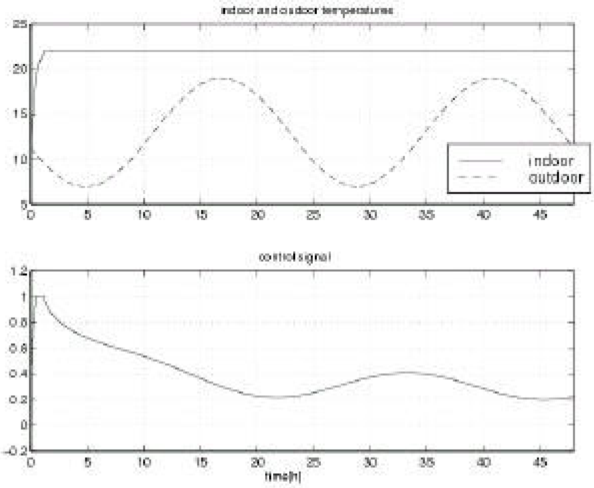

Figure 4: Temperature control using the FLC strategy.

Fig. 4 illustrates the performance of the fuzzy logic controller. It can be noticed that the temperature control performance is improved, in relation to the on-off scheme. The steady state error is zero even on the presence of external temperature disturbances. The control system takes around 0.62 hours to lead the room temperature from its initial state into the admissible temperature band. During the simulation, the registered total energy consumption is 284.4 KWh, that is, an increase of 5.4% in relation to the on-off controller. However, the FLC (Fuzzy Logic Control) system requires only 8.7% of the total time using more than 70% of the available power and, in a steady-state condition, it operates consuming less than 40% of the maximum power. These characteristics reduce the electrical power system demand.

CONCLUSIONS

This paper presented the development of a Matlab-based tool for hygrothermal building simulation and performance analysis of HVAC automatic control systems. The proposed software version is modular allowing easy expansion and interchangeability of building, HVAC and control systems. A description of its block-oriented organization was given and an example of a mathematical model for a thermal zone and for a HVAC system existing in the software tool were also described.

Five control techniques usually applied to HVAC systems (On-Off Control, PID, Robust Control, Adaptive Control and Intelligent Control) were discussed.

A simulation example illustrates the use and the capabilities of the proposed environment in the analysis of control performance and energy consumption.

In future works, the libraries will be extended in order to permit test and analysis of the hygrothermal condition of building system using different types of controllers and HVAC systems. An example is the evaluation of different proposed HVAC control techniques for a summer period using an air conditioning system coupled to a building zone simulation.

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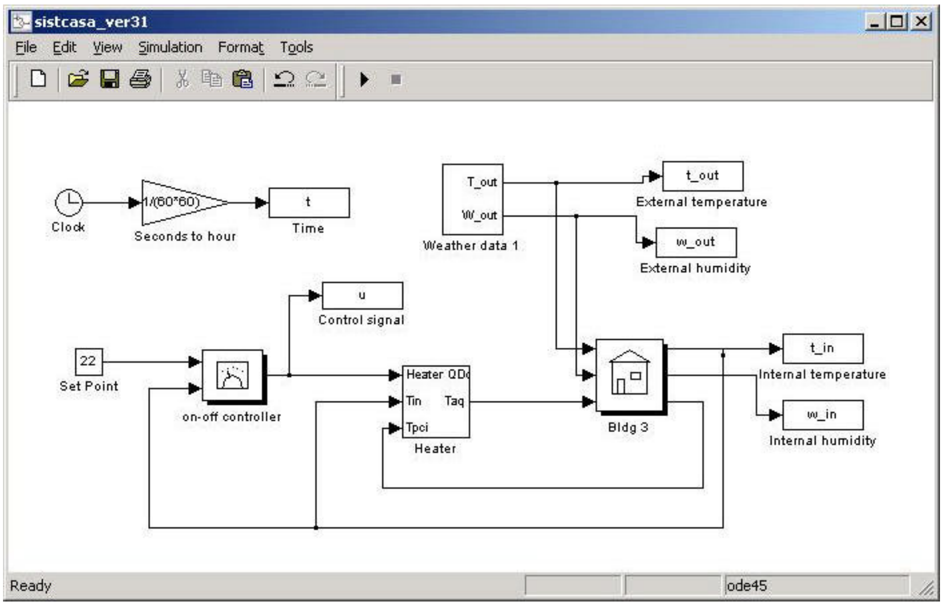

Figure 5: Simulation tool workspace example.

Table 1: Thermal properties.

	ρ (kg/m^3)	c (J/kg-K)	λ (W/m-K)	H (W/m^2-K)
Heater (c)	884.1	1909	---	5.0
Room (A)	1.16	1007	---	5.0
Sensor (s)	8933	385	---	5.0
Walls and ceiling	2050	950	1.92	5.0
	1900	920	0.985	
	2050	950	1.92	
Floor	2050	1840	0.52	5.0
	998	900	1.4	
	550	2385	0.2	

Table 2: Dimensions.

	A (m^2)	L (cm)	V (m3)
Heater (c)	5	---	0.002
Room (A)	25*	---	62.5
Sensor (s)	1.26e-5	0.1	4.2e-9
Walls and ceiling	12.5	2	0.25
	12.5	10	1.25
	12.5	2	0.25
Floor	25	20	5.00
	25	250	62.50
	25	10	2.50

* Floor and ceiling surface area.